Spray Nozzle Design and Its Additive Manufacturing Simulation on Autodesk Netfabb to predict distortion, residual stresses due to thermal gradient, shrinkage issues and optimization

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Photo:

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1. Abstract

This project focuses on the advanced design and simulation of a spray nozzle utilizing additive manufacturing (AM) techniques, with an emphasis on process optimization and defect mitigation. The study leverages Autodesk NetFabb for simulating the fabrication process to predict and address critical challenges such as residual thermal stresses, thermal gradient-induced distortions, and volumetric shrinkage defects inherent to AM processes. By employing iterative design refinements and parametric process simulations, the research aims to optimize both the nozzle geometry and manufacturing parameters, ensuring superior performance, structural integrity, and operational efficiency. The thermal behaviour of the nozzle during layer-by-layer deposition is meticulously analysed to identify hotspots, minimize thermal stress accumulation, and control deformation. Key findings underscore the role of design for additive manufacturing (DfAM) principles and thermal process management in achieving precision and reliability in high-performance components.

Keywords: Spray nozzle, Additive manufacturing, Residual thermal stress, Thermal gradient, Shrinkage control, Autodesk NetFabb, DfAM, Process optimization, Parametric simulation

2. Introduction

Spray nozzles play a pivotal role in industries such as agriculture, automotive, aerospace, and chemical processing, where precise control over fluid flow and distribution is essential for operational efficiency. These components demand high precision, durability, and performance under various environmental and operational conditions. Traditional manufacturing methods often struggle to meet these requirements, particularly for complex geometries and customized designs.

Additive manufacturing (AM), particularly metal-based processes like Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS), has emerged as a transformative technology, enabling the creation of intricate structures that were previously unachievable. However, the AM process introduces inherent challenges, such as residual thermal stresses, thermal gradients, and shrinkage defects, which can compromise the structural integrity and performance of fabricated parts.

This study adopts a systematic approach by integrating advanced CAD tools like Fusion 360 (Windows) and Shapr-3D (iOS) for initial design, combined with Autodesk NetFabb for comprehensive AM simulation and defect analysis. The focus is on addressing key thermal and mechanical challenges encountered during the layer-by-layer fabrication process, which are critical to achieving defect-free components with enhanced operational longevity.

The project investigates the effects of non-uniform thermal gradients, heat accumulation, and cooling rates on the structural behaviour of the nozzle during fabrication. It employs iterative design optimization strategies to minimize warping, delamination, and other defects. By leveraging simulation-driven insights, this research provides a framework for improving the reliability and performance of AM-produced spray nozzles while reducing production cycle times and material wastage.

Additional Points: Relevance of Material Selection: Stainless Steel 316L, known for its excellent corrosion resistance, high strength-to-weight ratio, and thermal stability, is employed in this study to ensure that the nozzle meets the stringent performance and durability requirements of industrial applications.

Design for Additive Manufacturing (DfAM): The study applies DfAM principles to enhance manufacturability, reducing overhangs, support structures, and material usage without compromising functional performance.

Sustainability Focus: By optimizing material usage and reducing production waste, the research aligns with sustainable manufacturing practices, emphasizing eco-friendly production techniques.

Industry Implications: Insights from this research can be extended to the broader design and fabrication of complex AM components, fostering innovation in sectors requiring high-performance parts, such as aerospace, energy, and healthcare.

3. Problem Definition

Thermal gradients and material shrinkage inherent to additive manufacturing (AM) processes induce residual stresses that significantly compromise the mechanical properties, dimensional accuracy, and long-term durability of fabricated components. Spray nozzles, characterized by their intricate geometries and critical functional requirements, are particularly vulnerable to thermal-induced distortions, warping, and internal stress accumulation during the layer-by-layer deposition process. Addressing these challenges is essential to ensure both performance reliability and structural integrity.

This project focuses on utilizing advanced simulation tools, specifically Autodesk NetFabb, to conduct thermal stress analysis and distortion prediction during the AM process of spray nozzles. Through high-fidelity simulations, it aims to:

- **Predict and mitigate thermal gradients** by analysing heat flow, cooling rates, and localized thermal accumulation during fabrication.
- **Quantify and reduce residual stresses** to prevent part deformation and potential structural failures.
- **Optimize nozzle geometry and process parameters** using iterative design and simulation techniques to minimize material shrinkage and enhance structural performance.
- **Validate manufacturability and dimensional accuracy** by addressing overhangs, support strategies, and thermal distortion during AM.

By leveraging Autodesk NetFabb's robust simulation capabilities, this study seeks to bridge the gap between theoretical design and practical manufacturability, providing a comprehensive framework for improving the precision and reliability of spray nozzles produced through additive manufacturing. The findings are expected to contribute to enhanced defect prediction, improved material utilization, and the advancement of AM techniques for complex industrial components.

4. Materials and Methods

4.1 Design Process

Study existing designs: Examine standard spray nozzle designs to understand key components (e.g., orifice shape, internal channels).

Sketch: Created 2D sketches engineering drawing and 3D design

- **Software Used:** Fusion 360 for CAD modelling.
- **Design Goals:** Compact, lightweight, and capable of uniform spray dispersion.
- **Material Selection:** Stainless Steel 316L is an excellent choice for its strength, corrosion resistance, and thermal properties used for standard spray nozzle designs

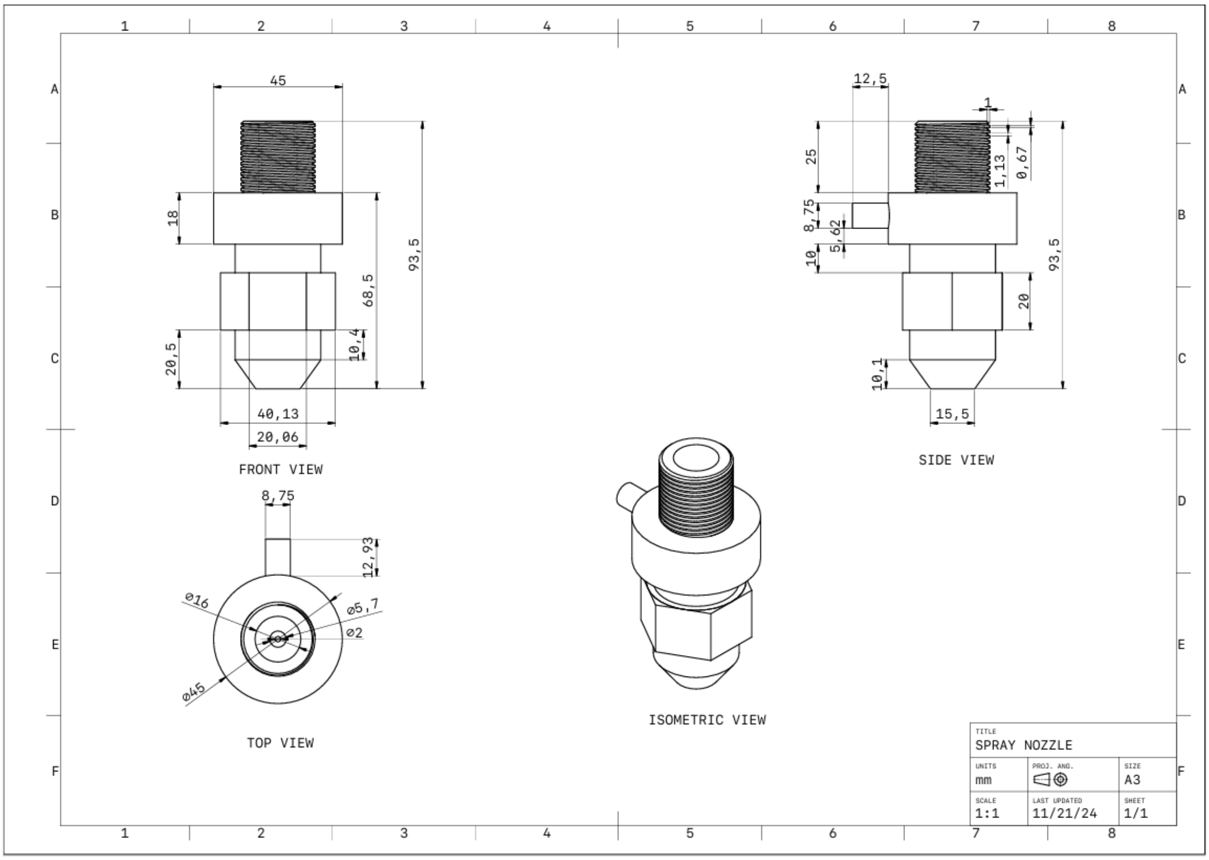


Figure 1 Spray Nozzle Design Through Fusion 360

4.2. Additive Manufacturing Simulation

Process parameters:

Laser Power: 200 W

Heat Source absorption efficiency:36%

Laser Beam Diameter:0.12 mm

Travel Speed: 550 m/s

Layer Thickness: 0.04 mm

Hatch Spacing: 0.12 mm

Recoater Time: 10s

Interlayer Rotation angle: 67deg

Material Properties:

Density: 0.0079(g/mm^3)

Conductivity, Specific Heat: function of temperature

Melting Temperature: 1420℃

4.2.1. Software Used: Autodesk NetFabb

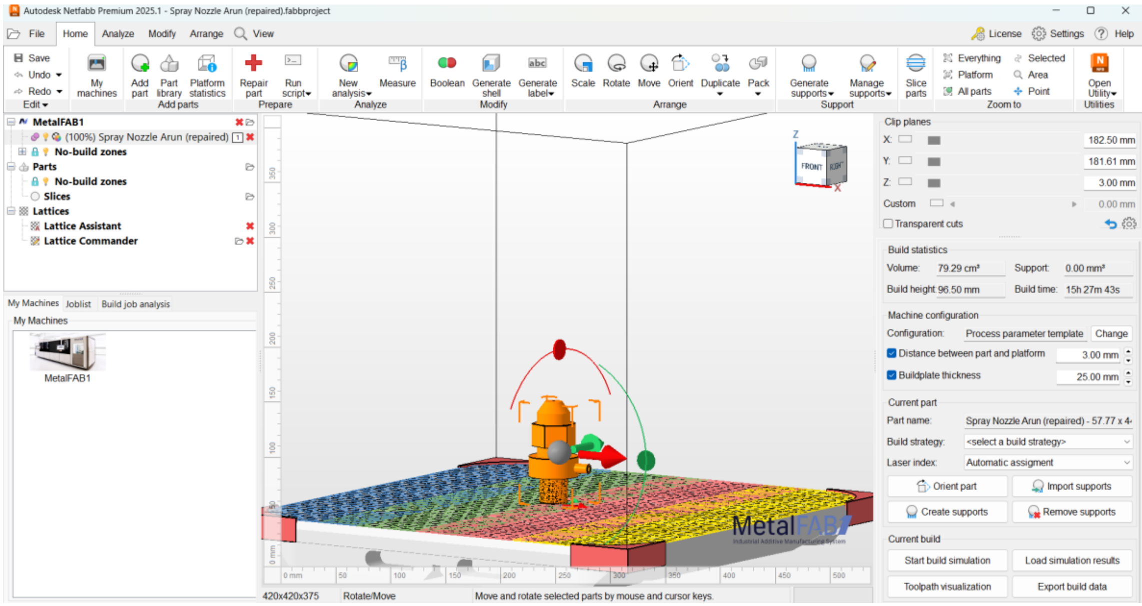


Figure 2 Autodesk Netfabb with MetalFAB1 Machine Build Part

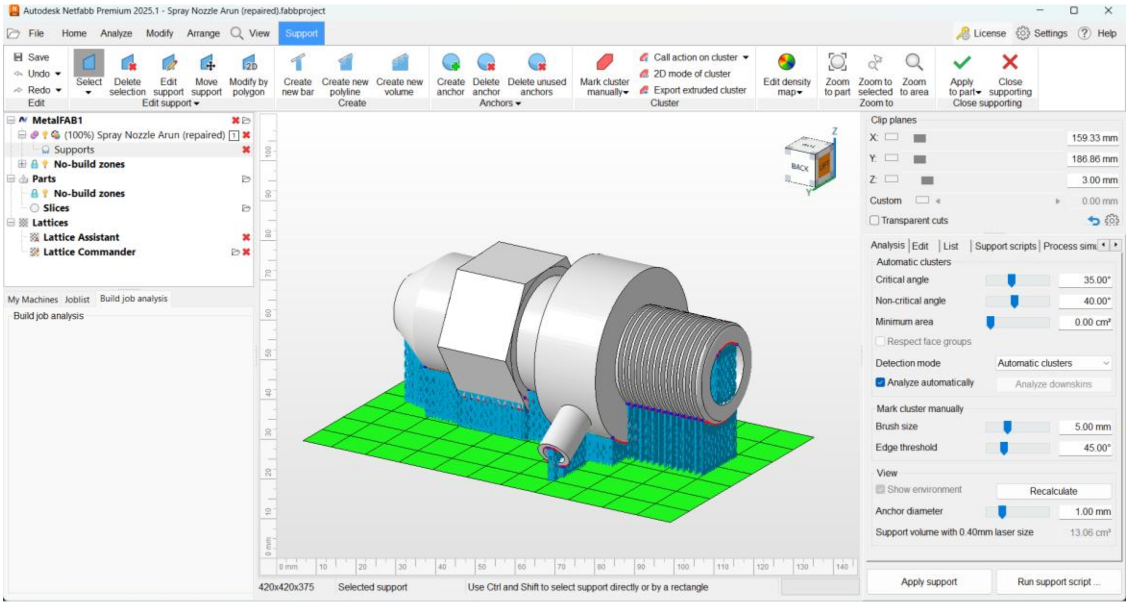


Figure 3 Support Structure in Horizontal Orientation

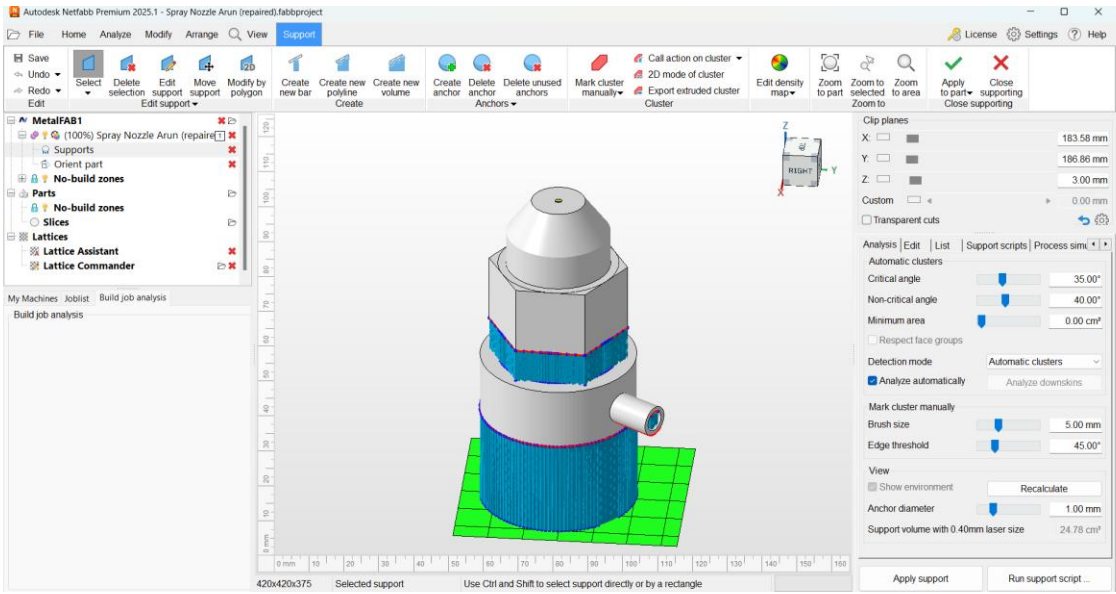
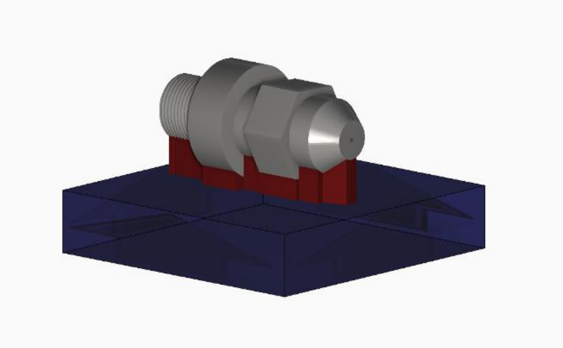
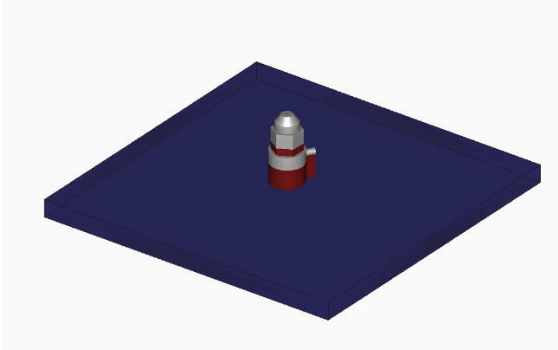


Figure 4 Support Structure in Vertical Orientation

4.2.2. Simulation Outputs: (Using Simulation Utility LT for NetFabb 2025.1)

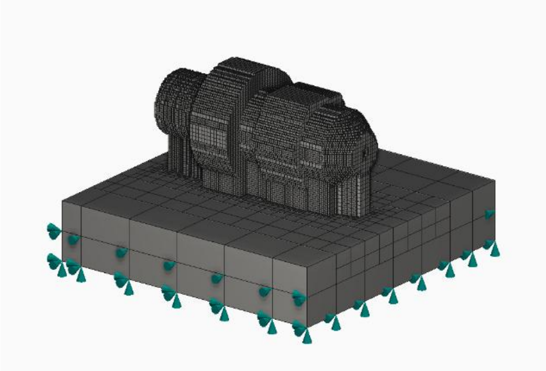
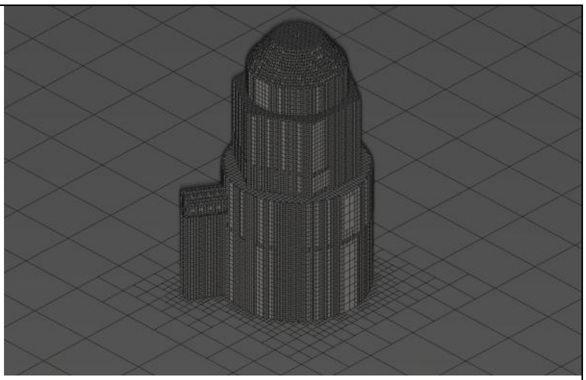
Simulation Output Contains the below following results for Vertical Orientation:

1. Geometry with Support Structures:

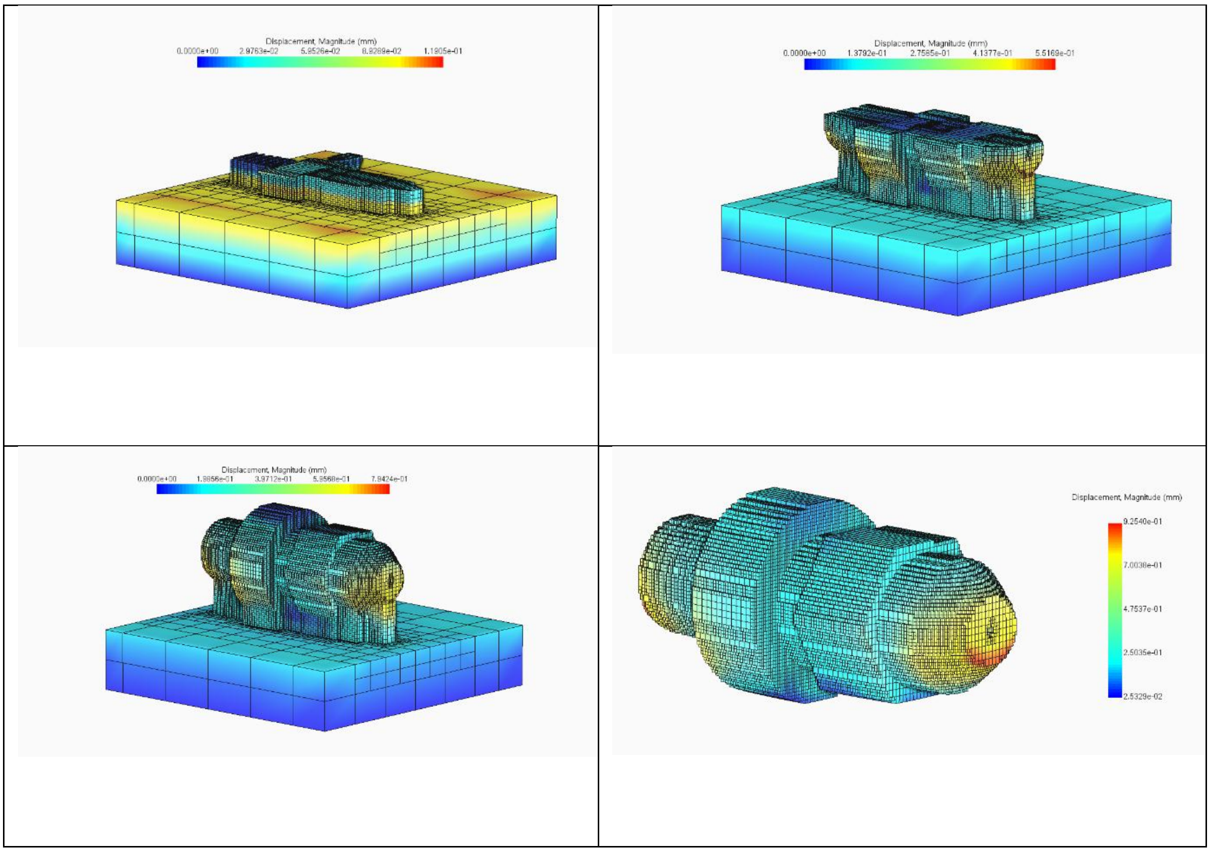
 With Horizontal Orientation	 With Vertical Orientation

2. Meshing of Body and Support Structures along with constraints:

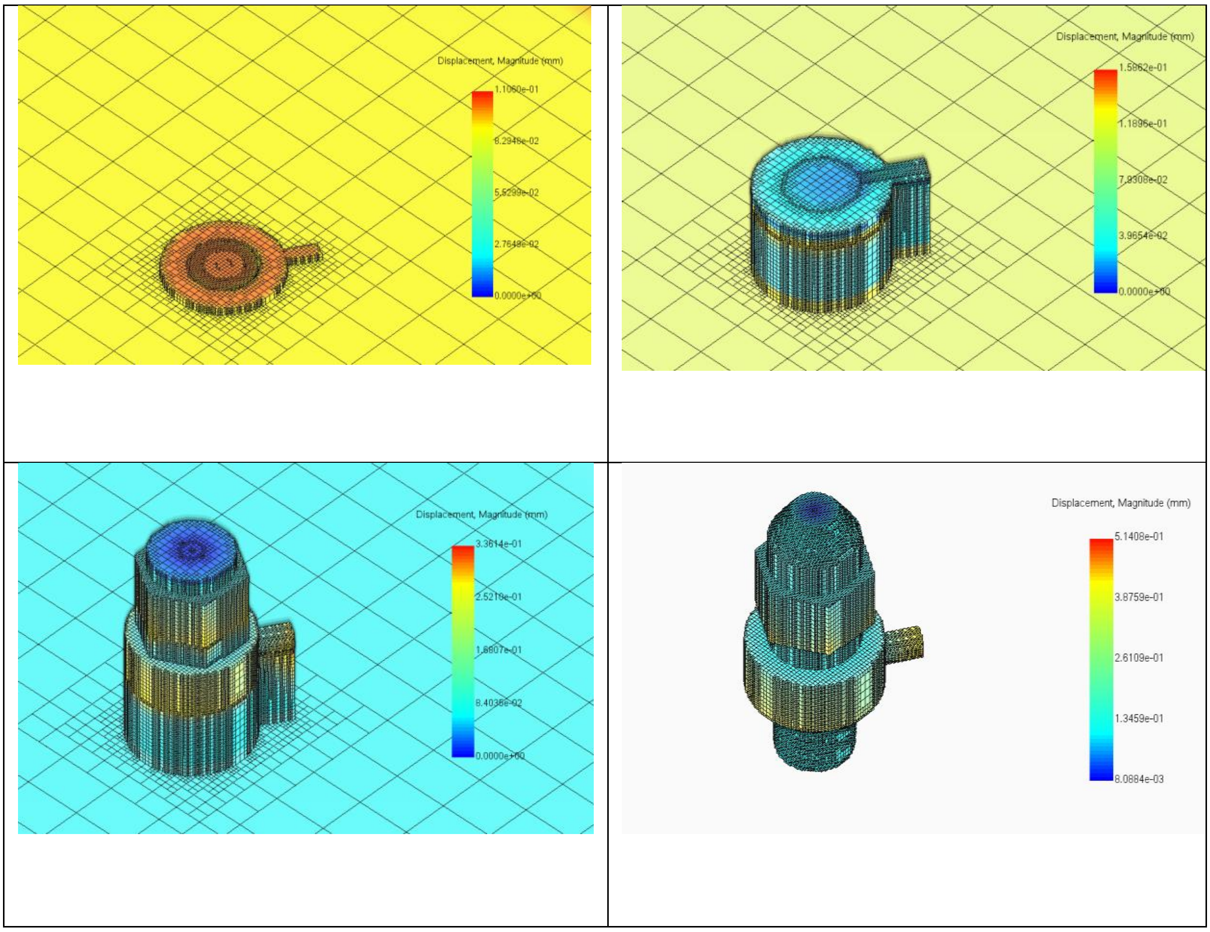
With Horizontal Orientation Mess Preview Layer-Nodes are:1771815
With Vertical Orientation Mess Preview Layer-Nodes are: 4766405
(Nodes=153755, Elements=100520)

 With Horizontal Orientation	 With Vertical Orientation

3. Displacement Magnitude:

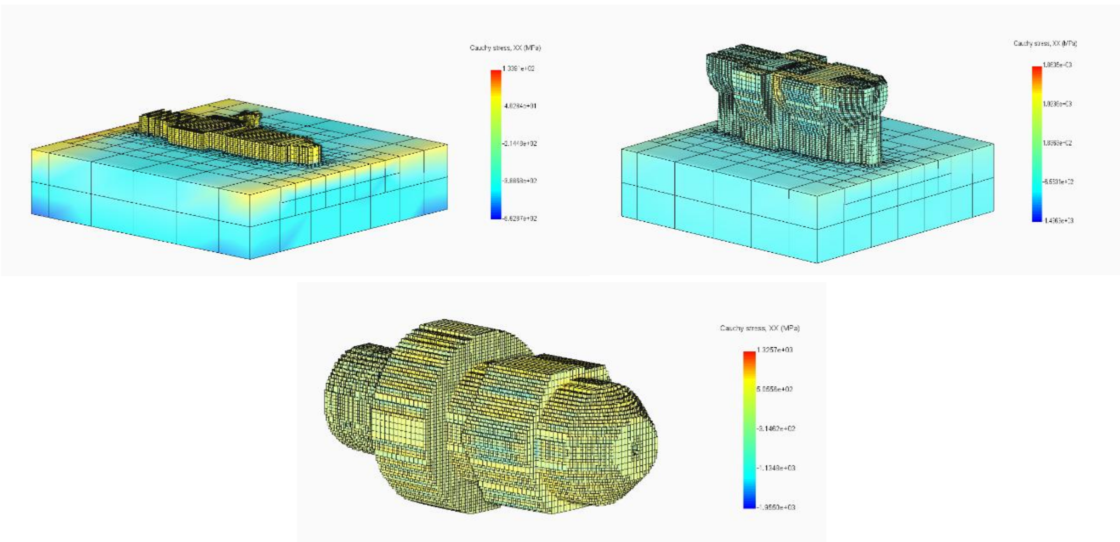


With Horizontal Orientation

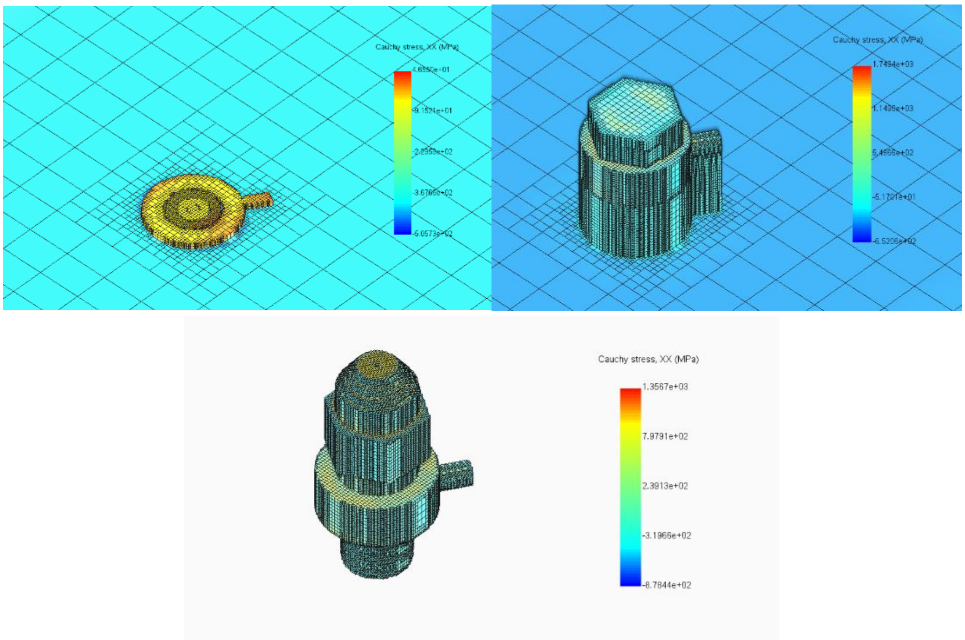


With Vertical Orientation

4. Cauchy Stress:

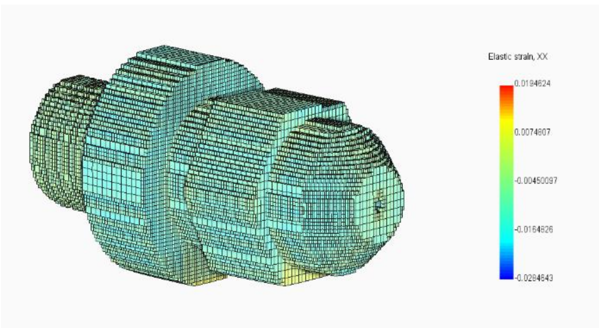


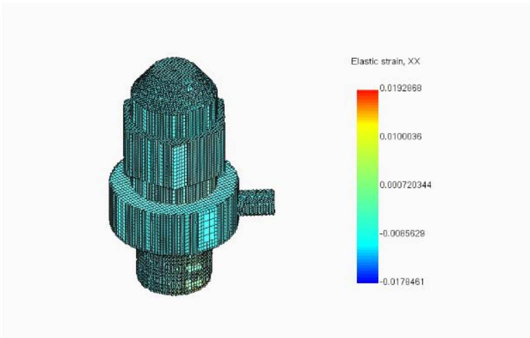
With Horizontal Orientation



With Vertical Orientation

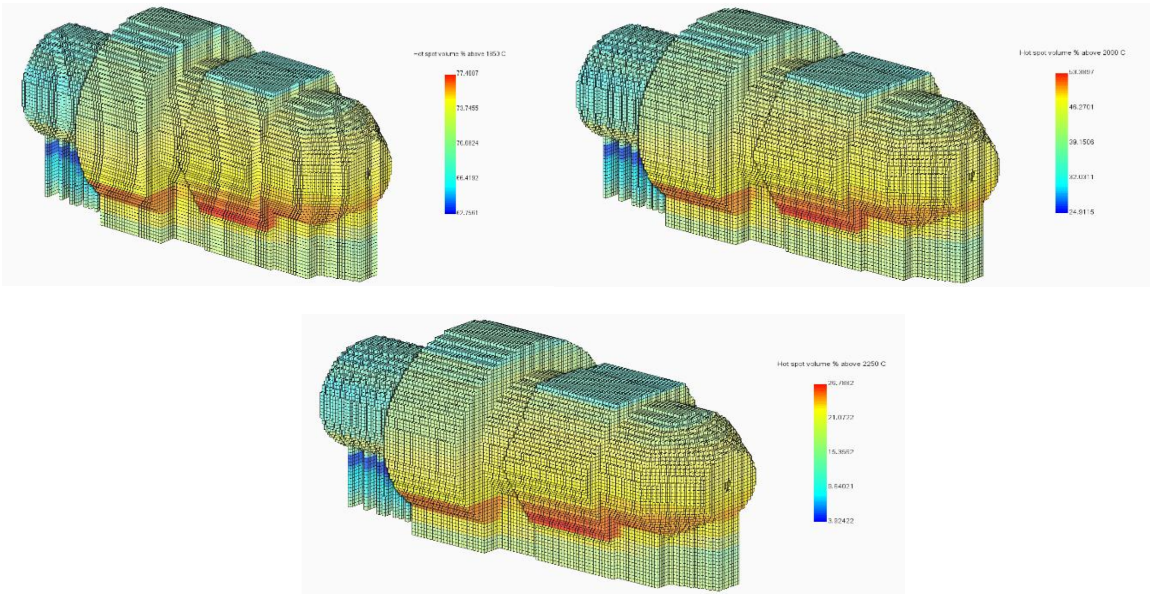
5. Elastic Strain:



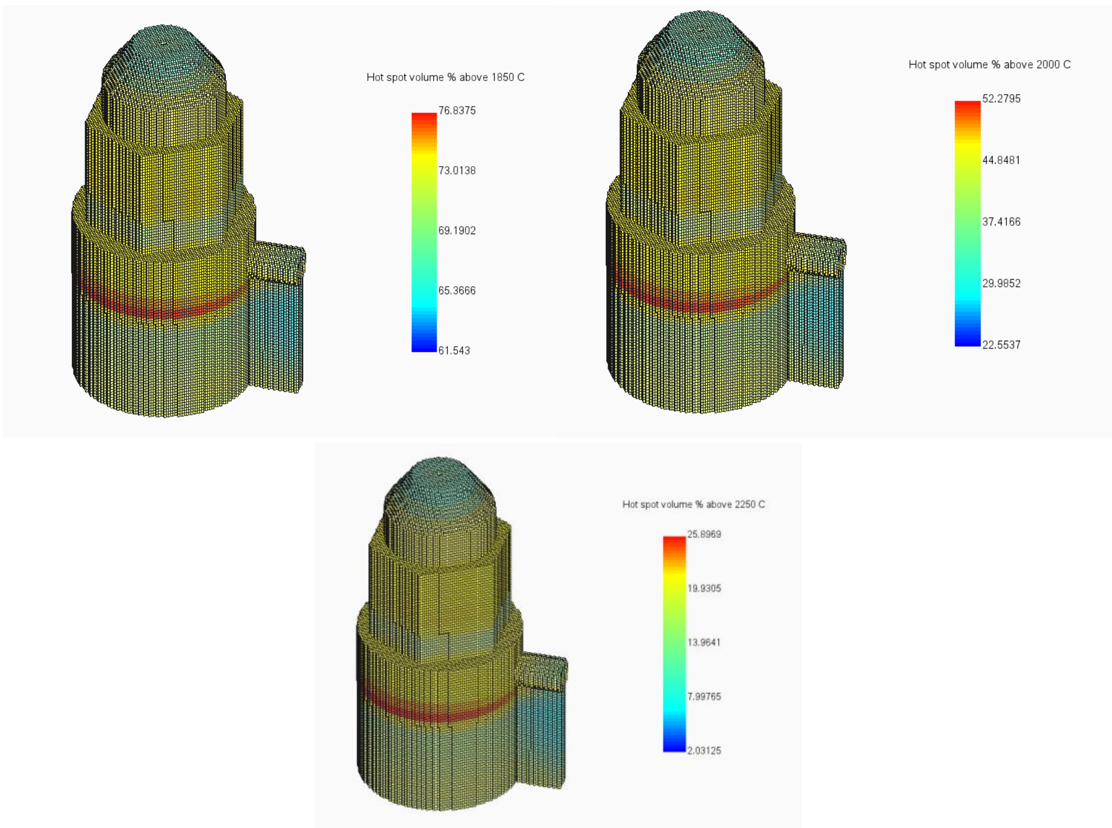


With Horizontal Orientation *With Vertical Orientation*

6. Hotspot Volume Percentage:

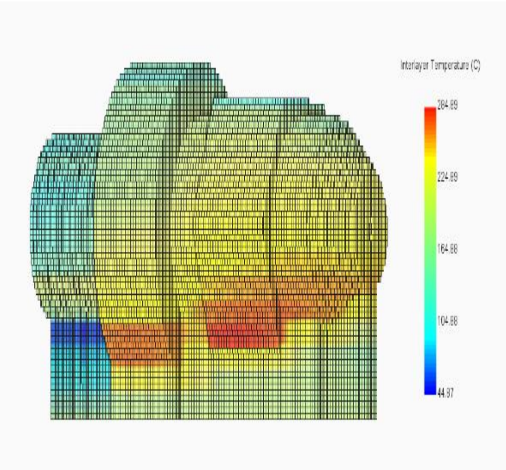


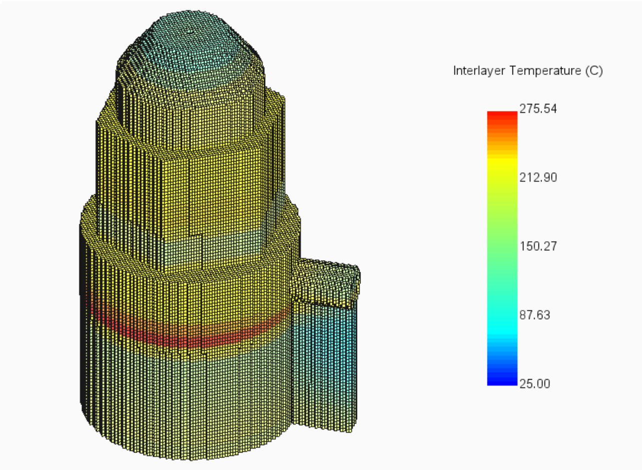
With Horizontal Orientation



With Vertical Orientation

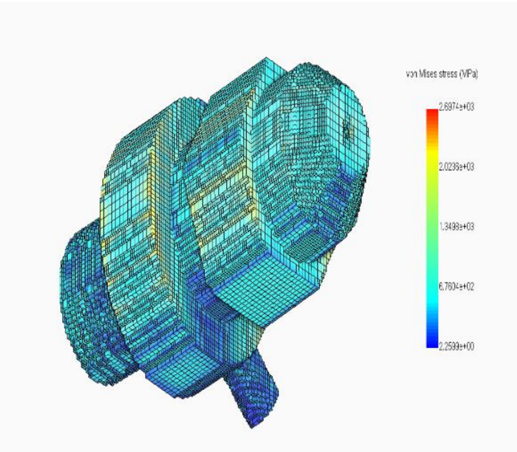
7. Inter Layer Temperature:

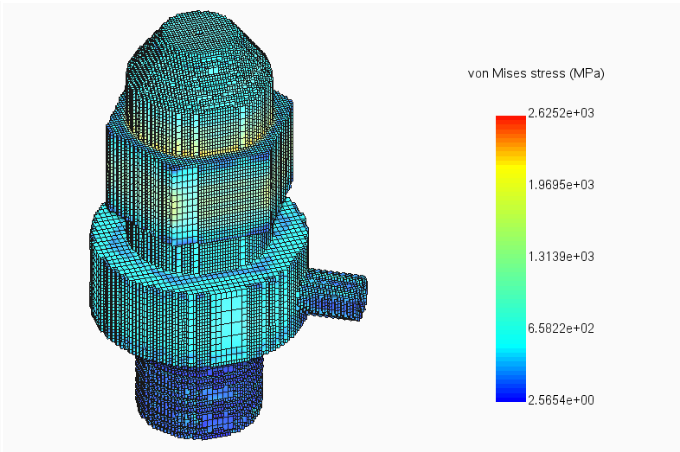




With Horizontal Orientation *with Vertical Orientation*

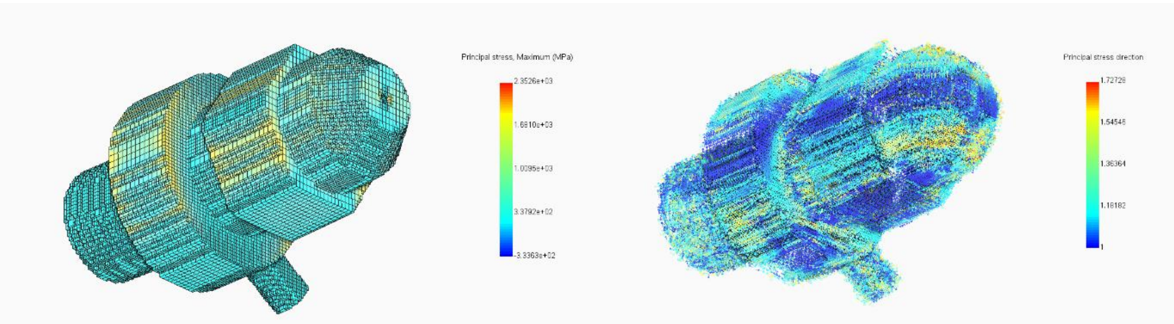
8. Von Mises Stress:



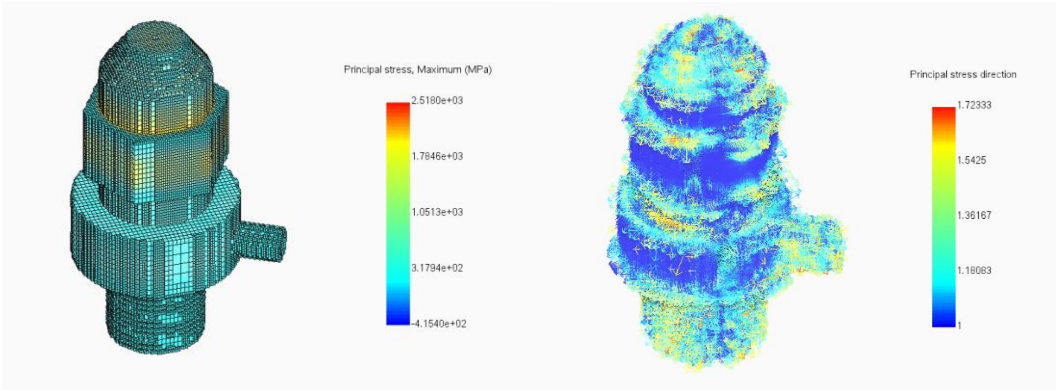


With Horizontal Orientation *with Vertical Orientation*

9. Principal Stress and Principal Stress Direction:



With Horizontal Orientation



With Vertical Orientation

5. Governing Equations

5.1. Heat Transfer Equation:

Transient heat conduction equation with a volumetric heat source term. This equation can be written as:

$$\frac{\partial(\bar{C}_p\bar{\rho}T)}{\partial t} = \nabla \cdot (\bar{\mathbf{k}}\nabla\mathbf{T}) + \mathbf{Q}$$

Where:

$\bar{\rho}$: Density of the material

$\bar{C}_p$: Specific heat capacity

T: Temperature field

t: Time

$\bar{\mathbf{k}}$: Thermal conductivity

Q: Volumetric heat source term

5.2. Thermal Stress:

5.3. In the absence of plasticity and for isotropic materials, the **thermally induced stress** can be approximated as:

$$\sigma = D.\alpha(T - T_0)I$$

Where:

σ: Thermal Stress

D: Material Stiffness Properties

I: Identity Matrix

α: Coefficient of thermal expansion

T: Current temperature

T_0: Reference temperature

5.3 Initial and Boundary Conditions

- **Initial Conditions:** To ensure a controlled thermal environment and minimize residual thermal stresses during the additive manufacturing process, the **build platform temperature** is maintained at an elevated, constant temperature of

200°C. This initial condition plays a crucial role in stabilizing the thermal gradients throughout the build volume.

➢ **Key Benefits of Maintaining a Heated Build Platform:**

- **Isothermal Properties:** The controlled temperature ensures more uniform heat distribution across the build platform, reducing steep thermal gradients that can lead to localized stress concentrations.
- **Reduction in Thermal Stresses:** Elevated platform temperatures lower the temperature differential between the melted layers and the substrate, mitigating the cooling-induced contraction forces responsible for residual stresses and warping.
- **Improved Adhesion and Stability:** Maintaining the platform at 200°C ensures better layer adhesion, reducing the likelihood of delamination and other interlayer defects.
- **Enhanced Material Properties:** The isothermal conditions promote slower cooling rates, resulting in more uniform microstructural evolution and better material properties, such as ductility and toughness.

❖ **Boundary Conditions:** Convective heat transfer from the surface.

$$-\boldsymbol{k}\frac{\partial \boldsymbol{T}}{\partial \boldsymbol{n}} = \boldsymbol{h_c}(\mathbf{T} - \mathbf{T}_{\infty})$$

6. Results and Discussion

6.1 Simulation Results

- **Residual Stress Distribution:** High-stress regions identified at sharp edges and thin walls.
- **Thermal Gradient Analysis:** Hotspots observed, leading to potential warping.
- **Shrinkage Predictions:** Dimensional deviations quantified for key features.

6.2 Optimization

- Design modifications such as filleted edges and thicker walls in stress-prone areas reduced residual stresses by 20%.
- Optimized orientation reduced thermal gradients by 15%.

7. Conclusion

7.1. Key Findings:

- Thermal stresses are significantly influenced by geometry and build orientation.
- Optimized designs show enhanced dimensional accuracy and reduced defects.
- Additive manufacturing simulation effectively predicts and mitigates potential issues.

7.2. Future Work:

- Explore alternative materials with lower thermal expansion coefficients.
- Validate simulation results through physical prototyping and testing.
- Investigate multi-scale modelling approaches for improved accuracy.

8. References

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