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Additive Manufacturing: Understanding and Applying Key Design Considerations

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LEARNING OBJECTIVES

- Explain the process of metal additive manufacturing, namely laser powder bed fusion
- Identify key variables that affect the quality of a metal 3D-printed part
- Apply sustainable best practices to influence the design and make of a metal 3D-printed part
- Implement design variables to your workflow using Netfabb and Netfabb Simulation Utility

DESCRIPTION

Laser powder bed fusion (LPBF) is one of the most predominantly used additive manufacturing (AM) technologies today, producing functional metallic parts in several industries such as aerospace, medical, and automotive. As an emerging and complex technology, the manufacturing design guidelines and rules of LPBF along with its impact on sustainability are not well understood. This session builds off design for additive manufacturing (DfAM) principles as they apply to specific process parameters and machine dynamics defined in LPBF. These include recoater blade interference, support structure, and part distortion. This session also provides insight into the impact of AM on sustainability, as well as highlighting key design considerations to improving the implications on sustainability. With these considerations in mind, the session will explore how a user can implement design variables into their workflow using Netfabb and its Simulation Utility.

SPEAKERS

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Brian Jeong is a Shop Supervisor at the Autodesk Technology Centers in Toronto, Canada. Brian has a background in automotive and mechanical engineering, additive manufacturing, and project management. Brian has an extensive research and laboratory background in process optimization methods in laser powder bed fusion additive manufacturing and design for additive manufacturing. Brian is passionate about exploring new ways of designing and making.

Tyson Fogel
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Inspired by circularity and biomimicry, Tyson is an avid maker and sustainability advocate. He works directly with residents, innovation communities and researchers to provide technical expertise and fabrication consultation through the Autodesk Outsight Network. A designer and cabinetmaker by trade, Tyson's past work includes everything from additive, subtractive manufacturing, woodworking to CAD/CAM, Generative Design, construction and more recently - robotics.

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1.1 WHAT IS ADDITIVE MANUFACTURING?

Additive manufacturing (AM), also known as 3D printing, is the process of joining materials to make objects from 3D model data, usually layer-upon-layer, as opposed to subtractive manufacturing methodologies. The process in AM is based on the same core concept of the technology. The process begins with a CAD model of the part, which is sliced horizontally into layers of specified thickness using software. The model is then interpreted by the AM system, converted into tool-paths, and printed in a layer-upon-layer build plan. The feedstock material can be in the form of plastic, metal, composite, wax, or paper.

AM offers great advantages, making it a unique manufacturing process compared to subtractive, formative, and joining. The layer-by-layer approach from a CAD model allows production of complex and customized parts, giving the designer creative freedom. Parts can be printed with complex and highly-accurate internal structures such as lattices or internal channels, which would otherwise be impossible, if not, difficult and time-consuming to produce using traditional machining, casting, or welding methods. Due to the additive process, material waste can be minimized, as the material is fused selectively in each layer, reducing costs and weight of the part. With the inputs essentially being a CAD model, an AM system, and feedstock material, parts can be printed in a few steps without the need for expensive tooling, dies, or casting molds. This is especially advantageous for printing in remote areas and for printing of spare parts.

Despite its unique advantages, AM also has some downsides worth mentioning. The complexity of AM requires extensive knowledge of the process and how each factor or parameter can affect the quality of the final part. The layer-by-layer process can lead to slow build rates, which in turn, increases costs. AM systems and feedstock material are also expensive, thus increasing production costs. Depending on the application of the part, additively manufactured parts will require post-processing to improve part density, geometric tolerance, and/or surface finish, usually increasing costs and lowering productivity.

Over the past three decades, the technology of AM has improved to account for seven different technologies (see Figure 1). These include vat photopolymerization, material extrusion, material jetting, binder jetting, powder bed fusion, direct energy deposition, and sheet lamination. The parts produced by AM today are not only purposed for hobbyists and desktop models, but also for a wide range of industries, such as medical, aerospace, and automotive – for applications ranging from prototyping to commercial production.
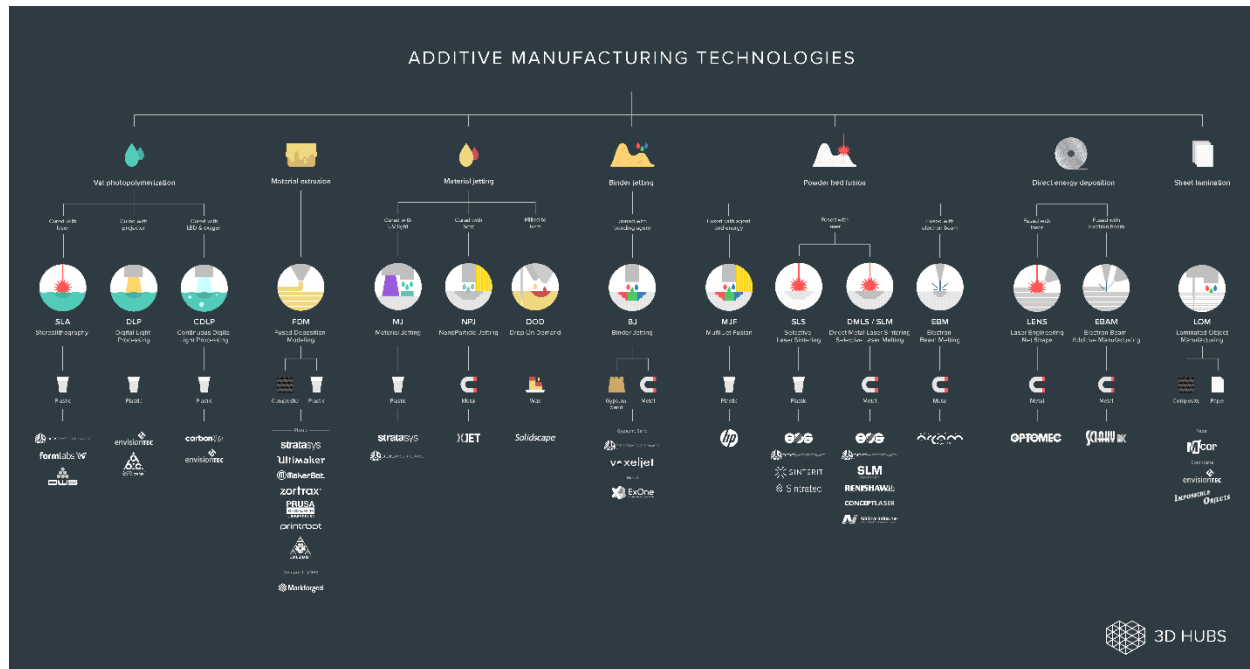
Figure 1: Additive manufacturing technologies (Figure courtesy of 3DHubs)

1.2 LASER POWDER BED FUSION ADDITIVE MANUFACTURING

Under the umbrella of powder bed fusion, there are four similar but distinct technologies – multi-jet fusion, selective laser sintering, laser powder bed fusion, and electron beam melting. Laser powder bed fusion (LPBF) is also known as direct metal laser sintering (DMLS), direct metal laser melting (DMLM), or selective laser melting (SLM). This process uses a focused laser beam to selectively melt metal powder in a layer-by-layer approach.

1.2.1 PROCESS DESCRIPTION

The feedstock material that is used in the LPBF process is in the form of metal powder available in a variety of different alloys. These metal powders are microscopic in size, usually ranging in sizes from 15 to 80 microns. Smaller grain sizes will tend to have desirable effects on the finished part, such as better surface finish, density, and mechanical properties. Depending on the powder production method or the powder atomization process, the morphology of the powder can be spherical or irregular in shape.

The LPBF build chamber essentially consists of a powder roller/recoater, powder bed or build bed, laser(s), powder delivery system, and the feedstock material enclosed in a controlled inert atmosphere (see Figure 2). The powder delivery system is generally driven by a piston and supplies the feedstock powder to the system. As the powder delivery system is lifted by a piston, the roller or recoater will coat an even layer of metal powder to the build bed, usually made of metal, at a thickness of the slice layer as defined by user input. The roller or recoater also acts to compact the powder to prevent the formation of any voids within the powder that may cause problems during printing. Then the laser selectively melts the first slice layer according to the

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tool-paths generated by the slicing software. The first few layers of the part will essentially be welded onto the build plate due to the penetration of the high-powered laser, causing fusion of the part and build plate. The types of lasers used in LPBF systems can be CO_2 or fiber, with the latter being more effective and predominant in modern systems. The inert gases supplied through the chamber are typically argon or nitrogen and provide an oxygen-reduced atmosphere to prevent oxidation of metals during the printing process. Once the first layer is complete, the build bed will lower by the specified layer thickness to allow a new layer of powder to be applied by the recoater, and the process will repeat layer-by-layer until the part is fabricated. The end result in the printer is a fused part that is welded onto the build plate, surrounded by loose metal powder.

Once printed, the loose powder will be cleaned from the build chamber, and the manufactured part will undergo part removal post-processing (or stress-relief heat treatment, if required). Some LPBF systems are equipped with a wire electrical discharge machining (WEDM) system that can automatically remove the part from the build plate, and can make for an easy part removal process. The fabricated part(s) can also be manually cut off the build plate using a hacksaw or horizontal bandsaw. Once removed, the part can undergo further post-processing methods to improve mechanical properties, density, geometric tolerance, corrosion resistance, and surface roughness. In many cases, the heat treatment is done before the part is removed off of the build plate to relieve the residual stresses from the build process. This reduces part warping or cracking once the part is removed.
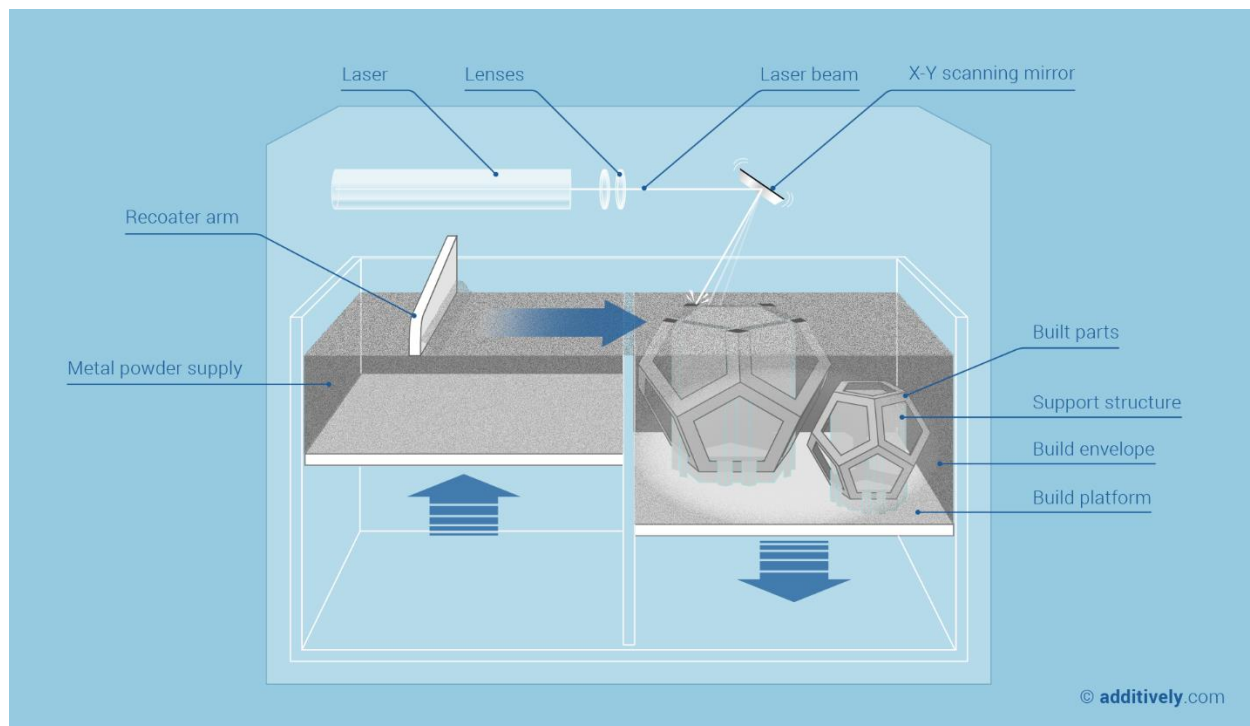

Figure 2: Schematic overview of the laser powder bed fusion process (Figure courtesy of additively)

In LPBF, there is an extremely wide range of parameters that can affect the in-process performance and final part quality. Some of these include process parameters, feedstock material/powder properties, ambient conditions, and the motion device of the equipment. The key process parameters having the greatest influence on the part quality are outlined below, and include powder characteristics, layer thickness, laser powder, scan speed, and hatch distance.

Powder characteristics, specifically the particle size distribution (PSD) and morphology, are critical parameters in determining the final part quality and in-process performance. In LPBF, typical particle size ranges from 10 to 60 microns. Depending on the method of atomization used for powder production, it will affect the PSD as well as the morphology. For example, if water atomization is used, it will produce powders with irregular morphology, and if plasma atomization is used, it will generally produce a particle size range between <1 and 200 microns with spherical morphology (see Figure 3). PSD is the range of particle sizes in a given batch of powder. Understanding the PSD of the feedstock powder being used in a LPBF process is critical to understand what process parameters need to be used, as it impacts powder behaviour during melting, sintering, spreading, and compaction, which in turn impacts the physical properties of the final part. When it comes to choosing the particle size in LPBF, there is no optimal particle size range for every build and every part design. It is dependent on the 3D printer, the part geometries, the type of powder recoating mechanism used, other powder characteristics, etc.
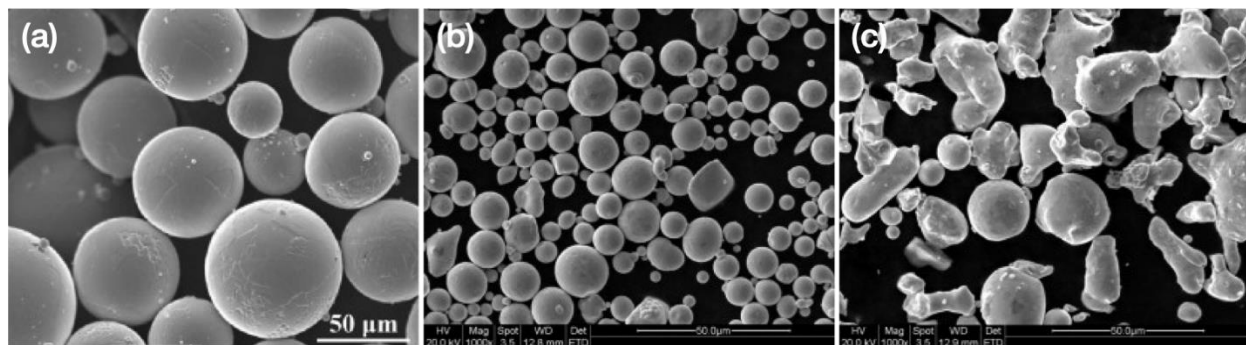

Figure 3: SEM images showing surface characteristics and morphologies of (a) plasma-atomized Ti-6Al-4V powder, (b) gas-atomized stainless steel 316L powder, and (c) water-atomized stainless steel 316L powder

Layer thickness or slice thickness is the height of each layer in the Z direction. Layer thickness directly affects the process productivity, as thicker layers provide a faster rate of producing a part. Moreover, layer thickness will also affect surface roughness of the resulting part especially in the case of angled surfaces. Generally, a lower layer thickness will result in an improved surface finish. With LPBF being a layer-by-layer process, the phenomena known as the "staircase effect" or "stair step effect" is a factor worth considering when optimizing the surface roughness of an angled or curved surface.
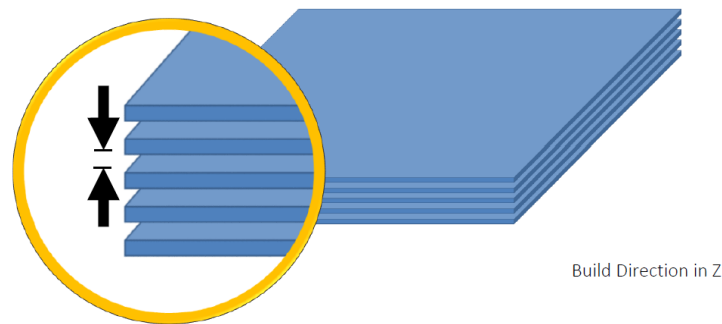
Build Direction in Z

Figure 4: Layer thickness or slice thickness in additive manufacturing (Figure courtesy of Renishaw)

Laser power is the intensity that the laser has when interacting with the powder to create melt pools. Just like in a welding process, the heating rate and cooling rate play a big role in the quality of the part. Determining the correct laser power to use is dependent on many variables such as the type/alloy of metal being printed, its powder characteristics (PSD, powder morphology), and layer thickness. Usually, metal powder production companies will provide correct parameters to use for their powders, but in the case of printing using a new type of alloy unknown in the AM industry; research, tests, and simulations can help determine the correct process parameters. During printing, when the molten material does not wet well to the substrate or the fabricated and solidified layers underneath due to low laser power, high surface tensions create a breakup of the melt pool into small spheres – a phenomenon known as balling. There is an upper limit though, when the power is too high the laser can cause excessive energy intensity in the melt pool. The excessive energy tends to cause the powder around the melt pool to spatter, causing defects, poor surface finish, internal pores, and could even lead to print failure.

Scan speed is the speed of the laser on its lateral movement across the build plate, i.e. how fast the laser scans from one point to another. In the case of modulated systems, such as Renishaw printers, pulse duration of exposure time is used. Pulse duration or exposure time, which is the amount of time the modulated laser exposes a certain point on the surface, have direct influence on the scan speed of the laser. Slow scan speeds can lead to lower print productivity and increased energy density. High scan speeds can produce balling defects due to insufficient energy density. Similar to laser power, finding the correct scan speed is determined by the provided metal powder parameter sets or through iterative research.

Hatch distance, or sometimes referred to as the beam offset or scan spacing, is the perpendicular distance between successive laser scan lines (see Figure 5). In LPBF, there are a variety of infill hatch types or scan strategies that determine the pattern of the laser tool-paths. The meander pattern fill type is a straight-line vector path from each side of the border to the other, and is the most commonly used due to its productivity and efficiency. It is recommended to have a hatch overlap of about 1/3, as too large of a hatch distance can produce porosity between the hatch lines and cause insufficient melting of the interface between the scan tracks. Too small of a hatch distance (large overlap of scan tracks) will increase the temperature of the previously fabricated scan track producing larger heat affected zones (HAZ) and less desirable microstructure.
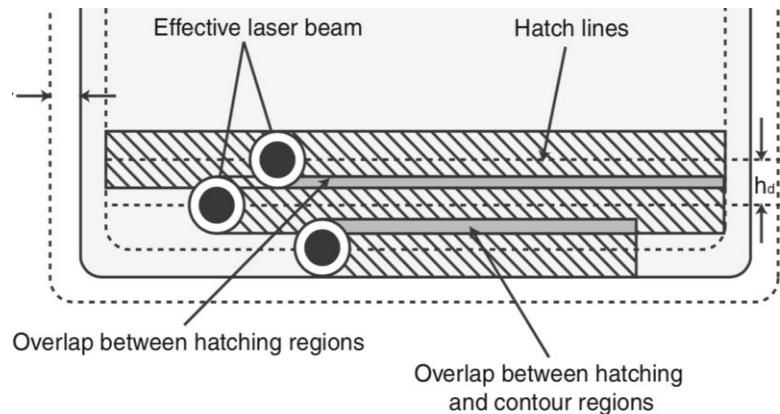
Figure 5: Schematic representation of hatching regions in LPBF

1.3 DESIGN FOR ADDITIVE MANUFACTURING

Design for Additive Manufacturing (DfAM) is defined as a synthesis of shapes, sizes, geometric mesostructures, and material compositions and microstructures to best utilize manufacturing process capabilities to achieve desired performance and even to maximize product performance (Rosen 2007). Kumke defined DfAM in two classifications in his paper "A new methodological framework for design for additive manufacturing" – the strict sense and the broad sense. DfAM in the "strict sense" includes approaches intended for the core design process, such as AM design rules, guidelines, and methodologies for ensuring AM-producible parts, manufacturability analysis, selection of applications, etc. DfAM in the "broad sense" includes methods not directly related to the design process itself, but to additional approaches beyond that such as upstream/downstream activities, costs, lifecycle analysis, supply chain, etc. Because of this and the overall complexity of the AM technology, DfAM can be incredibly convoluted. During the process, the involvement of design engineers, scientists in physics, materials, polymers, welding professionals, software engineers, business development units (and many more) are essential to the success in metal AM components.

Support structures are generally essential when printing a part or component. There are two different types of supports – primary and secondary supports. Primary support structures are those developed within the CAD model of the part. Secondary support structures are those developed by the build preparation software such as Autodesk Netfabb. Supports are needed when designing a part with overhangs, certain fillets or chamfers, angled surfaces less than 45 degrees, and holes or tubes that run perpendicular to the build direction. Support structures are also used between the build bed and the part to prevent damage during the part removal process or to allow the heat from the laser energy to be dissipated more quickly to prevent distortion of the part. Support structures are essential in holding down certain features of the part to prevent it from warping or cracking due to high residual stresses, which can lead to a failed build.

Residual stress is an important factor to consider in a LPBF process. As the LPBF process results in rapid cooling rates, it is very likely that residual stresses will occur while printing. As the un-fused layer of metal powders are melted by the laser, it fuses with the layer(s) below within a matter of micro-seconds. When the new layer begins to cool and solidify, contraction occurs and brings about a shear force for the subsequent

layers below, causing distortion, curling, and cracking defects. Design considerations prior to printing is important to analyze in order to avoid residual stresses from occurring. To avoid residual stresses, choosing the right scan strategy for the geometry of the part can affect the level of stresses that can build up on the part. Other methods include using heated or thicker build plates to slow the dissipation of heat, and altering the volumetric energy density and scan speeds of the print.

2. KEY DESIGN CONSIDERATIONS

Due to the complexity, cost, and time-consumption of a LPBF process, it is essential to closely examine the design considerations for the part(s) being printed. Understanding areas of potential failure during the print and applying those considerations to the AM process to mitigate or prevent those failures will save costs, improve print quality, and reduce material waste and scrap. The three key design considerations described in depth below are recoater interference, support structure, and part distortion.

2.1 RECOATER INTERFERENCE

2.1.1 RECOATER INTERFERENCE DESCRIPTION

As described in Section 1.2.1, during the LPBF process, in order for delivery of feedstock metal powder to the build plate, a roller or recoater will coat an even layer of powder to the build bed at thicknesses as low as 20 microns. While there are a few mechanisms for powder delivery, the most common in LPBF systems today is the blade mechanism. Recoater blades can be either soft and compliant, usually made of silicon or rubber, or hard and stiff, usually made of steel or ceramic. Soft blades are advantageous as they reduce the likelihood of part interference causing damage, but they provide less layer thickness certainty compared to stiff blades. However, stiff blades have a higher tendency of collision with the part leading to failed prints.

Due to the rapid cooling rates during print, contractions and shear forces due to residual stresses can cause part deformation where parts will warp upwards in the Z-direction. During the print, the powder recoating process can happen several thousand times depending on the height of the print. Moreover, with the complexity of the print/part(s), small feature sizes, small layer thicknesses, and most importantly, part deformation during print, it can lead to the recoater blade colliding with the print below, leading to damaged recoaters, damaged parts, incomplete powder layers, or a failed print.
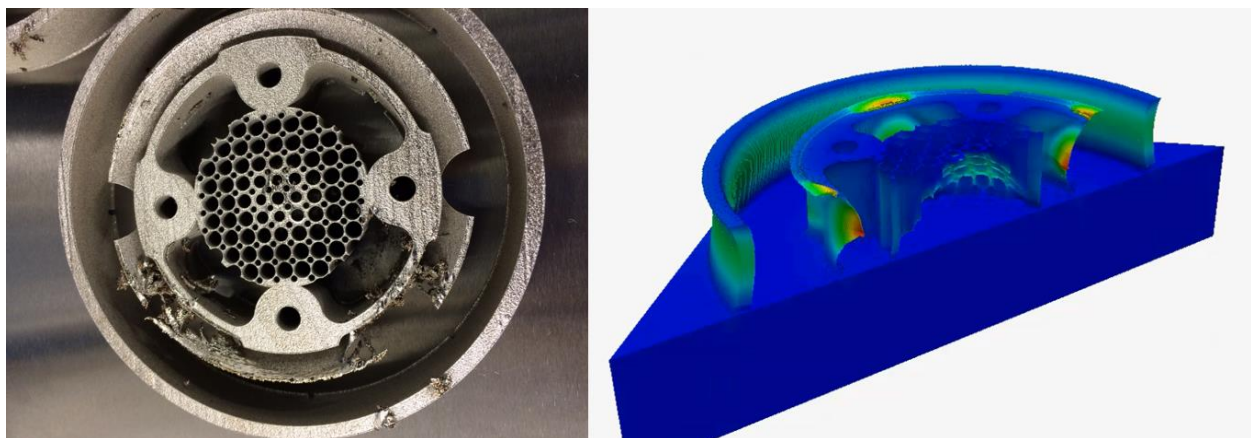

Figure 6: Failed LPBF build of a piston crown and a simulation of the part predicting recoater interference using Netfabb (Figure courtesy of Dr. Tim Simpson, Penn State University)

In an ideal case, the recoater clearance during powder recoating process should be at 100% (or in other words, 0% overlap) – see Figure 7a. Recoater clearance/tolerance is the percentage of the next powder layer that is not impinged upon by the upward deflection of the part. The default value for recoater tolerance in Autodesk Netfabb Simulation is 80% (20% overlap). If the actual tolerance drops below this level, warnings are reported in the log files indicating that the part is likely to collide with the recoater blade.
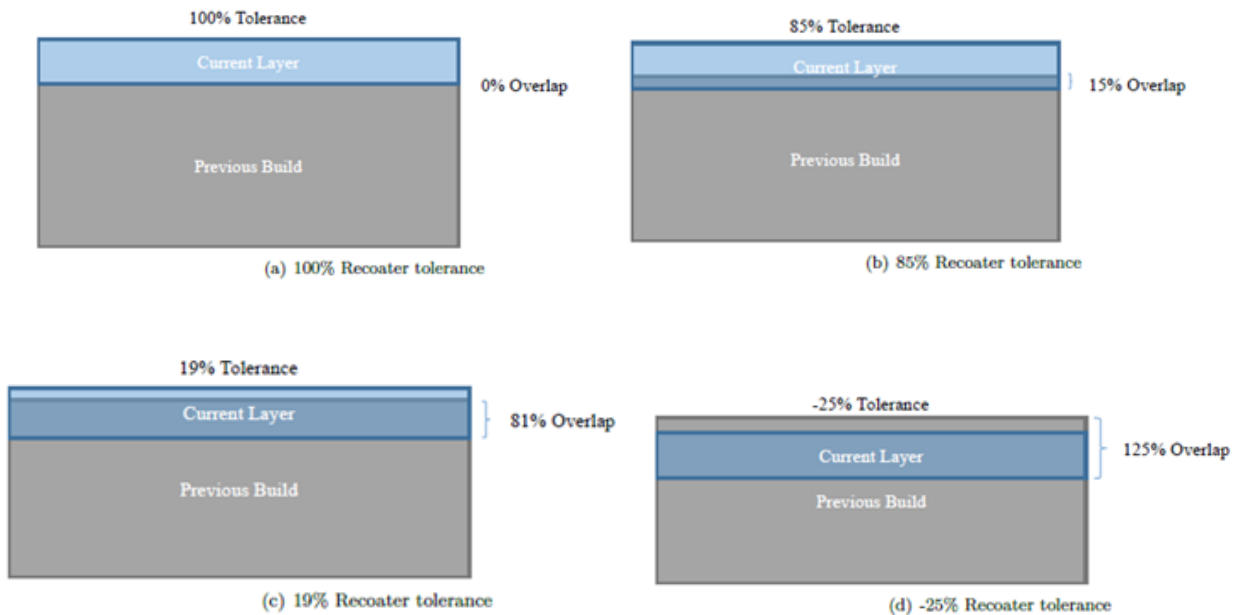
Figure 7: Schematic showing different cases of recoater tolerances (Figure courtesy of Autodesk Netfabb)

In Figure 7b, residual stresses caused slight upward distortion of the solid part, leading to a 15% overlap or 85% recoater tolerance, which would be acceptable if the recoater tolerance was set to 80%. In Figure 7c, only 19% recoater clearance remains due to part distortion, which would issue a warning message as the tolerance is well below the set threshold of 80%. In a more extreme case, Figure 7d shows a 125% overlap or -25% recoater tolerance, which would certainly issue a warning message.

2.1.2 NETFABB DEMO: PREDICTING RECOATER INTERFERENCE

Using Netfabb and its Simulation Utility, recoater blade interference can be predicted based on the deformation of the part during the printing process. After importing the part to the chosen machine build bed, setting the orientation, support structure and choosing process parameters, we can go ahead and start the build simulation.

1. In Autodesk Netfabb, click **Start build simulation** under **Current Build** on the right dialog box.
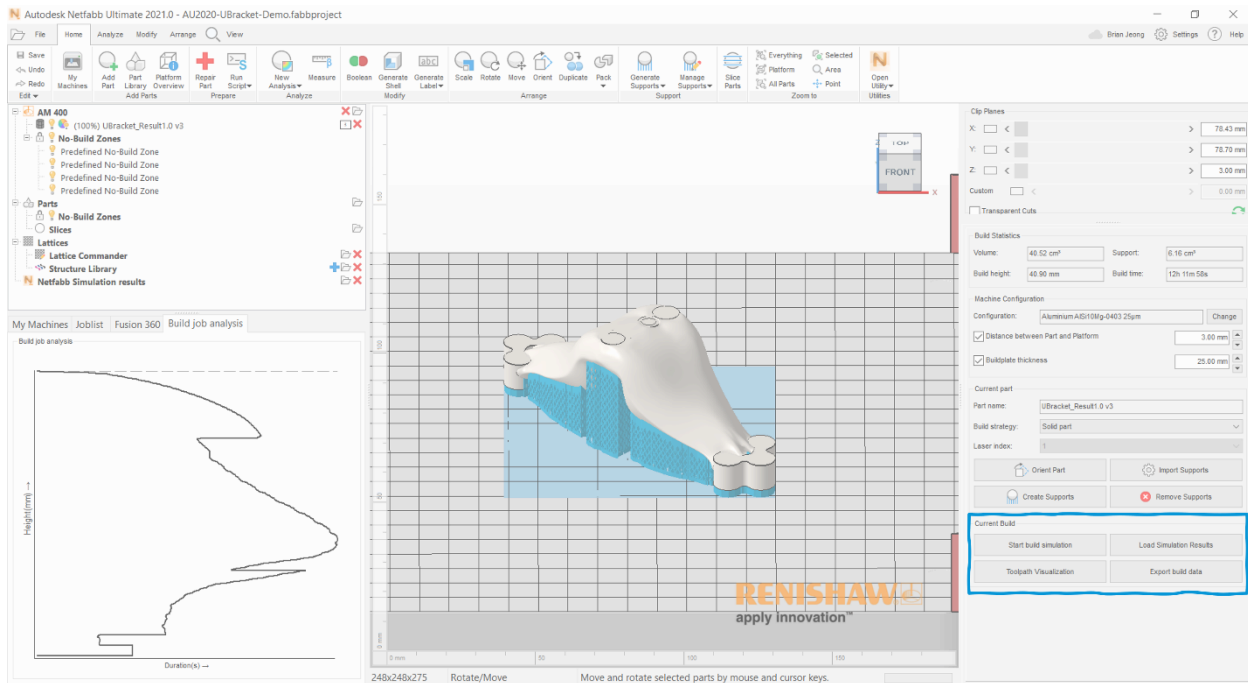
2. Once the Simulation Utility is open, navigate to the **Home** tab and click **Solver Settings** under the **Analysis** pane.

3. In the **Solver Settings** dialog box, enter the desired Recoater tolerance value, then click OK. This value is defaulted to 80% tolerance. More details on the settings can be found here.
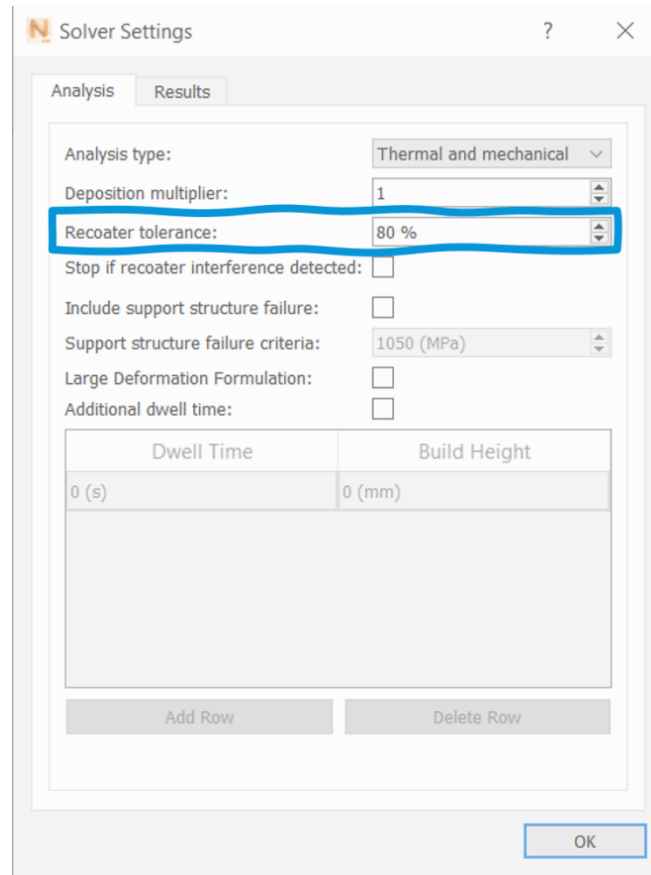
4. Click **Solve** under the **Analysis** pane.
5. Once the simulation analysis is complete and loaded, play through the animation while in the Displacement view by navigating to the **Animation** pane under the **Results** tab. Note any significant upward part deflection illustrated in red.
(Side note: To remove element edges in the part simulation, right-click on **Displacement** on the left View tree and click **Render Properties**. Un-check **Element edges**).
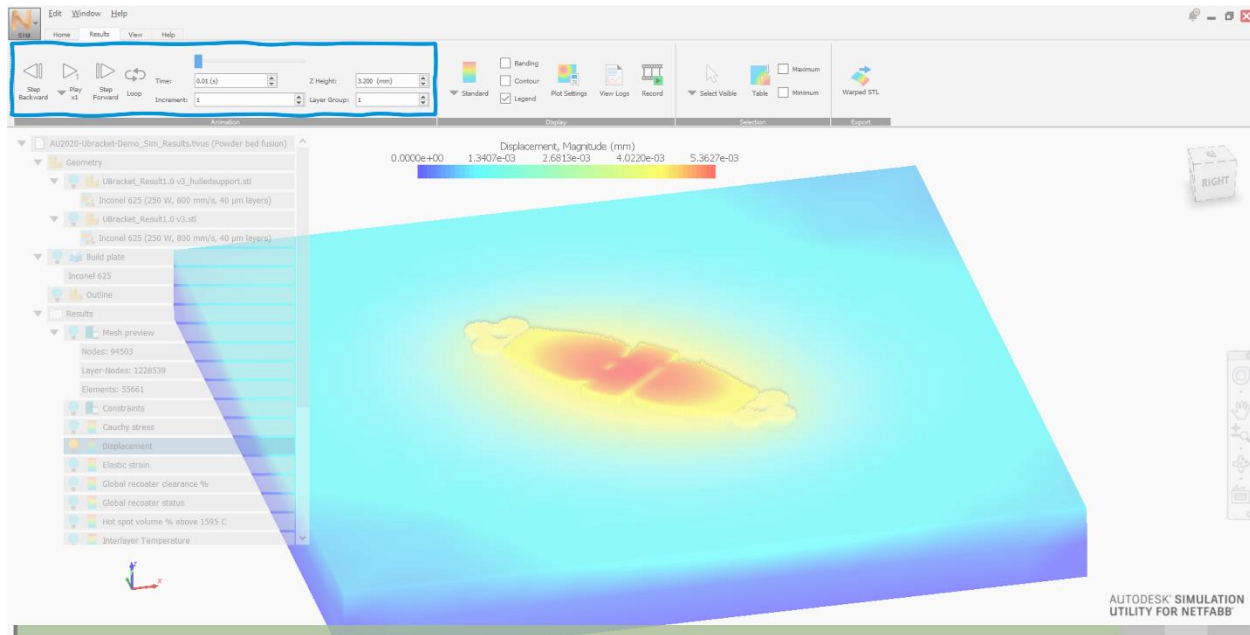
6. To review the simulation analysis more in detail, specifically recoater blade interference warnings, navigate to the **Display** pane and click **View Logs**.
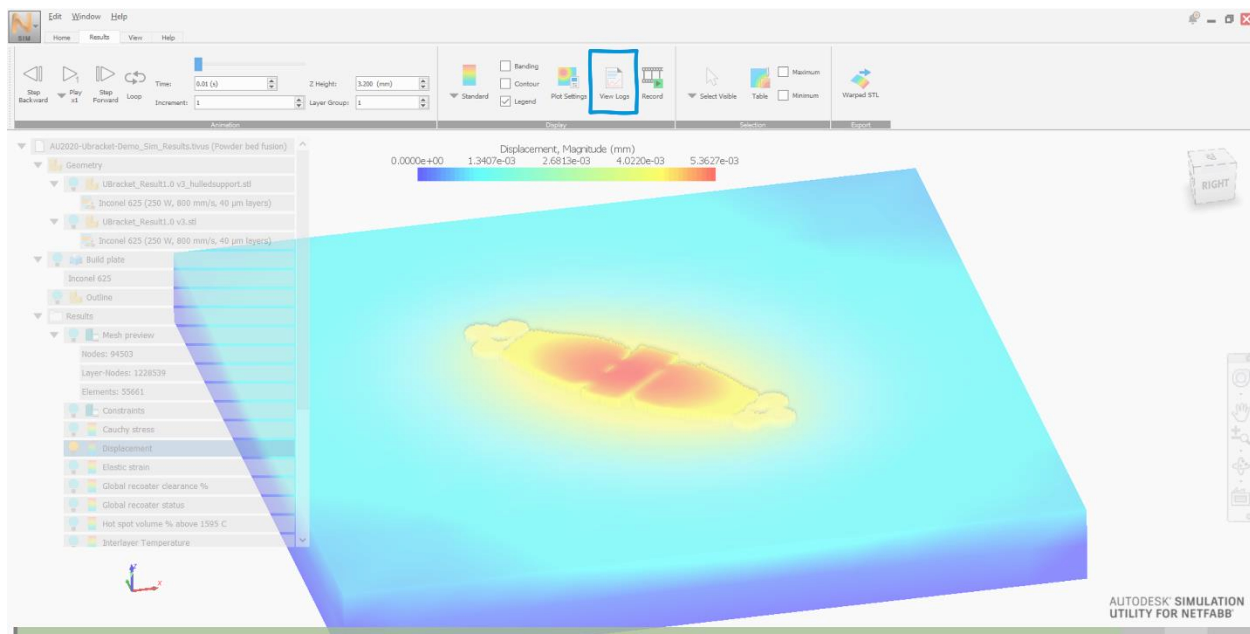

7. In the Logs window, there are three tabs – Thermal, Mechanical, and Recoater Blade Interference. Click the **Mechanical** tab and scroll to the bottom of the log to check for warnings.

There are two classes of warnings you may see:

Warnings – This class of warnings indicate a solver event occurred which may need user attention to ensure the quality of the simulation or may alert the user about certain simulation results, like Recoater Interference or Support Structure Failure. These are viewable from the log files.

Critical Warnings – This class of warnings occur when the solver detects a model input or event which is likely to impact the results of the simulation, which may need to be addressed and the simulation re-run. These are viewable from the notifications system and the log files.

In this case, there are 8 warnings and one critical warning.
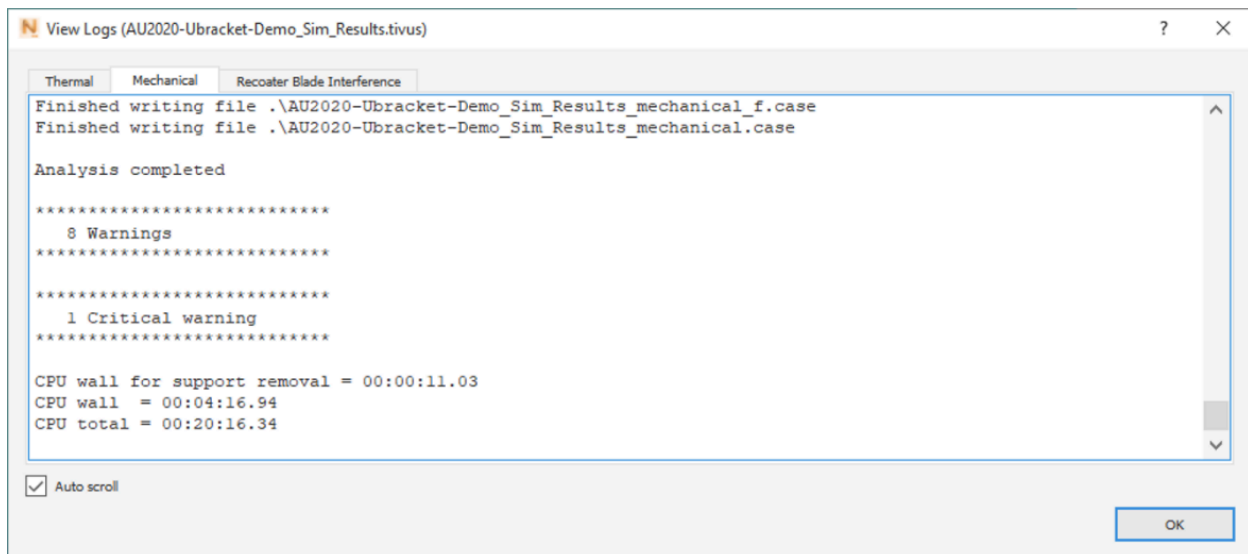
8. Scroll up in the Mechanical log to find the actual warning and critical warning details. In this example, the critical warning indicates that there are recoater interference detections at five different layer groups. This means that 5 of the 8 warnings are recoater interference warnings that fall below the specified 80% recoater tolerance.
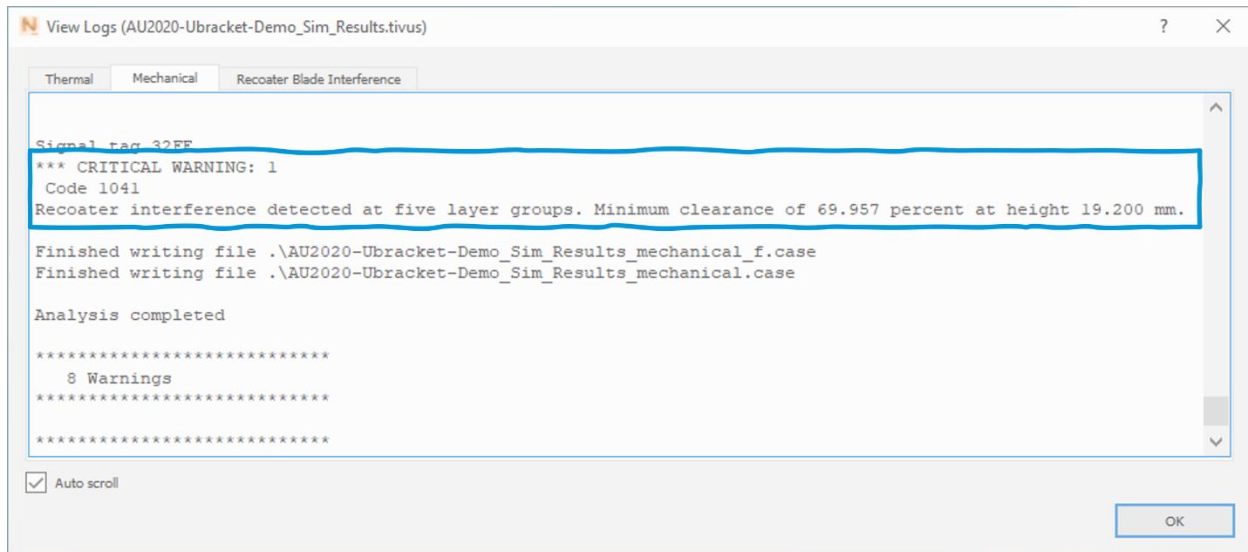
9. Click on the **Recoater Blade Interference** tab. In this log, it can be verified that there are 5 layer groups that fall under the 80% recoater tolerance – layer groups 5, 6, 7, 8, and 11. The log also specifies the time stamps as well as the layer height at which the recoater interference occurred.
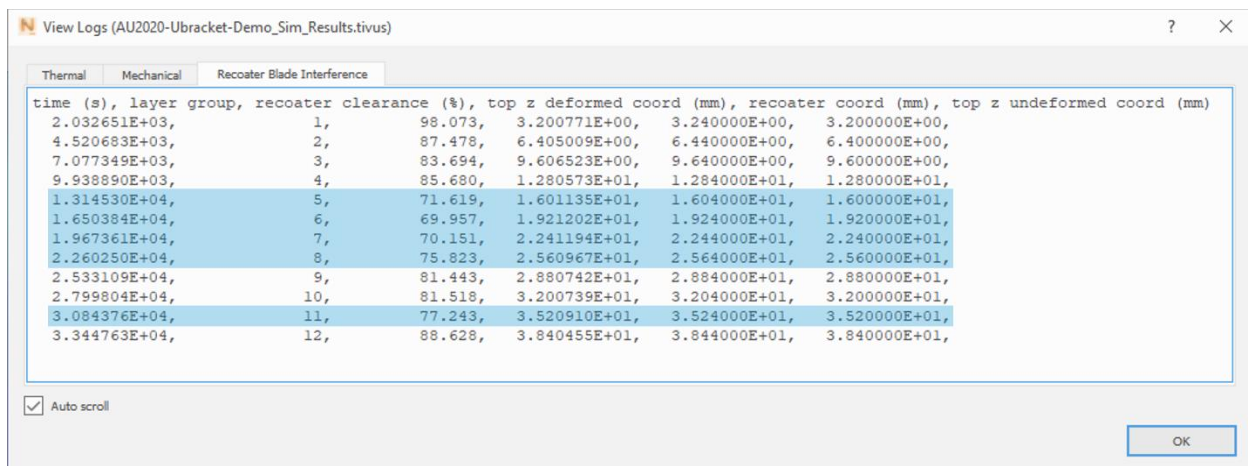

10. Noting these time stamps and layer heights, we can return to the **Animations** pane and review where the part deflection occurs. Furthermore, we can go back to the Netfabb software and get a more accurate view of the layer at which the deflection occurs.
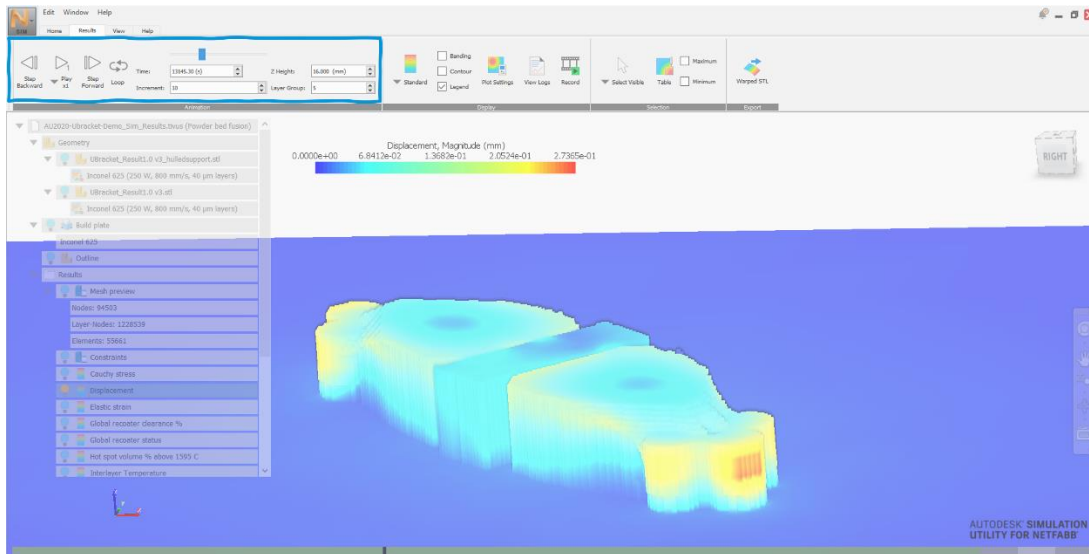
11. In the left View tree, there are four types of recoater results to further analyse the results – the **Recoater clearance %**, the **Global recoater clearance %**, the **Recoater status**, and the **Global recoater status**.
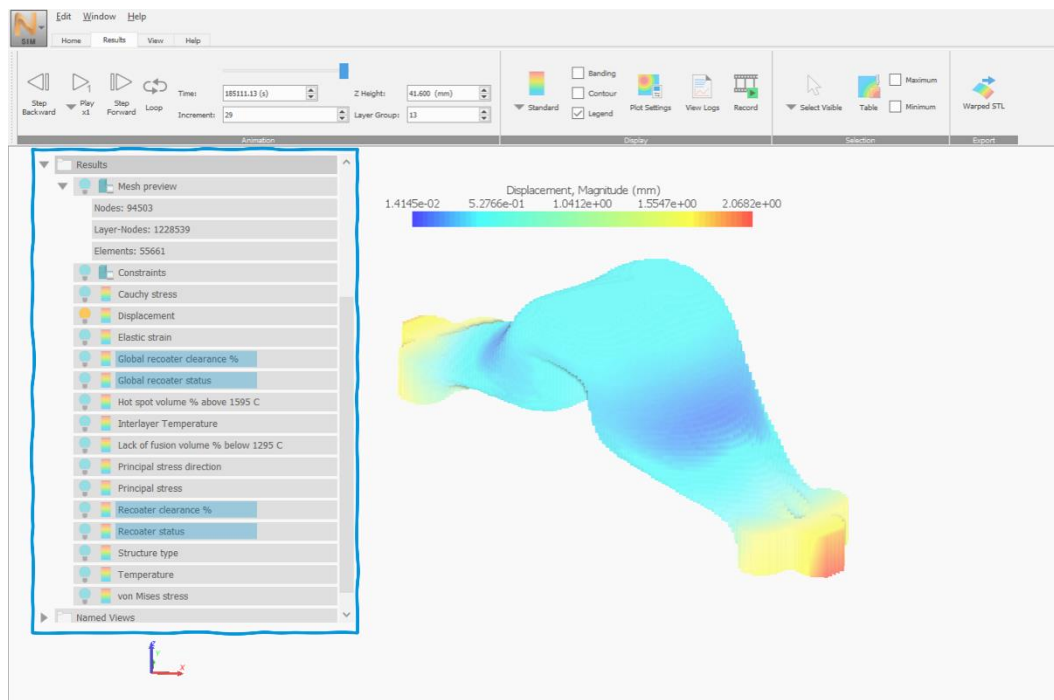

12. The **Recoater clearance %** results allow you to step through the build increments in the **Animation** panel to analyze how the clearance values change as the build progresses. It helps to observe the legend, noting the specified recoater tolerance value, and identifying regions of significance in red where collision is likely to happen.
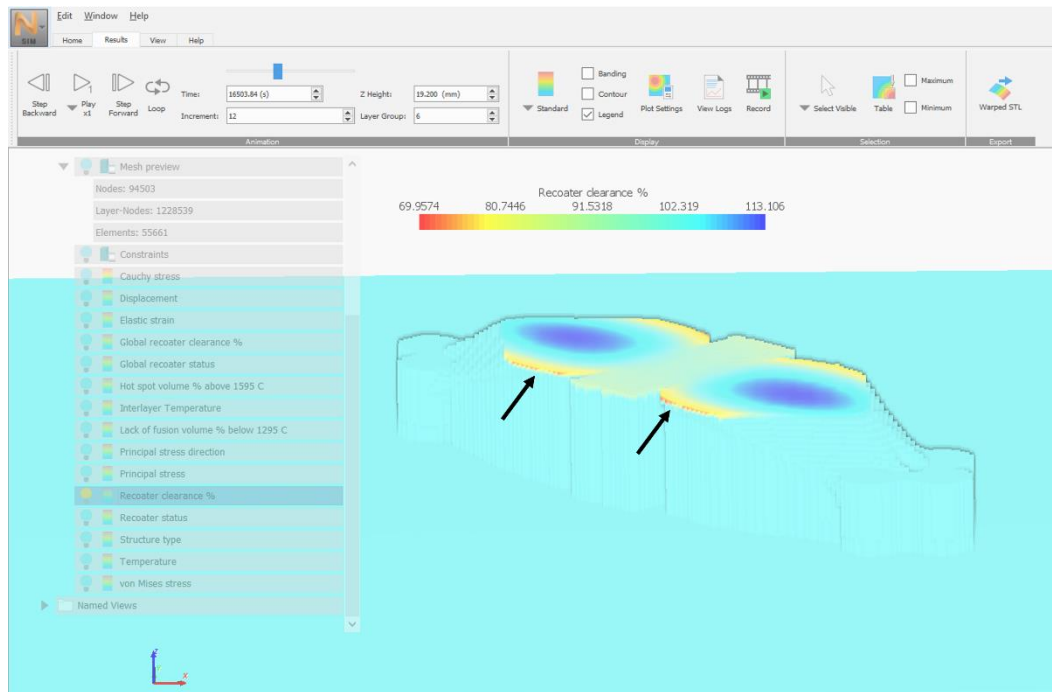
13. The **Global recoater clearance %** results display, in one view, the full range of unacceptable clearance values and locations for the entire simulation/build.
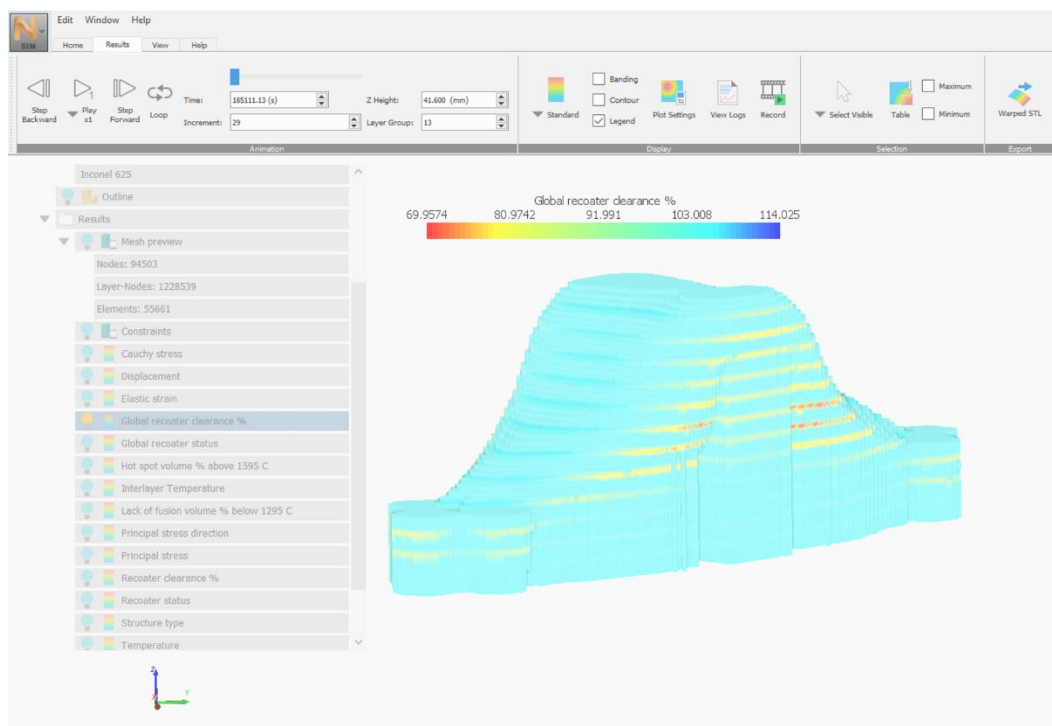
14. The **Recoater status** results allows you to step though the build increments using the Animations panel to see when and where exactly recoater interference occurred in binary values of 0 for no interference (indicated in blue), and 1 for interference detected (indicated in red).
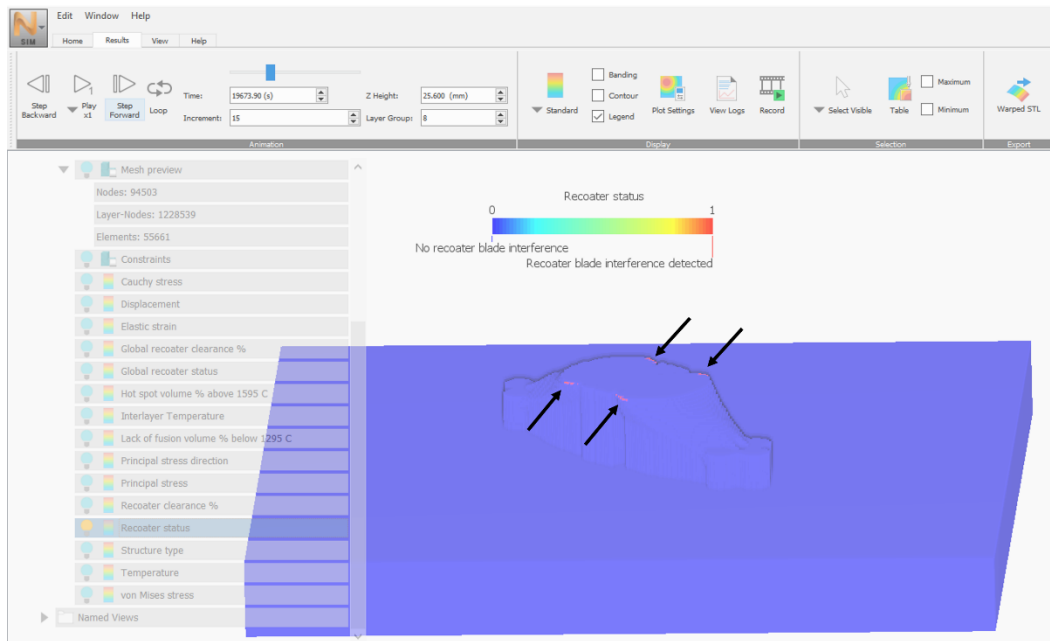
15. The Global recoater status results display the binary value of recoater status for the entire build: 0 for no interference, 1 for interference detected, all in one view.
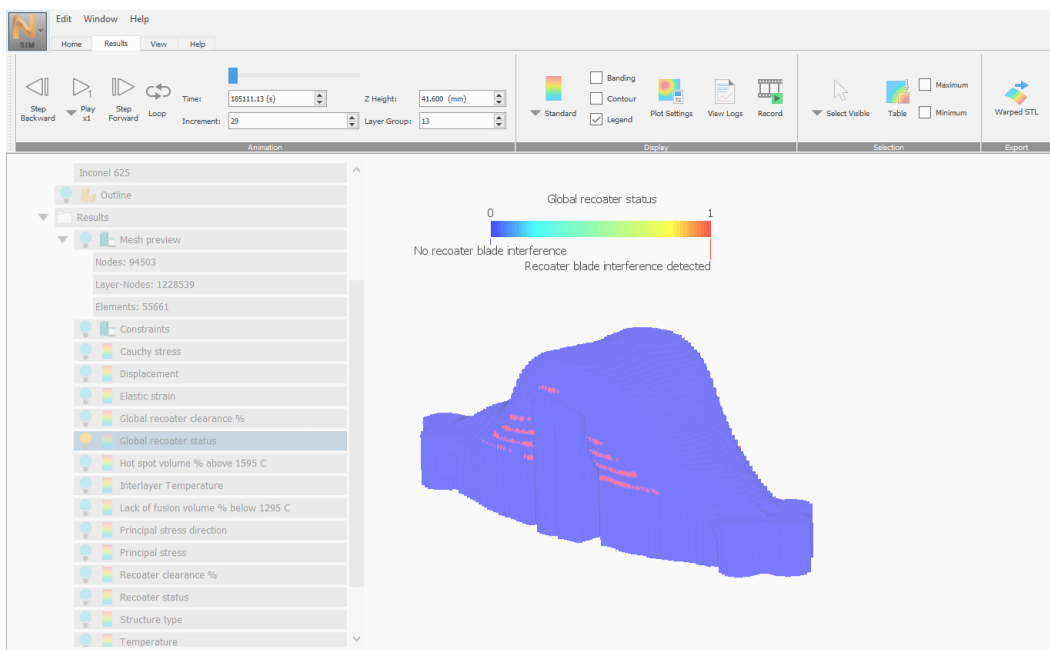
2.1.3 WAYS TO AVOID RECOATER INTERFERENCE

If the Simulation Utility predicted a recoater interference and a likelihood of a print failure – what now? There are a few ways to mitigate this issue.

1. **Selecting appropriate scanning strategies**. The root problem of recoater interference is due to the high build-up of residual stresses during the print. To minimize this, an appropriate scanning strategy can be used that is best suited for the part geometry being printed. The scan strategy is the method or pattern in which the laser will selectively scan or 'fill' the part. This is also known as the fill hatch pattern/type. Although quick and efficient, a disadvantage of the meander pattern is that there is inconsistent heat distribution throughout each layer, and therefore, will likely cause part distortion for large XY cross section geometries. If the part being printed has large XY cross section geometries, consider using the stripes or chessboard pattern. Although these patterns may be less efficient, they will provide consistent heat distribution throughout the layer, reducing the likelihood of part distortion. Also, ensure that a rotation of 67 degrees is used between each layer to ensure that stresses are not aligned in the same plane layer-by-layer, which increases residual stress.
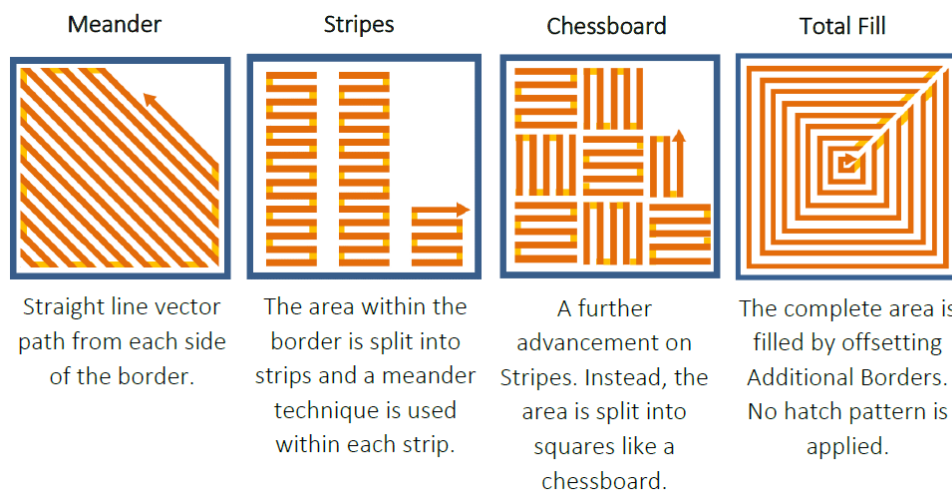

Figure 8: Common fill hatch patterns (Figure courtesy of Renishaw)

2. **Using a heated build plate**. Another technique to reduce residual stresses is to ensure that the build plate is heated to reduce the rapid cooling of the layers due to conduction. A heated build plate will help maintain consistent heat distribution during the build. Using thicker build plates can also help alleviate the build-up of residual stresses.

3. **Part orientation**. During the powder recoating process, the stiff blade creates a pressure wave across the build plate, packing and forcing powder to the front edge of the solidified part underneath (see Figure 9). Continuous force of the blade and pressure of the powder on the solidified part can lift the front edge of the part upwards, especially for parts that have thin walls or small features. This part will eventually collide with the recoater, which may lead to a failed build. To minimize this effect, the part(s) and supports should be oriented away from the recoater direction so that the recoater's first

point of contact is a smaller edge surface such as a corner feature of the part (see Figure 10). This will distribute the pressure wave alongside the edge of the part and not directly perpendicular to it, reducing the likelihood of part distortion.
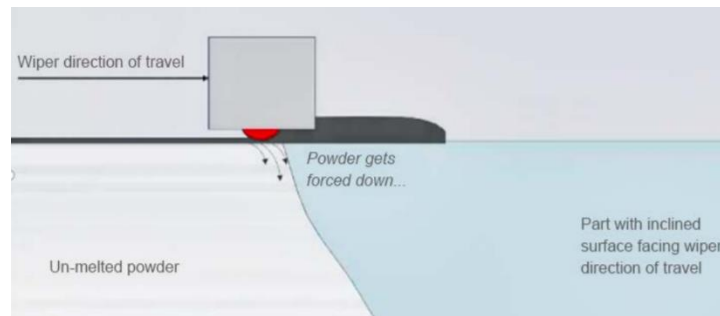

Figure 9: Schematic showing the interaction of the recoater blade and the front edge of the part (Figure courtesy of Renishaw)
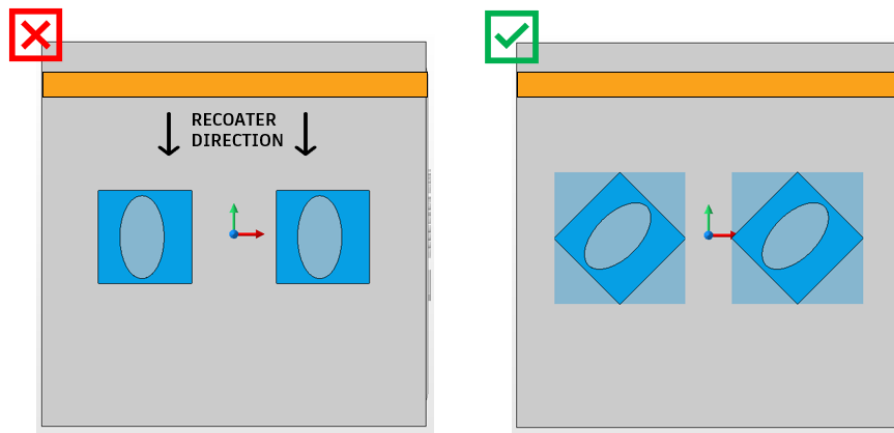
Figure 10: Schematic showing the suggested way to orient part within the build

4. **Part placement**. If printing more than one part on the build, it is suggested that the parts are not placed directly in line with one another relative to the recoater direction. If there is a recoater collision causing part deformation, the powder spread will be affected in the area directly behind that part (along the recoating axis). This will significantly impact the quality of the print for that part, and

could eventually lead to a failure. To mitigate this, stagger parts on the build plate in reference to the recoater direction (see Figure 11).
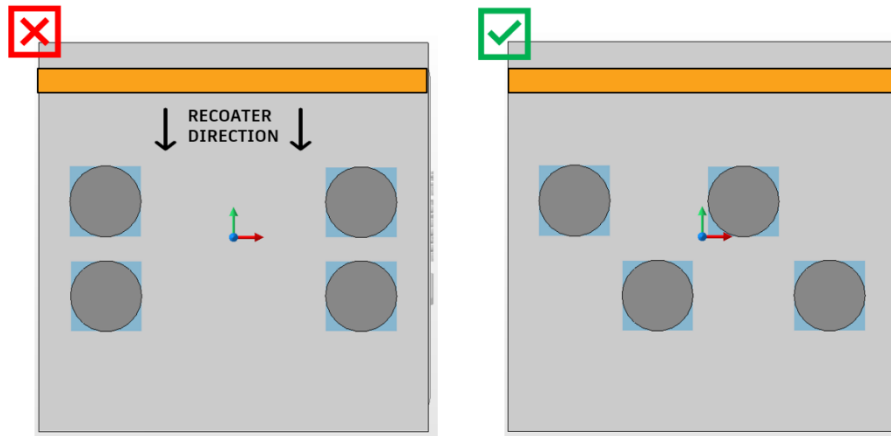

Figure 11: Schematic of parts and recoater direction in a build bed. Left figure shows potential print failure, and the right figure shows best practice of part placement

2.2 SUPPORT STRUCTURE FAILURE

2.2.1 SUPPORT STRUCTURE FAILURE DESCRIPTION

As stated in section 1.3, support structures in LPBF have numerous purposes. One of their purposes is to prevent part distortion during print. Support structures act as anchors to hold down the part as it builds up residual stresses. In most cases, support structure are less dense to reduce support removal time and save material, as they are sacrificial material. There are many different types of supports, most being thin-walled, lattice-like structures that are weaker in tensile strength. With high residual stresses acting on the part during printing, supports experience high tension that could lead to support structure failure, which in turn could lead to recoater blade interference. Usually, these failures occur at the interface between the part and supports due to a lack of connection or "adhesion", a defect known as delamination.
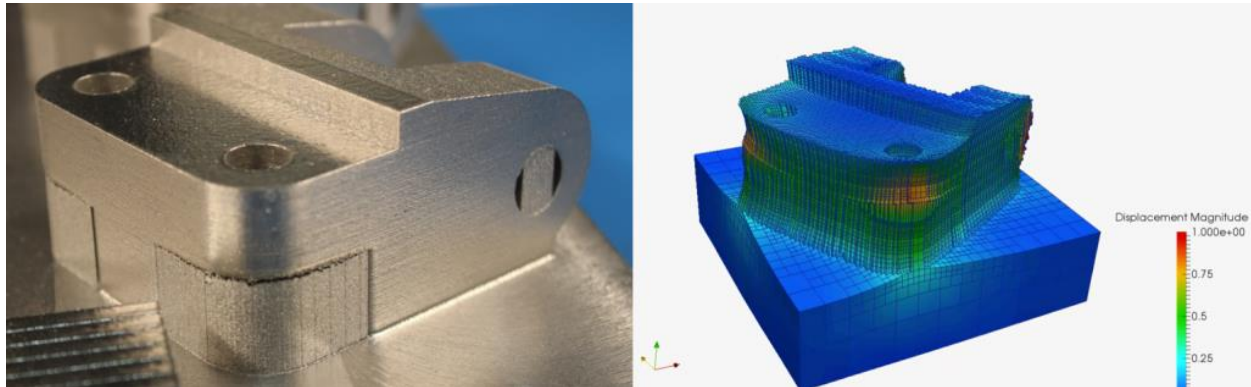
Figure 12: Experimental build showing support structure failure (left) and simulation results (right) showing support failure (Figure courtesy of Dr. Ed Demeter, Penn State University)

2.2.2 NETFABB DEMO: PREDICTING SUPPORT STRUCTURE FAILURE

Leveraging Autodesk Netfabb Simulation Utility, the user is able to detect locations where support structures will have insufficient strength to hold down the part due to residual stresses. After importing the part to the chosen machine build bed, setting the orientation, support structure and choosing process parameters, we can go ahead and start the build simulation.

1. In Autodesk Netfabb, click **Start build simulaton** under **Current Build** on the right dialog box.
2. In the **Start build simulation** dialog box, ensure that you check **Combine support volumes for simulation**.
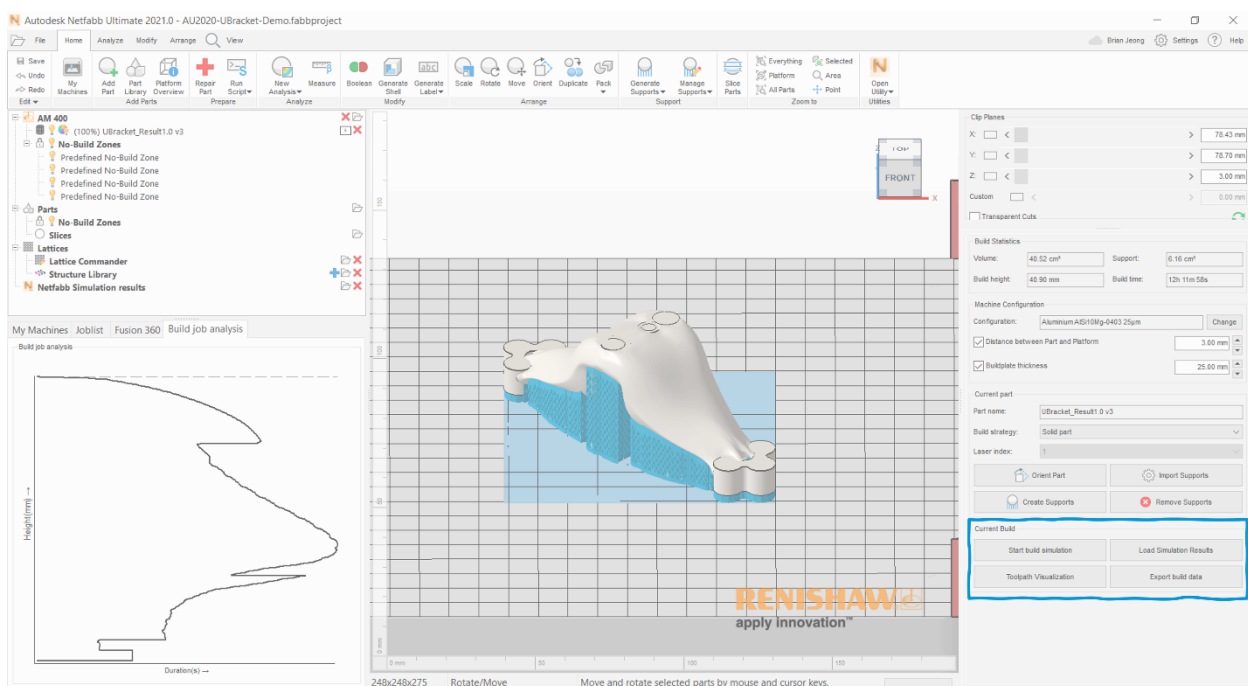
3. Once the Simulation Utility is open, navigate to the **Home** tab and click **Solver Settings** under the **Analysis** pane.
4. In the **Solver Settings** dialog box, activate **Include support structure failure**, and set the **Support structure failure criteria** to **500 MPa**. More details on the settings can be found [here](#).
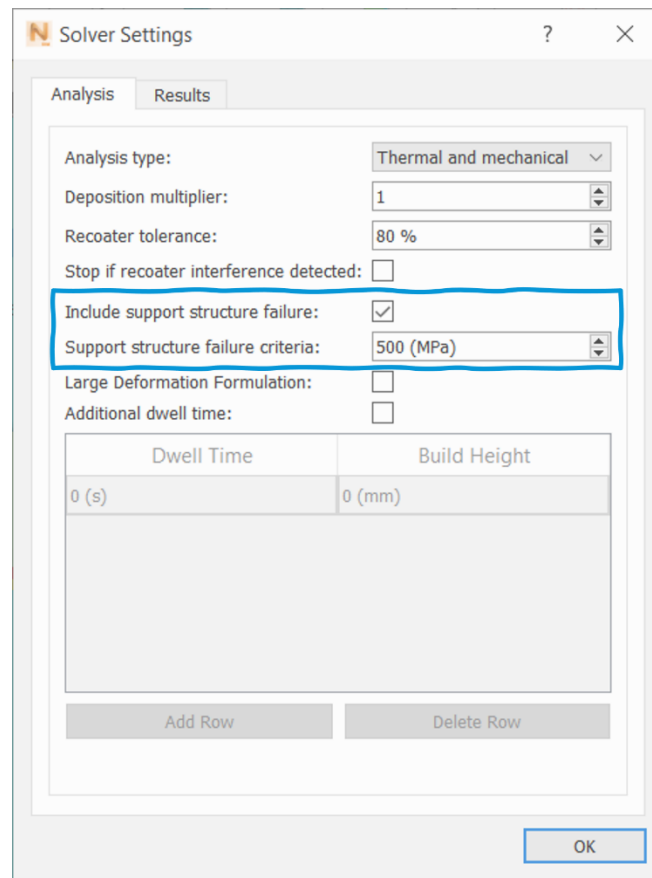
.
5. Click **Solve** under the **Analysis** pane.
6. Once the simulation analysis is complete and loaded, navigate to the left View tree and change the results display to **Structure type**. Failed areas of support structure failure are simulated in red.
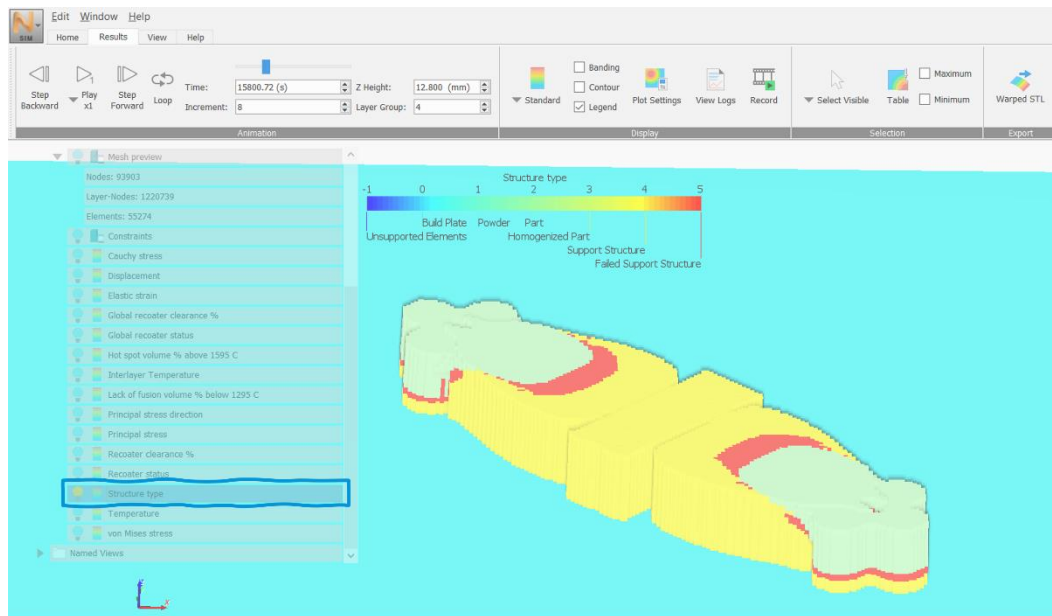
7. To review the simulation analysis in detail, specifically recoater blade interference warnings, navigate to the **Display** pane and click **View Logs**. The simulation has detected a support structure failure at 97.5% of support-to-component interface elements, which tells us that major changes need to be made in terms of strengthening the supports to prevent build failure.
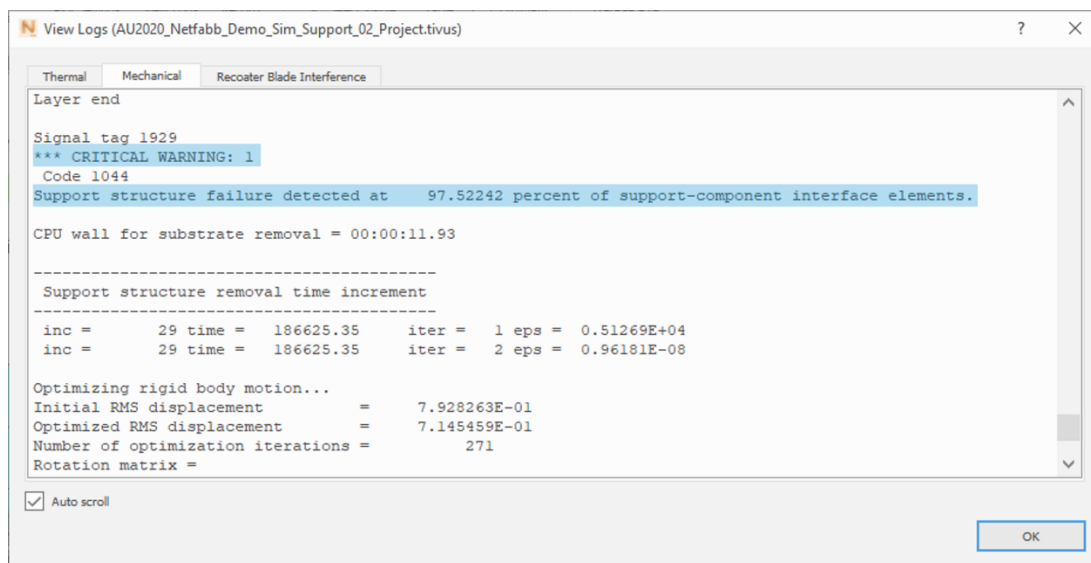
2.2.3 WAYS TO AVOID SUPPORT STRUCTURE FAILURE

Once simulation results show that the supports will fail, there are a few ways to avoid this from happening.

1. **Re-design support structures**. A large benefit of the Netfabb Simulation tool is that it specifies the region of concern of support structure failure. This allows engineers and manufacturers to go back to the design and modify and strengthen the supports at that region of concern. This can be done by adding more points of contact at the part-support interface, increasing the surface area of supports, or using an entirely different type of support structure. In Autodesk Netfabb, numerous support types are available to choose from such as bar, polyline or volume. Supports can either be generated manually or automatically by using the support scripts dialog. Modify the connection points at the part-support interface by going to the Support Scripts dialog, expanding Support Properties > Connection (see Figure 13). More details on support settings can be found here and here.
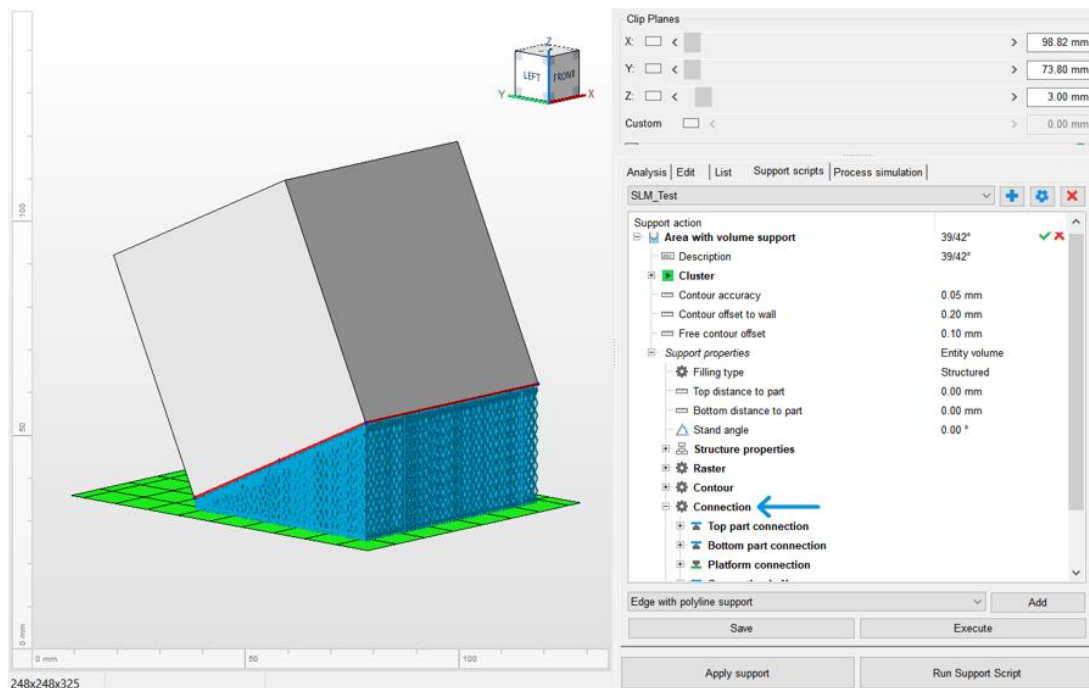
Figure 13: "Connection" settings found under Support Scripts dialog in Autodesk Netfabb

2. **Re-orient the part**. An option might be to re-orient the part as a whole to reduce regions of high residual stress build-up. Use Netfabb's automatic part orientation tool to determine the desired orientation based on multiple factors such as supported area, support volume, and part height. Large surface area layers will likely cause significant part distortion due to residual stresses, therefore, stand the part up high to reduce build-up of stresses.

2.3 PART DISTORTION

2.3.1 PART DISTORTION DESCRIPTION

Although metal AM has advanced over the decades, when a CAD model is printed, the as-built part will most likely not have the exact dimensions and geometries as the model. This is due to part deformation caused by thermal expansion during the process. These thermal effects are unavoidable in the LPBF process. Due to layer-by-layer printing, the material melts, rapidly cools, solidifies, then repeats thousands of times. This causes extreme thermal contraction and expansion which forces the part to bend upward in permanent deformation.

Because of this challenge, designers and manufacturers experiment with trial-and-error prints to find the desired shape and geometry of components after printing. With every test print, costs of manufacturing and consumables, and time increase significantly and can cause major delays in the process.

2.3.2 NETFABB DEMO: PREDICTING PART DISTORTION
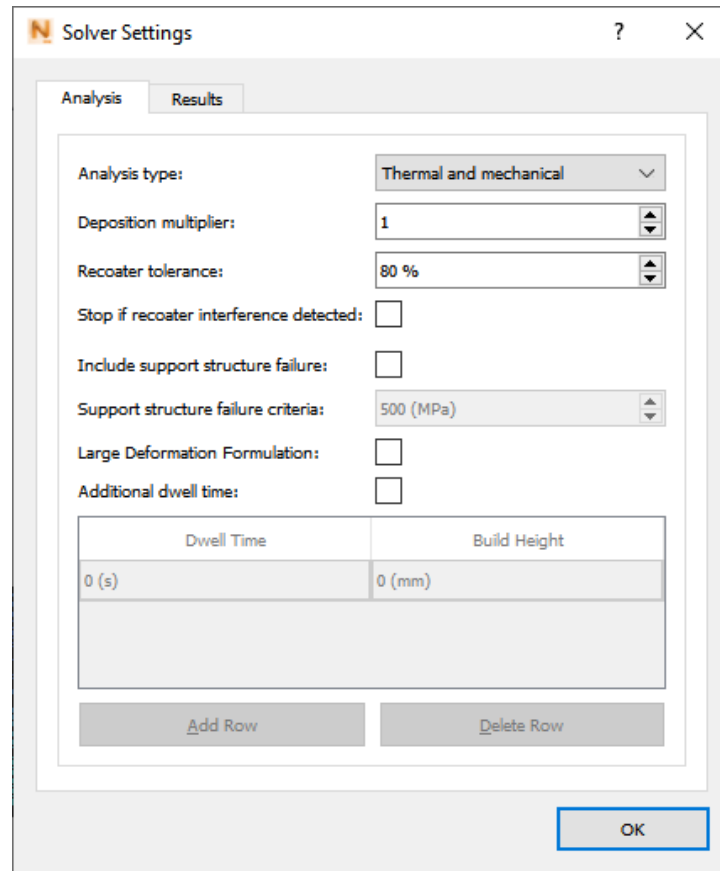
Using the Autodesk Netfabb Simulation Utility, users can predict part distortion and apply corrected geometric compensation, where a part is altered based upon the measured or simulated distortion so it warps into the correct geometry. Let's first determine how to predict part distortion.

1. In Autodesk Netfabb, click **Start build simulaton** under **Current Build** on the right dialog box.
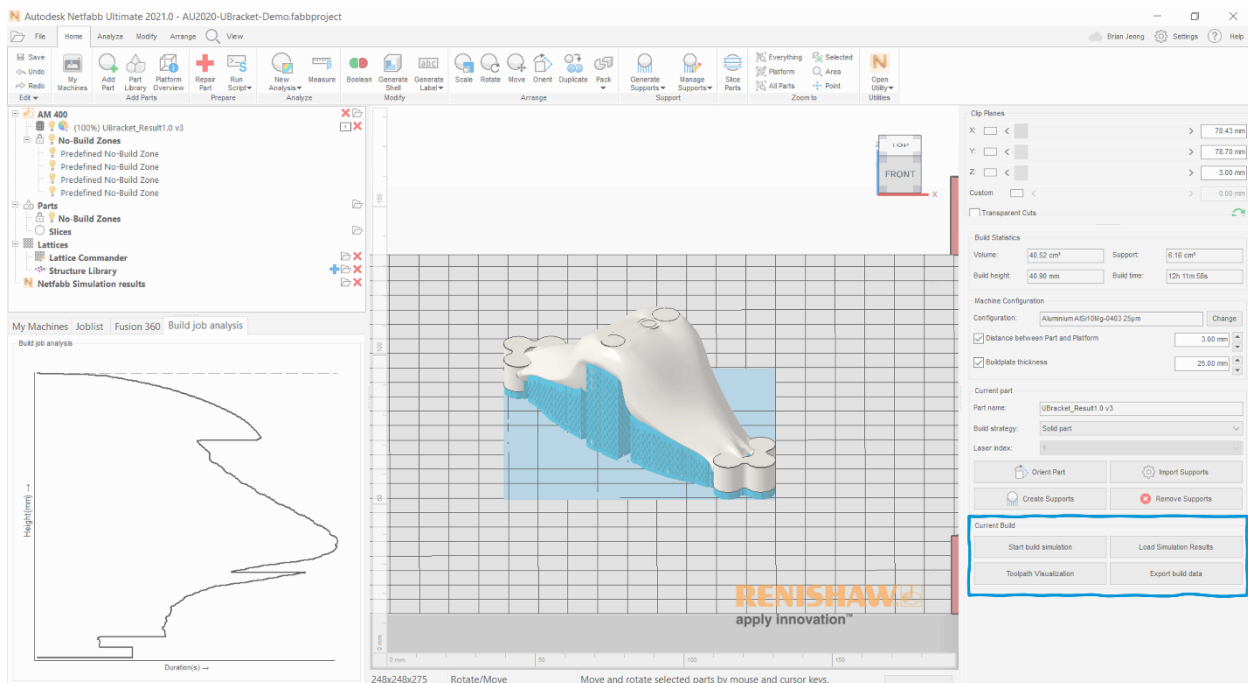
2. Once the Simulation Utility is open, navigate to the **Home** tab and click **Solver Settings** under the **Analysis** pane.

3. In the **Solver Settings** dialog box, enter the desired settings for analysis and results, then click OK. More details on the settings can be found [here](#).

4. Click **Solve** under the **Analysis** pane.
5. Once the simulation analysis is complete and loaded, play through the animation while in the **Displacement** results view by navigating to the **Animation** pane under the **Results** tab. Note any significant part distortion illustrated in red.
    Note: The default displacement results show Magnitude, but this can be changed.
6. Navigate to the **Display** pane under the **Results** tab, and click **Plot Settings**.
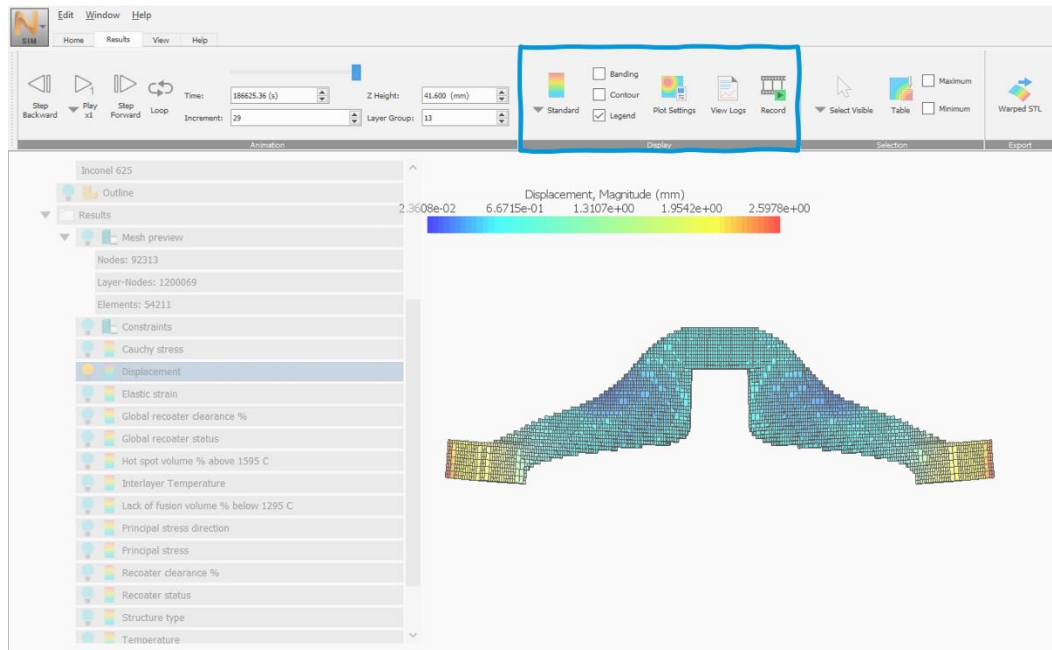
7. Using the **Component** setting, the simulation can show displacement along a single axis: X, Y, or Z. In this **Plot Settings** dialog, you can also set a **Displacement scale** greater than 1.00 to exaggerate the displacement, and change the display style to **IsoSurface** or **Vector**.
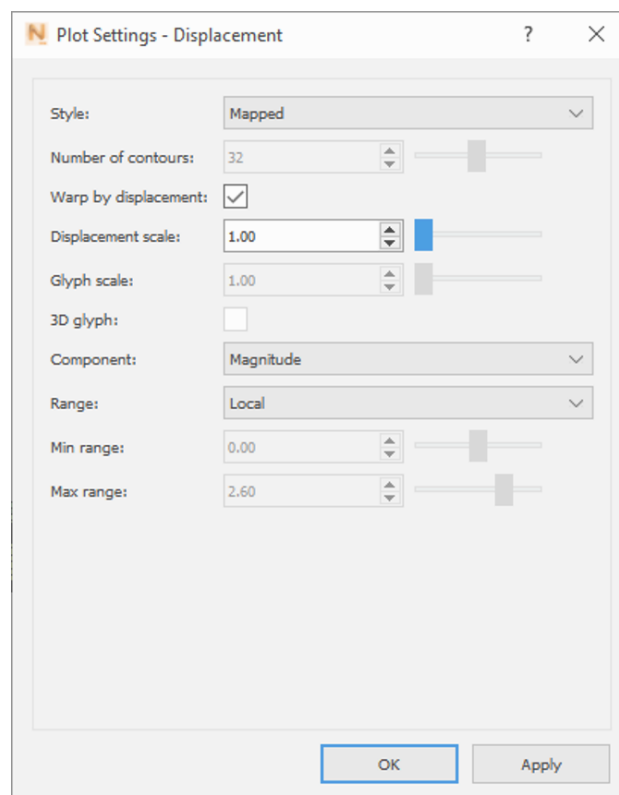
2.3.3 NETFABB DEMO: APPLYING GEOMETRY COMPENSATION

Once you've analyzed part distortion in the Autodesk Netfabb Simulation Utility, you can apply geometry compensation to export a calculated, warped STL that will distort into the desired final shape. The feature will offset the nominal geometry in the opposite direction from the anticipated distortion. The theory is that the distortion will displace the part into the desired shape.
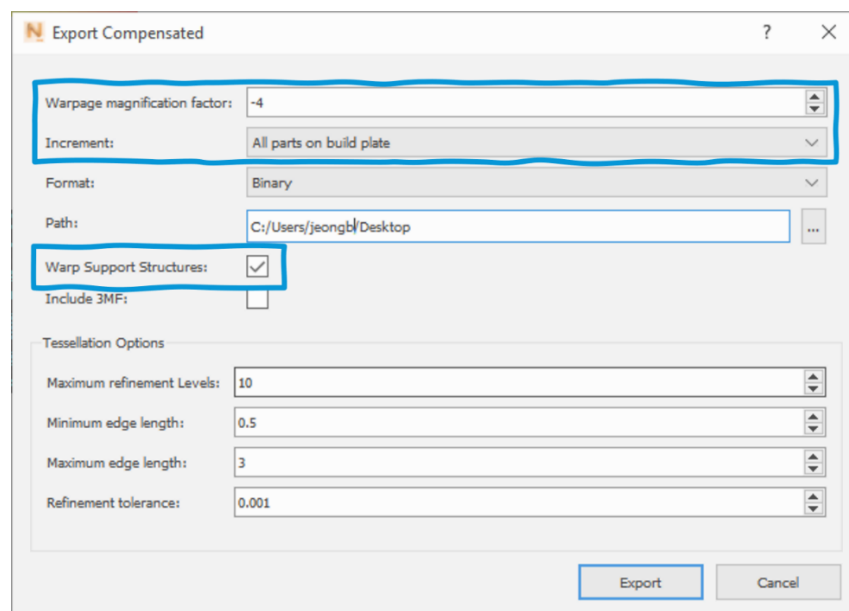
1. From a simulated project, in the **Displacement** results, the part is showing displacement on the red-highlighted sections shown.
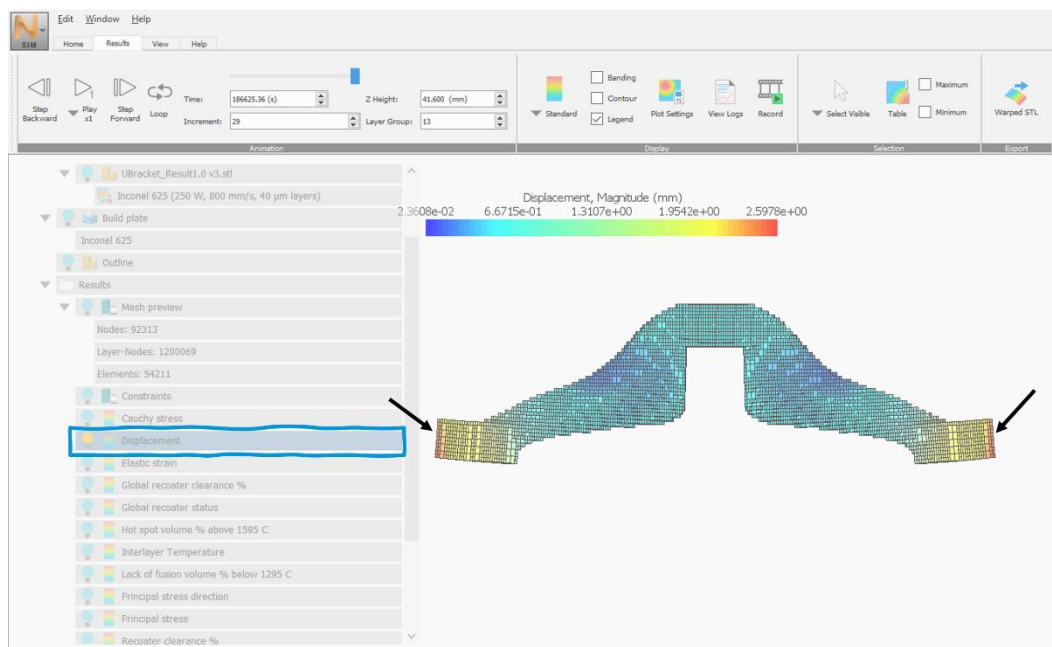
2. Navigate to the **Export** panel under the **Results** tab and click **Warped STL**.
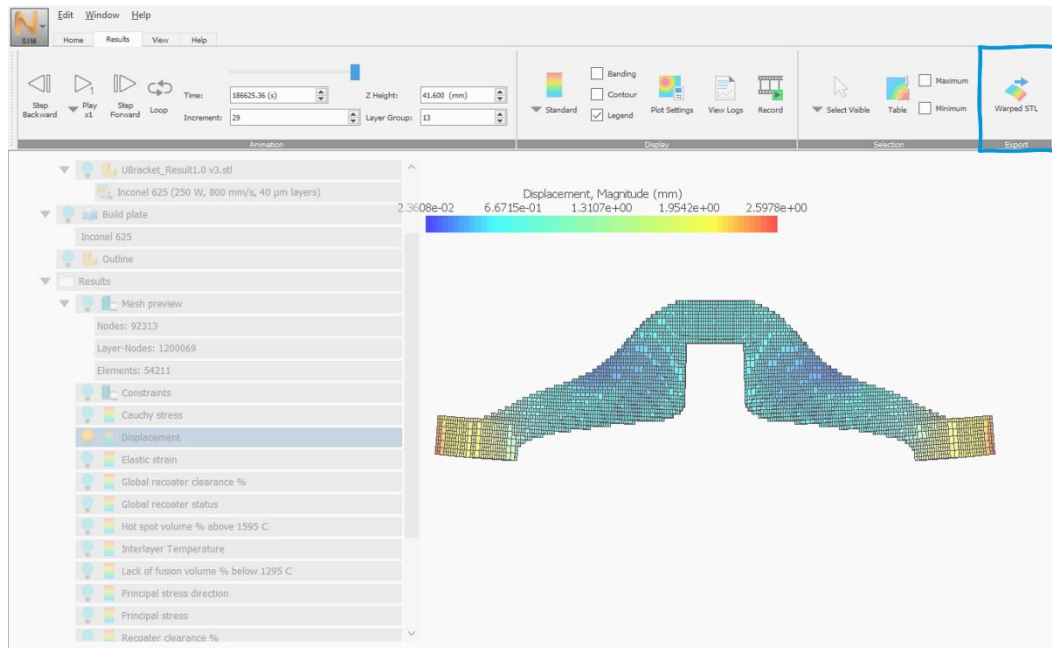
3. In the **Export Compensated** window, the **Warpage magnification factor** specifies the value to multiply all simulated displacements applied to the reference geometry. Negative values are used to create compensated STLs and positive values are used to create distorted STLs. Start with a high **Warpage magnification factor** of **-4** to make the results more visible. Under **Increment**, there is an option to compensate warpage either for the parts on the build plate, for the parts after removal from build plate, or for the parts after removal from build plate and removal of support structures. Choose **All parts on build plate**.
    More details on the settings can be found [here](#).

4. Once the compensated STL is complete, it will export into the specified path.
    If Increment was set to **All parts on build plate**, file name will include *Pre-Removal*.
    If Increment was set to **After removal from build plate**, file name will include *Post_Plate_Removal*.
    If Increment was set to **After removal from build plate and support structure removal**, file name will include *Post_Support_Removal*.

    In Netfabb Simulation, click **Import** under the **Home** tab and open the compensated STL file.

5. Toggle the view on for the compensated STL file that was imported and see the compensation applied in the opposite direction of the expected displacement.
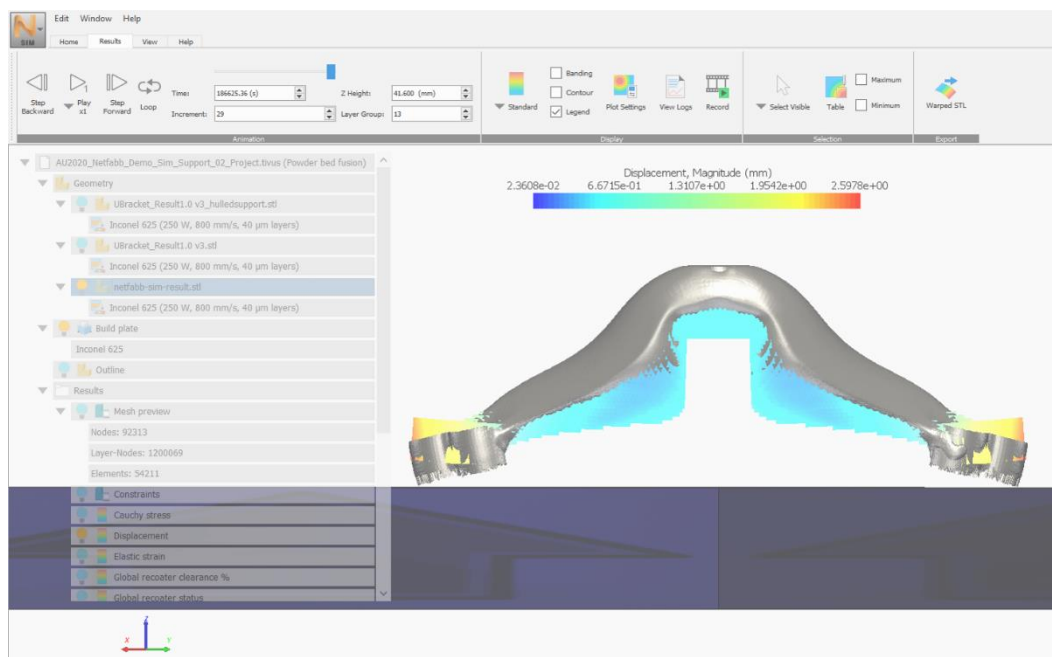
3. SUSTAINABILITY

3.1 WHAT IS SUSTAINABILITY?

Climate change, pollution, embodied carbon, greenhouse gases – the language can be difficult to navigate. The fact of the matter is sustainability is our best way of gauging a system's ability to maintain and thrive indefinitely.

Collectively, we are on the cusp of an unprecedented opportunity. With rapid population growth and accelerated urbanization. It's estimated that worldwide energy demand will double by 2050, requiring more productive use of energy and materials. Autodesk is empowering designers and makers around the globe to create a sustainable future.

When put into the context of product design and manufacturing, an over-consumption of energy and material can directly impact our ability to be sustainable. One method of measuring this is by understanding a product, process or machine's net carbon output and embodied carbon levels. Embodied carbon is the locked-in amount of carbon emitted during the design, supply chain, and manufacturing phase. On average, 80% of a product's environmental cost and performance is locked in at the design and prototyping phase creating cascading downstream effects. This is crucial in understanding and limiting (or eliminating) carbon hotspots within the product development process.

3.1.1 SUSTAINABILITY AT AUTODESK

Autodesk's 10th annual Sustainability report was recently released. Here are some of the highlights:
- Over the past ten years Autodesk has managed a 41% reduction in greenhouse gas emissions 100% of facility and data center energy is now sourced from renewable energy.
- Employees have volunteered over 800,000 hours of time and given over 6 million dollars in contributions.

EC3
the Embodied Carbon in Construction Calculator, integrated with Autodesk® BIM 360® software

1%
target of operating margin to contribute to the Autodesk® Foundation for the next three years

100%
of office and data center electricity from renewable sources

Achieved
our fiscal year 2020 science-based GHG emissions reduction target (baseline 2009)

43%
reduction in GHG emissions footprint compared to fiscal year 2009

Target set
to achieve climate neutral GHG emissions for Scopes 1, 2, and 3 annually, beginning fiscal year 2021

$1.31 million+
in employee volunteering time (29,700+ hours)

$9.70 million
in company and Autodesk Foundation cash contributions

$39.9 million
in Autodesk product donations

COMMITMENTS
- Continue to report climate change information in mainstream financial reports (see Autodesk FY2020 Annual Report).
- Continue to conduct responsible corporate engagement in climate change policy (see Public policy).
- Continue to use an internal price on carbon.
- Continue to integrate sustainable design capabilities into our products and services (see Customers).

TARGETS
We committed to following our Corporate Finance Approach to Climate-Stabilizing Targets (C-FACT) methodology through 2020, to reduce GHG emissions in line with an 85% absolute decrease by 2050.

Reduce carbon dioxide equivalent (CO_2e) emissions across our value chain by 43% by fiscal year 2020, compared to fiscal year 2009.

Achieve climate neutral GHG emissions for Scopes 1, 2, and 3 annually, beginning fiscal year 2021.

PROGRESS IN FY2020

Achieved. Compared to our fiscal year 2009 baseline, we decreased absolute GHG emissions by 43% through efficiency, renewable energy, and Gold Standard certified carbon offset projects with our customers.

Power our facilities and cloud services with 100% renewable energy by fiscal year 2021.

Achieved.

Remove commodity-driven deforestation from Autodesk's supply chain by 2020.

In progress.

Reduce short-lived climate pollutant emissions.

In progress.

3.2 TRADITIONAL VS. CIRCULAR ECONOMY

A traditional economic model is very linear. We take raw materials, create something, use that 'thing' and then dispose of it. Given the limited amount of raw materials available for consumption, this model is ephemeral and requiring us to think differently about how we produce the things we need.

Having a strong understanding of the downstream effects of a product beyond the design phase can help you better address the core product need, create something more sustainable, and better expose you to unconventional design inspiration. This includes how a product will exit its lifecycle and where it may end up beyond initial usage – e.g. a landfill. The idea of keeping materials and products in perpetual use by eliminating waste and pollution by design is referred to as circularity. In the broader context of manufacturing, circularity is the North star. Circularity is different from upcycling or recycling in that materials and products must be repurposed to be of equal or lesser value at the end of their lifecycle.

3.3 SUSTAINABILITY IN ADDITIVE MANUFACTURING

Designers, engineers, and technicians alike are often acutely aware of how best to dial in machine parameters to get the best possible results out of an AM build or job. It is understood that a more efficient build setup and strategy will be less time and capital-intensive. However, rarely are these same implications viewed from a lens of sustainable best practice. The truth is, changes in manufacturing have direct correlations to an organization's bottom line (for better or worse). Emerging industry trends for designers and manufacturers suggest that **effectively reducing a product's environmental impact can positively influence an organization's bottom line**. If saving money is the driving factor to adopting sustainable practices in additive manufacturing, then we must be pragmatic in our approach. Ultimately, it's less about changing *'what'* you do, and more about changing *'how'* you do it. Sustainability means recalibrating your AM workflow to be more pragmatic and thoughtful.

The brilliance of additive manufacturing is that it is capable of using the smallest amount of raw material to produce a functional part. Any additional material usage is required to support certain features, calibrate the machine, or ensure layer adhesion. Despite the limited material usage, additive manufacturing can be quite

energy intensive, thus begging the question, how do we optimize the parameters we can control? Through our experience we have noticed there are effectively three pillars that contribute to an additive process' ability to be sustainable: **Material Consumption, Energy Consumption, Runtime and Preparation**.
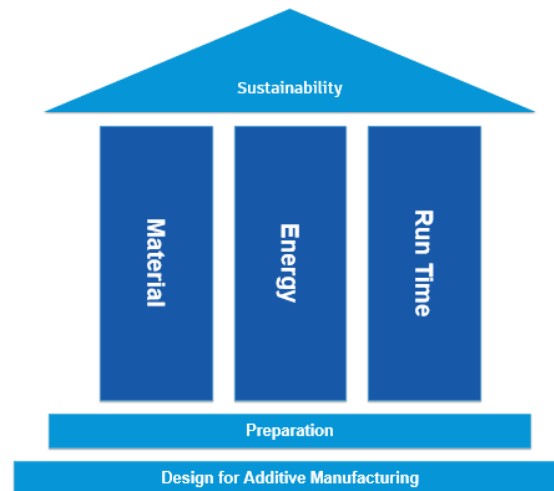
Furthermore, we recognize that, to actively alter or limit one pillar, it would mean indirectly affecting another. This extrapolation can lead to a reduction in failed prints or resulting carbon emissions generated through the manufacturing process. This reduction is considered a sustainable best practice. While this may seem like a minor adjustment, consider this impact when compounded over time and over thousands of parts for production

3.3.1 CARBON-EMITTING AM PITFALLS – WAYS THAT PRINTS FAIL.

The road to sustainable best practice is paved by workflow pain points, pitfalls, and outliers in the labour/cost breakdown. It is best to audit and track process and in-machine data, as insights can be difficult to extract on the clearest of days. In our experience, a high majority of additive manufacturing complications stem from a lack of operator/designer foresight. The inability to project downstream pitfalls can cause error to compound incrementally to the point of failure. Below are some of the additive manufacturing pitfalls we have noticed in working at the Technology Centers:

1. **An abundance of failed prints** – Not an uncommon occurrence and often a necessity. However, a line in the sand can be drawn in how many failed prints are an acceptable amount. This is especially true when we start thinking about more complex additive processes that cost thousands of dollars in materials, energy and labour to produce; the negative impact on the environment and carbon emissions are multi-fold. Although many factors can contribute to a failed print, the operator is best positioned to understand these factors and actively work to combat them. This deliberately holds true for forces even beyond operator control, like a malfunctioning machine.

2. **Failure to slice, section & scale** – Mission critical, in our opinion, is failure to ramp up the prototype. Scaling refers to both scaling the part in its entirety or the action of scaling the amount being printed

(e.g. sectioning the part to focus on certain critical features). Immediately rushing to the machine in hopes of collecting an end-use part without first being diligent about the part's ability to meet the fit, form and function requirements is a recipe for disaster.

3. **Overly long print times** – Orientation aside, there are a lot of factors that contribute to a build's run time. While some of these are a bit more nuanced, many are well within operator control. The ability to analyze the fit, form and function of a part to determine where compromises in parameters like the infill, layer thickness, speed and support structure can occur is crucial in minimizing run times without sacrificing the component's integrity. Especially true in larger volumes and builds, there are typically a few key parameters that can drastically fluctuate a part's run time. If we are doing a large production run of parts, these compromises can pay dividends in the amount of energy being consumed throughout the process.

4. **Overly complex geometries and assemblies** – . Although it seems counter-intuitive, both are missteps in the battle for sustainable best practice and require a degree of balance. An argument can be made that additive manufacturing can provide additional detail at no extra cost. However, the trade-off can sometimes be an increased print time and the need for additional support structure. While it's true that additive manufacturing can handle more complex and organic geometries for the purposes of lightweighting (like that of Generative Design), it's important to note that a lightweight or Generative outcome is created specifically for an AM process and adheres to underlying DfAM principles. Determining how complexity factors into the long-term objectives of your part can be critical in evaluating its ability to minimize carbon footprint.

5. **Selecting the wrong AM process or material** – Not all additive processes and materials are made equal – some are better suited for certain types of parts and applications. They each have inherent properties, constraints, and limitations. Having a strong understanding of a product's requirements can better position the designer's ability to be successful in achieving certain tolerances, forms and in minimizing post-processing. Fundamentally, this boils down to having a working knowledge of a machine process/manufacturing limitation. Understanding the parameters that are within an operator's control can aid in selecting the right AM technology and material, while better predicting how or why print failures commonly occur in-situ.

6. **Extraneous post-processing** – Post-processing is dependent on other parameters, but it is worth pointing out as a pitfall because it is a downstream factor that needs to be taken into consideration at the forefront of a job. Support removal and clean up can be labour-intensive or in some cases impossible depending on the complexity of geometry. Overlooking this can stall forward progress and force another design or setup iteration. Furthermore, post-processing for improving mechanical properties, surface finish, surface features/geometries, among many other qualities/requirements need to be taken into deep consideration from the customer's point of view and needs, as they add extra cost, time, effort, and sometimes processes that emit additional carbon. An example of this is in metal AM, when a generatively-designed part requires further machining to improve surface quality or to mill certain features, holding onto and finding a point of reference across this organic geometry can be extremely challenging.

7. **Not enough post-processing** – Time and time again, people try to force tolerances out of additive machines. Other manufacturing equipment (CNC mills) are better suited to provide dimensional accuracy and hold extreme tolerances during a post-process. If there are many critical features and

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not all of them can be printed in similar axial planes, this may be an indication that these features will require post-machining.

8. **Ignoring DfAM principles** – Designing for an additive manufacturing process is the building block for prototype success and further navigating the other manufacturing pitfalls. Internalizing these guidelines means that parts will start to be more conducive to producing successful results earlier in the conceptual phase. If a deviation from a DfAM principle should occur, it should be informed by the need to meet an equipment limitation or parameter.

9. **Lack of calibration or machine maintenance** – Nothing is worse than waiting on a technician to fix your machine or having to spontaneously add that extra day or two to fix an issue. DO NOT assume your equipment is dialed in. Conducting any preventative maintenance and doubling checking the calibration on your equipment axis, offsets, build level, etc. can go a long way. Determining how or why a failure occurred is commonly done by process of elimination. Taking the machine out of the equation by giving it the time and care it deserves to deliver the best possible results is something you will thank yourself for later.

10. **Ignoring simulation** – During the fabrication of a part, there are additional simulations that can occur and are specific to in-process fabrication (like that of metal AM or subtractive manufacturing). The importance of this should not be understated. In the same way that we want to ensure our product lives up to certain standards once in the market, we want to ensure the product is made with the same diligence and we are extending this level of care to the machines doing the work

To summarize, some of these pitfalls are, in many ways, intrinsically connected. This interconnectivity and sphere of influence in resolving certain pitfalls become even more apparent when evaluated against our sustainable pillars in AM. Effectively, each of these pitfalls are capable of affecting each pillar in one way or another.

3.3.2 SUSTAINABLE STRATEGIES FOR ADDITIVE MANUFACTURING

Now that we know what to avoid, what can we do to avoid it? While attempting to do the inverse action of the (above) AM pitfalls is one method of aligning more closely with sustainability, the tactics outlined below attempt to go a step beyond the obvious. Further, there is not always a definitive answer for each pitfall – likely a consequence of how interwoven they can be. Although resolution will be application and operational-specific, these are some strategies and (digital) tools you can leverage in our journey to greener, more thoughtful additive manufacturing:

- **Use Generative Design (GD)** – GD is a workspace and design exploration technology native to Fusion 360. GD uses an artificial-based algorithm that creates multiple design solutions and permutations for one design challenge. This allows you to simultaneously generate multiple CAD-ready solutions based on real-world manufacturing constraints and product performance requirements. The sustainable benefits in using GD include, but are not limited to:
    - **Consolidation** – Generative Design has the innate capability of making very organic and fluid connections to critical features. Effectively reducing complex and multi-part assemblies into a single geometry.

- o **Light weighting** – Optimize the material needed throughout a part to meet the structural and functional requirements of your product and then explore what this means across material selections. Light weighting is a direct byproduct of any Generative Design study.
- o **Enhanced Performance and Quality** – Following a study, GD allows you to filter through massive amounts of performance data to better understand how your part performs and meets different criteria, expediting time to market (including, but not limited to: cost, mass, volume, factor of safety, stress and displacement).
- o **Ease of Manufacturing** - Generative Design considers how a part will be fabricated and creates design solutions specific to certain manufacturing process. Since GD only adds material where necessary, it cuts through the noise to produce better results than even those of highly experienced design and manufacturing engineers (E.g. minimum thickness, overhang angles, etc.).

- **Design for (dis)assembly** – Although this is less of an additive strategy and more of a deliberate action in during the design phase, identifying features in your design that see significant wear throughout their usage and could potentially be connected, embedded or modular might help simplify the areas to be printed. The art of disassembly is better suited for providing value to a part beyond its consumer life cycle, as individual components can be removed or replaced.

- **Prototype Fit, Form and Function** – Target critical features to test, by isolating these sections of your parts and run a mini print job to verify their fit, form and function. These could be connection points, joints, clearances, etc. Focusing your prototyping energy on component slices effectively eliminates the degree and frequency of prototyping errors as well as the amount of material needed.
  - o **Dry run post-processing** – An extension of fit, form and function testing, take the time to conduct a dry run on certain post-processes. This could include support removal, surface finish and additional manufacturing in a post-operation. Many questions could be answered throughout this process, including how to hold on to your part during a post-op? Will there

be surface quality issues in given regions? What types of tools will I need? How long can will post-processing take?

1ST PROTOTYPE   **2ND PROTOTYPE**   **3RD PROTOTYPE**

- **Leverage post-processing** – Lean into the fact that your geometry will require an additional machining or manufacturing process to be market ready. Rather than struggling to alter the orientation and minimize the support structure in regions that struggle with tolerancing and dimensional accuracy, recognize this early in the design phase. Block these areas out with more primitive geometry with the expectation that they will be addressed after printing. This will reduce the amount of print time and create ease during post-processing.

- **Capture (in-machine) data** – The true value of data comes from the ability to draw insight. While some data can be pulled directly from a machine (especially in metal AM), some can be recorded manually. Insights are operator-driven, and although there is no explicit answer to what this data should be, establishing benchmarks that can be leveraged in future prints can provide operator foresight (e.g. volume vs. run-time, material vs. infill density, vs. run time, etc.).

Photo courtesy of Renishaw Inc.

- **Material Graduation** – DO NOT run your initial prototype on your material of choice. We've seen more failures than can be counted by individuals who were overly confident in their design. Use more recyclable materials in the beginning working your way up to your material of choice (e.g. laser cut an assembly using carboard first vs. acrylic or wood, or 3D printing using thermoplastics before a metal AM process). The goal through material graduation is to avoid print failure by limiting the possibility of foolish parameter, equipment, or design errors.

- **Infill Management** – Generally speaking, a slicing software exerts control over how infill is managed across a part. Ideally, we would like to concentrate infill density specific to certain regions in a part that require greater structural integrity. Some slicers give you a degree of flexibility over this, while others provide none. Currently, there is no standalone optimizer or tool that does this automatically within Fusion 360. However, working across platforms, the lattice generation tool in Netfabb can directly manipulate and produce concentrated lattice structures in a component-based finite element analysis. Beyond that, you will need to rely on user experience to determine when and where infills should be manipulated. Focus on changing density specific to certain regions based on their structural integrity and the type of prototype being created.
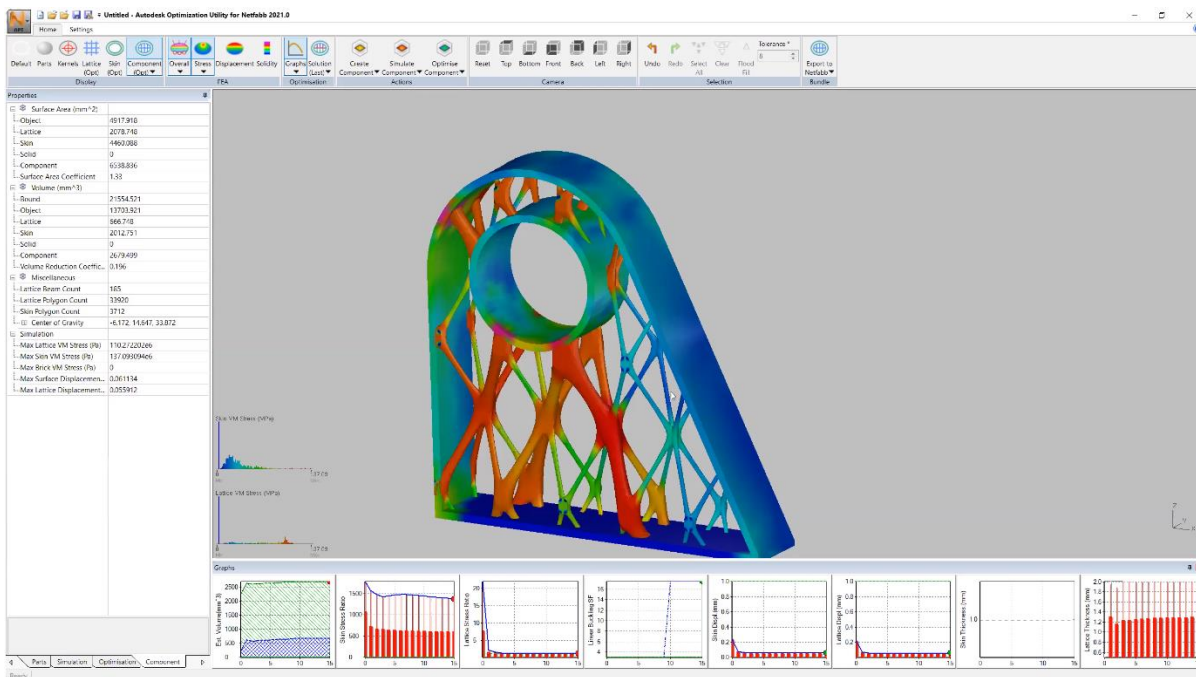

- **Support Structure Optimization** – Supports are a byproduct of part orientation. The more supports volumetrically and area to be supported, the more material will be used. Support structures can also be parameterized to minimize printing time and density (e.g. increased layer heights, fill type, etc.). Run an orientation script within Netfabb to get a better sense of how varying orientations will impact material usage across the following:
  - **Supported Area** – Volumetric amount of part geometry that exceeds the overhang limit and will require support structure
  - **Volume** – Volume of support structure that will be required across the entire part
  - **Outbox Volume** – Bounding box volume relative to the build platform. Could be factor worth minimizing in certain additive technologies
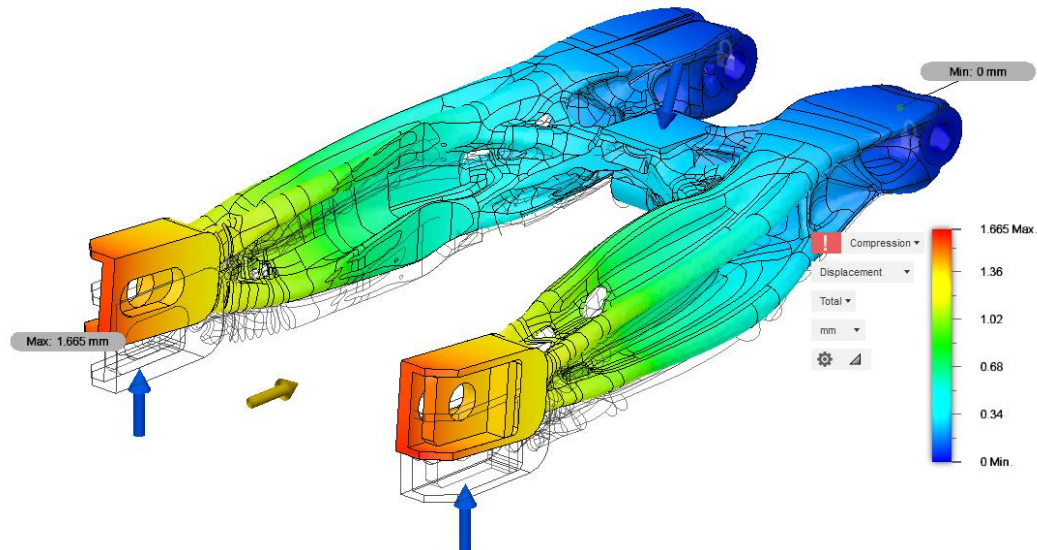
o   **Height** – Distance (of support) from the build platform to the tallest part feature
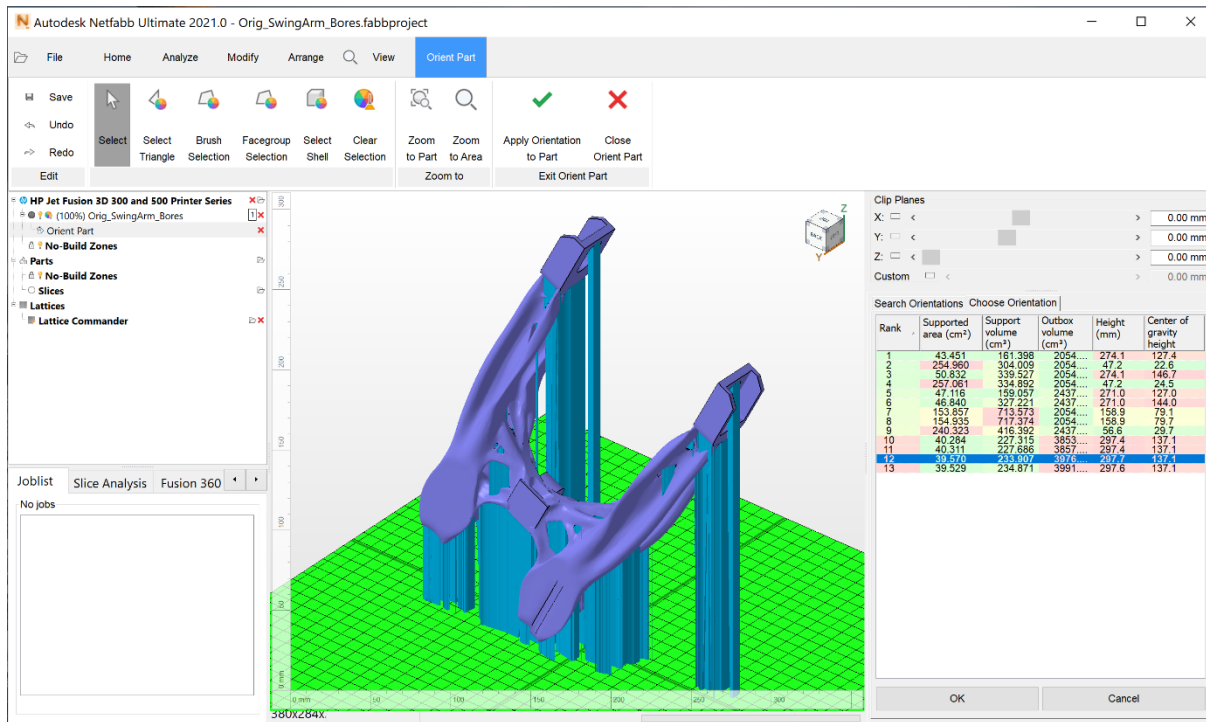
- **Packing** - Optimally arrange your geometry during manufacturing by using Netfabb. Netfabb can properly position and orient complex geometry within a build environment and near other geometry using their packing features to balance a build's density. To expand, there are a couple of major benefits that can be accessed using packing.
    o   **Minimize material usage** – Since the alogrithim is positioning parts to minimize the total size across a given material volume, the material yield can be maximized. This limits the amount of recycled, unused and excess material.
    o   **Minimize runtime** – Due to the proximal nature of the optimized parts and the ability to orient geometry in a very efficient way, there is a direct impact on enhancing the operational runtime of a job. Basically this function limits the build height, requiring the machine to do less work to complete the job.
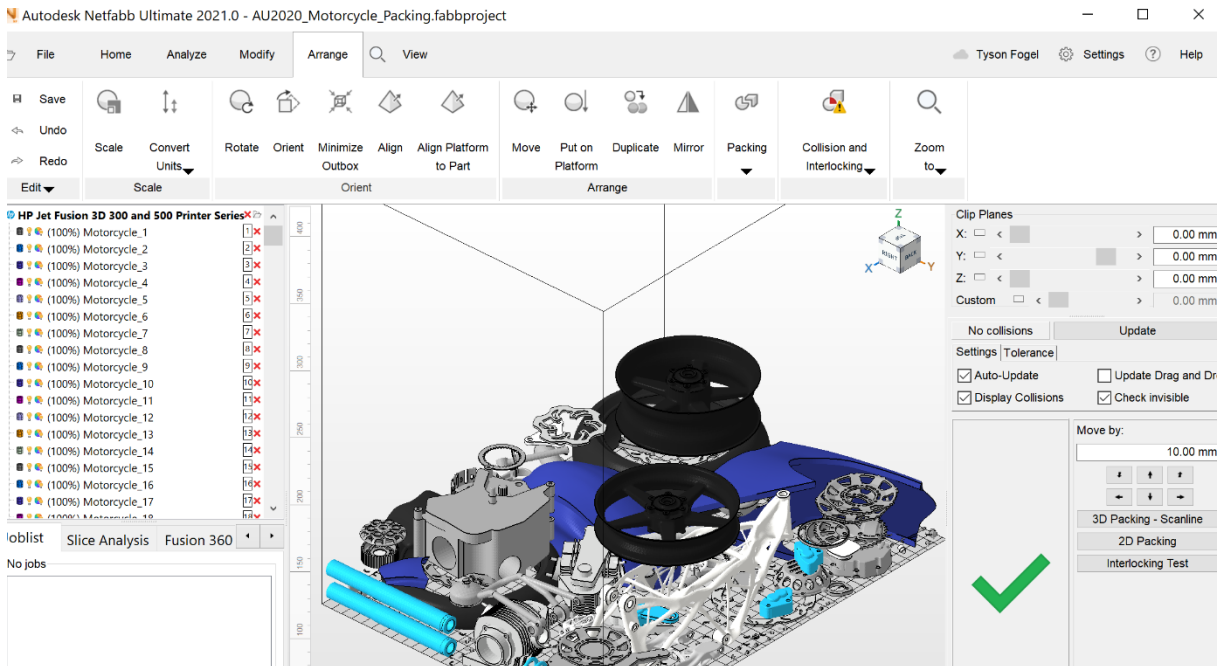
- **Simulation** – There are a variety of simulation types – some specific to design quality are native to Fusion 360 within the Simulation workspace. These are simulations of how a product will react under certain conditions. Some of these simulation types include: Static stress, displacement, modal frequency, thermal, thermal stress, non-linear static stress, event simulation, buckling and electronics cooling. Running your designs through a simulation tool prior to fabrication can help pinpoint areas of need and help identify opportunistic regions within a design. These could be areas that require further consolidation, light weighting through ribbing, latticing or bolstering. Essentially, simulation is a diagnostics tool to help a designer better understand a component's integrity, performance, and structure in different environments and under varying conditions. We know that the inability to project downstream pitfalls can cause error to compound incrementally to the point of failure. Simulation (both in process and usage) can give you this insight and the ability to adapt, improve and address any inefficiencies. Fusion 360 has an excellent simulation workspace that can be coupled with computer-aided fabrication or process simulation (Netfabb or Fusion).
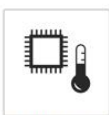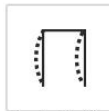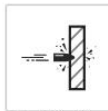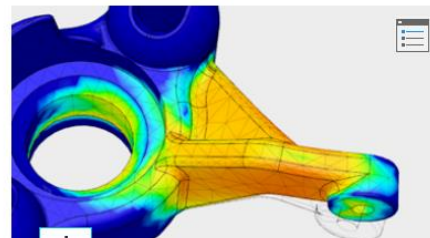
Sustainable practice in AM boils down to the ability to have foresight across the entire process. The ability to think downstream better equips an operator/designer/engineer to address issues up front.

ABOUT THE AUTODESK TECHNOLOGY CENTERS

The Autodesk Technology Centers are where the future of making takes shape. With locations around the world, we invite industry, academic, and entrepreneurial communities to reimagine what it means to design and make, and create a shared vision of the future that will enable people to turn ideas into new realities that shape a thriving future.

Autodesk provides the facilities, technology, equipment, training, and expertise for these communities to explore ideas that will shape the future. With locations in San Francisco, Boston, Toronto, and Birmingham, UK, the Autodesk Technology Centers are committed to exploring the future of making. From architecture, engineering and construction, to manufacturing, and generative design, these spaces exist to foster open innovation and advance the industries that help imagine, design, and make the world around us.

The Outsight Network at the Autodesk Technology Centers provides open workspaces for teams from industry, academic, and startup communities doing forward-looking work in the areas of architecture, engineering, and construction to manufacturing and design.

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KEY RESOURCES

AUTODESK SUSTAINABILITY
- Autodesk Sustainability – Landing page for sustainability at Autodesk. Outline the ways, approaches and active steps being taken to be more sustainable and the efforts to empower our customers to be sustainable
- Autodesk Sustainability Report – FY2020 report on Autodesk Sustainability areas.
- Autodesk Circular Design – Website outlining circularity at Autodesk and how you to can leverage/contribute to the circular economy.

FUSION 360
- Fusion 360 – Landing page for all things Fusion 360.
- Self-Paced Learning – Modules on all aspects of Fusion 360, including Simulation and Generative Design.
- Product Documentation – Written walkthrough on all aspects of Fusion 360.
- Fusion 360 Videos – YouTube webinar on different aspects of Fusion 360 .
- Fusion 360 Blog – Latest updates on all things Fusion 360.
- Fusion 360 Fusion 360 Live: 3D Printing Workflow – Walkthrough on how to use the additive manufacturing slicer native to Fusion.
- Command Map – Fusion 360 plugin to aid in self-paced learning.
- Fusion 360 Live: Simulation Basics – Great walkthrough on how to all aspects of Simulation within Fusion 360. Including how to set up a study and leverage the workspace.

GENERATIVE DESIGN
- Autodesk Generative Website – Main landing page for everything Generative Design.
- Customer Examples – Great examples of the diversity and capability of Generative Design.
- Resource Center – Customer success stories, interesting articles and white papers all in one place.
- Fusion 360 Live: Generative Design Tips & Tricks – Great and thorough walkthrough on all aspects of how to use and setup a Generative Design study.
- Article: Generative Design: What Can It Do For Sustainability? – Written by a member on the Autodesk Sustainability team and provides some really great questions and thought-provoking concepts.

NETFABB
- Advanced Additive Manufacturing in Fusion and Netfabb – A guided walk through on a Fusion to Netfabb workflow. Includes automated orientations and support structure optimization within Netfabb.
- Design for Additive Manufacturing: Lattices in Netfabb – A guided walk through on how to set up and configure lattice/infill structures within Netfabb. Includes how to apply a finite element analysis to an infill structure.
- Part Orientation – Quick breakdown on some of the key parameters within the orientation feature of Netfabb.
- Netfabb Tutorial: 3D Printing Orientation – A quick video on how to orient a part in Netfabb.
- Packing – A breakdown of the different types and parameters within Netfabb's packing environment.
- Netfabb Tutorial: Packing Demo – An in-depth walk through on how to leverage packing within Netfabb.

AUTODESK TECHNOLOGY CENTERS
- [Autodesk Technology Centers](#) – Landing page for anything and everything Technology Center related. Learn more about what it is, how it works and how to apply.
- [Projects at the Autodesk Technology Centers](#) – Great examples of how organizations and customers are leveraging the Technology Centers and the residency program.
- [Proposal Application](#) – Apply to become a resident! Have any questions related to this form? Feel free to reach out to technology.centers@autodesk.com with any questions.