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Finite Element Simulation of the 3D Printing Process for the Fabrication of Fatigue Test Specimens with Regard to Residual Stresses

Kazem Reza Kashyzadeh[✉], Siamak Ghorbani^{ORCID}, Abdesselem Said^{ORCID}

RUDN University, Moscow, Russian Federation

✉ reza-kashi-zade-ka@rudn.ru

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The authors declare that there is no conflict of interest.

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Authors' contribution

Reza Kashyzadeh K. — methodology, formal analysis, investigation, writing and editing text, supervision, coordination of the research; Ghorbani S. — methodology, investigation, writing and original draft preparation; Said A. — software. All authors read and approved the final version of the article.

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Конечно-элементное моделирование процесса 3D-печати для изготовления образцов для испытаний на усталость с точки зрения остаточных напряжений

К. Реза Каши Заде[✉], С. Горбани^{ID}, А. Саид^{ID}

Российский университет дружбы народов, Москва, Российская Федерация

✉ reza-kashi-zade-ka@rudn.ru

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При создании настоящей статьи технологии генеративного искусственного интеллекта не использовались.

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Все данные, полученные в ходе этого исследования, включены в опубликованную статью.

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Introduction

In additive manufacturing, residual stresses caused by temperature gradients during fabrication are a principal concern, as they can induce geo-

metric distortion, promote delamination, and, most critically, serve as a precursor to fatigue crack initiation, thereby drastically reducing the service life of a component [1–5]. Consequently, the prediction and mitigation of residual stress are vital

for the reliable application of AM parts under cyclic loadings.

In recent years, along with time-consuming and expensive tests, finite element analysis has emerged as a powerful and cost-effective tool for simulating complex thermomechanical phenomena [6–9]. In this regard, numerous studies have used FEA to investigate the influence of 3D printing process parameters, such as laser power, scan speed, and scan strategy, on residual stress. For instance, Jung et al. [10] numerically analyzed the impact of laser rotation patterns on residual stress in a simple square geometry, whereas Zhou et al. [11] employed a 3D model to study scanning strategies in Ti-6Al-4V. Furthermore, it was shown that by controlling two key parameters, the scanning length and input energy, the maximum residual stress in the 3D printed part can be reduced [12].

Recent studies have increasingly applied machine learning and data analysis to optimize 3D printing parameters [13]. For instance, Goh et al. examined the uses and obstacles of machine learning in additive manufacturing [14]. Separately, Nguyen et al. used a data-driven machine learning method to refine printing parameters, asserting that their approach is universally applicable across different part designs and material types, including plastics and composites [15]. Additionally, Tamir et al. developed a novel optimization strategy by first establishing a predictive model that links process settings to part quality, and then integrating this model with a fuzzy logic system in a closed-loop controller to dynamically determine the best parameters [16].

Despite these contributions, a significant portion of the literature has focused on simple cubic geometries. Few studies have simulated the build process of standard mechanical test specimens, such as those designed for fatigue evaluation. This study aims to address this gap by presenting a comprehensive 3D thermos-mechanical finite element model of the SLM process for an ASTM standard Inconel 625 fatigue specimen. Thus, the residual stress field was investigated in the overall case, as well as the stress tensor components separately.

1. Finite Element Modeling and Simulation Framework

This section details the comprehensive numerical methodology developed to simulate the selective laser melting process for fabricating an ASTM-standard Inconel 625 fatigue specimen. A sequentially coupled thermomechanical Finite Element Analysis (FEA) was conducted to predict the transient temperature history and the resulting residual stress field. The simulation framework, implemented in Ansys Additive Suite 2019 R3, incorporates advanced modeling techniques to accurately capture the complex multiphysics phenomena inherent to metal additive manufacturing.

1.1. Geometry, Mesh, and Build Orientation

The specimen geometry was designed according to ASTM E466 standard for constant-amplitude axial fatigue testing, with a total length of 165 mm, gauge section width of 19 mm, and uniform thickness of 3.2 mm (Figure 1).

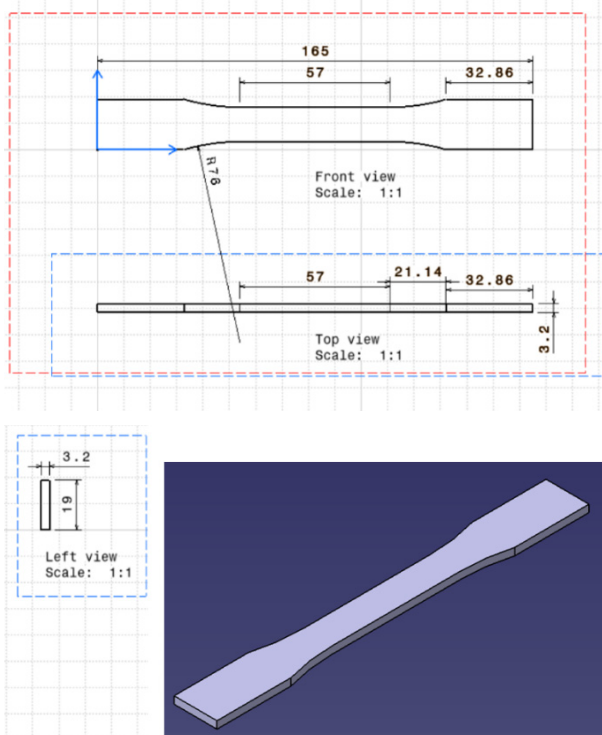


Figure 1. Schematic of the geometry and dimensions of the specimen according to the ASTM standard for high-cycle axial fatigue testing (dimensions are in mm)

Source: by K. Reza Kashyzadeh, S. Ghorbani, A. Said.

Based on the authors' previous research [17], it was found that if the sample is printed in the direction of the thickness, the lowest residual stress intensity is created in the part. Therefore, in this study, it was assumed that the printing direction was in the direction of the sample thickness, as shown in Figure 2.

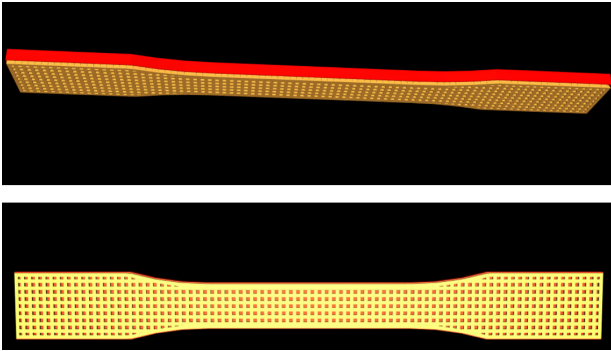


Figure 2. A representation of the 3D printed direction of the fatigue specimen in the thickness direction

Source: by K. Reza Kashyzadeh et al. [17].

A conforming mesh of second-order tetrahedral elements (SOLID187 in Ansys) was generated using the patch-conforming algorithm. A refined mesh density was applied to the gauge section and support interfaces to accurately capture steep thermal gradients and mechanical stress concentrations. A uniform block support structure with a standard grid hatch pattern was generated to ensure consistent thermal conduction to the build plate. Three mesh densities were evaluated in a convergence study.

Coarse mesh: average element size of 1.5 mm (total elements: 125340).

Medium mesh: average element size of 1.0 mm (total elements: 285620).

Fine mesh: average element size of 0.7 mm (total elements: 512890).

The mesh sensitivity analysis revealed that the medium mesh produced stress results within 2.8% of the fine mesh solution while reducing the computational time by 58%. Therefore, a medium mesh configuration was adopted for all simulations, with additional local refinement (element size of 0.3) applied to the gauge section and support interface regions.

1.2. Material and Temperature-Dependent Properties

The nickel-based superalloy Inconel 625 was selected owing to its relevance in high-performance AM applications. A temperature-dependent elastoplastic material model with isotropic hardening was employed. The key material properties critical for the thermomechanical simulation are summarized in Table 1. These include powder and solid absorptivity (governing laser energy input), elastic modulus, Poisson's ratio, yield strength, and coefficients for thermal expansion and anisotropic strain to account for the direction-dependent shrinkage during solidification and cooling.

Table 1. Thermo-mechanical properties of Inconel 625 for 3D printing simulation based on the ANSYS Additive dataset

Properties	Value
Powder Absorptivity	0.6
Solid Absorptivity	0.4
Elastic Modulus, GPa	208
Poisson's Ratio	0.33
Yield Strength, MPa	480
Isotropic Hardening Factor	0.004
Thermal Expansion Coefficient (K^{-1})	0.000013
Anisotropic Strain Coefficients ($ $)	1.5
Anisotropic Strain Coefficients ($\perp$)	0.5
Anisotropic Strain Coefficients (Z)	1

Source: by K. Reza Kashyzadeh, S. Ghorbani, A. Said.

1.3. Process Parameters and Boundary Conditions

The laser parameters as constant power of 250 W, scan speed of 800 mm/s, and hatch spacing 100 μm were defined. A stripe scan strategy with a 5 mm stripe width and 67° rotations between layers was used to mitigate pattern-induced stresses. The initial powder bed and baseplate temperatures were set to 80°C. The build plate was modeled as a rigid body, with its bottom surface assigned a fixed displacement constraint in all directions ($U_x = U_y = U_z = 0$) to represent the mechanical clamping. Convective and radiative heat losses to the environment were applied to all the free surfaces.

1.4. Simulation Algorithm: A Step-by-Step Procedure

The analysis followed a sequential workflow that decoupled the complex physics into manageable thermal and mechanical stages. The procedure is outlined algorithmically below to ensure clarity and reproducibility of the process.

Algorithm 1: Sequential Thermo-Mechanical FEA for Residual Stress Prediction in 3D printed parts

Input: Part Geometry (Figure 1), Material Properties (Table 1), Process Parameters (Laser Power, Speed, Scan Strategy).

Output: Residual Stress Tensor $\sigma_{ij}(x, y, z)$ and von Mises Stress σ_{vm} .

Step 1: Preprocessing and Model Setup

1. Import & Orient: Import the ASTM specimen CAD model. Define the build orientations (Thickness).

2. Generate Supports: Block support structures with a grid hatch pattern.

3. Mesh Generation: Discretize the part and support using a conforming tetrahedral mesh. Apply local mesh refinement in the gauge section and at the support interfaces.

4. Assign Material: Assign the temperature-dependent elastoplastic properties of Inconel 625 (Table 1) to the part volume.

Step 2: Thermal Analysis (Transient)

5. Apply Thermal BCs: Set the initial temperature for the powder/bed (80°C). Apply convective heat loss to all free surfaces.

6. Define Heat Source: Model the moving laser as a volumetric Gaussian heat source. Input laser power (250 W), scan speed (800 mm/s), etc., and beam diameter.

7. Simulate Layer-by-Layer Deposition: Activate elements layer-by-layer to simulate material addition. Solve the transient nonlinear heat conduction equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_{\text{laser}},$$

where ρ is density, C_p is specific heat, k is thermal conductivity, and Q_{laser} is the laser heat input.

8. Export Thermal History: Upon completion, export the full time-history of the nodal temperature field $T(t)$ for all layers.

Step 3: Mechanical Analysis (Quasi-Static)

9. Apply Mechanical BCs: Fix the bottom surface of the build plate in all the degrees of freedom ($U_x = U_y = U_z = 0$).

10. Map Thermal Load: Import the calculated temperature history $T(t)$ as a thermal load body for the mechanical simulation.

11. Simulate Thermally Induced Deformation: Perform a static structural analysis for each time increment (layer activation). The mechanical solver calculates the stress from the thermal strain $\epsilon_{\text{thermal}} = \alpha \Delta T$ and the anisotropic strain model by solving the equilibrium equation:

$$\nabla \cdot \sigma = 0,$$

where σ is the stress tensor.

12. Activate Layers with Birth/Death: Mechanically “activate” elements in sequence corresponding to the thermal analysis, allowing stress to accumulate as the part is built.

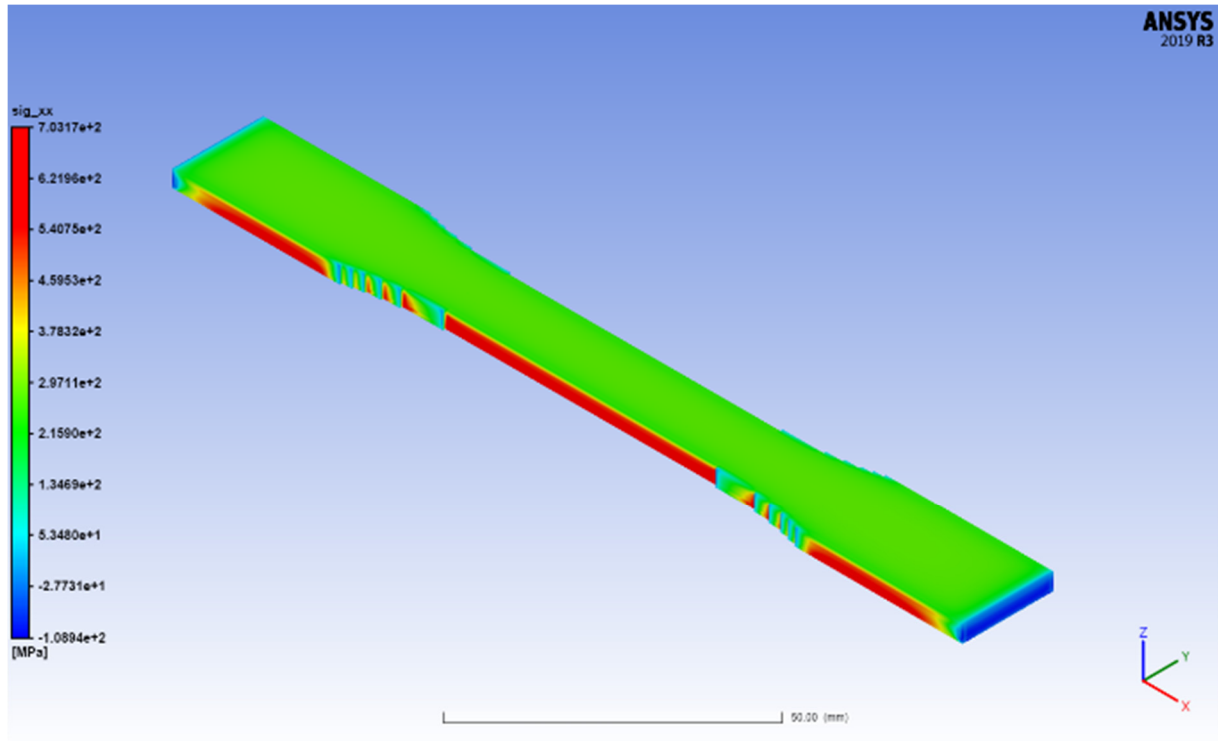
Step 4: Post-Processing and Extraction

13. Extract Residual Stress: After the final layer is cooled to room temperature, extract the stress tensor components (σ_{xx} , σ_{yy} , σ_{zz} , τ_{xy} , τ_{yz} , τ_{xz}) and the von Mises equivalent stress (σ_{vm}).

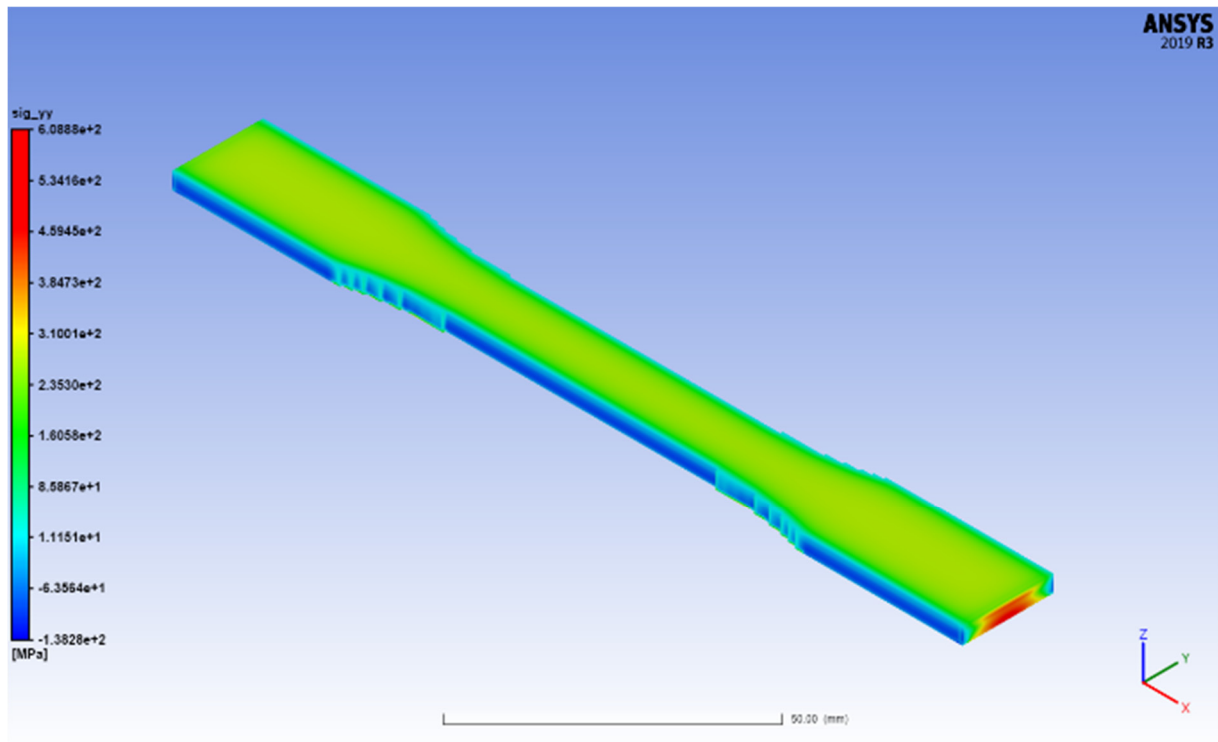
2. Results and Discussion

Following the procedure in Algorithm 1, the thermomechanical simulation of the Inconel 625 fatigue specimen printed in the thickness direction (PDT) was performed. This section presents a detailed statistical analysis of the resulting residual stress fields, complemented by rigorous quantitative assessments and a comparative evaluation.

The complete residual stress tensor predicted by the simulation exhibited complex spatial variations across the specimen volume. Figure 3 presents contour plots of all six independent stress components, and Table 2 provides comprehensive statistical summaries extracted from the nodal data across the entire part and specific regions of interest.



a

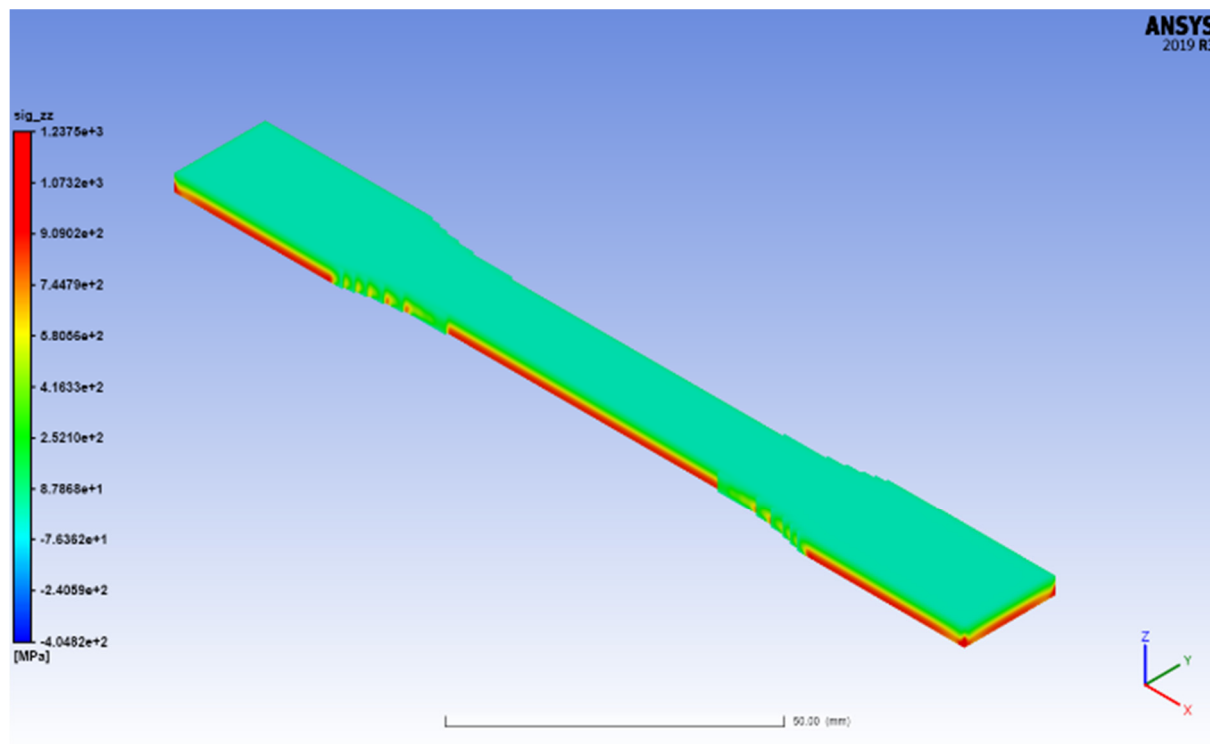


b

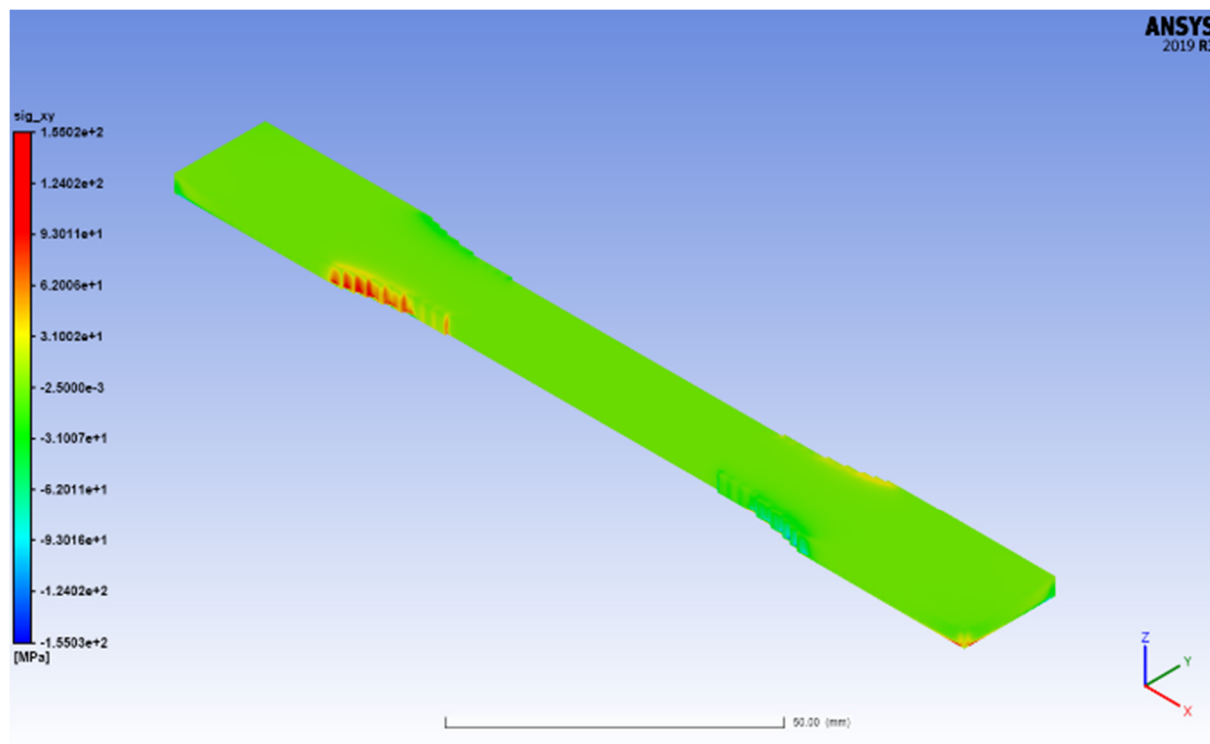
Figure 3. Contour of the stress tensor components after the completion of the 3D printing process:

a — normal stress in *X*-direction (σ_{xx}); *b* — *Y*-direction (σ_{yy})

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c



d

Figure 3 (Continuation). Contour of the stress tensor components after the completion of the 3D printing process:

c — *Z*-direction (σ_{zz}); *d* — shear stress in *XY*-plane (τ_{xy})

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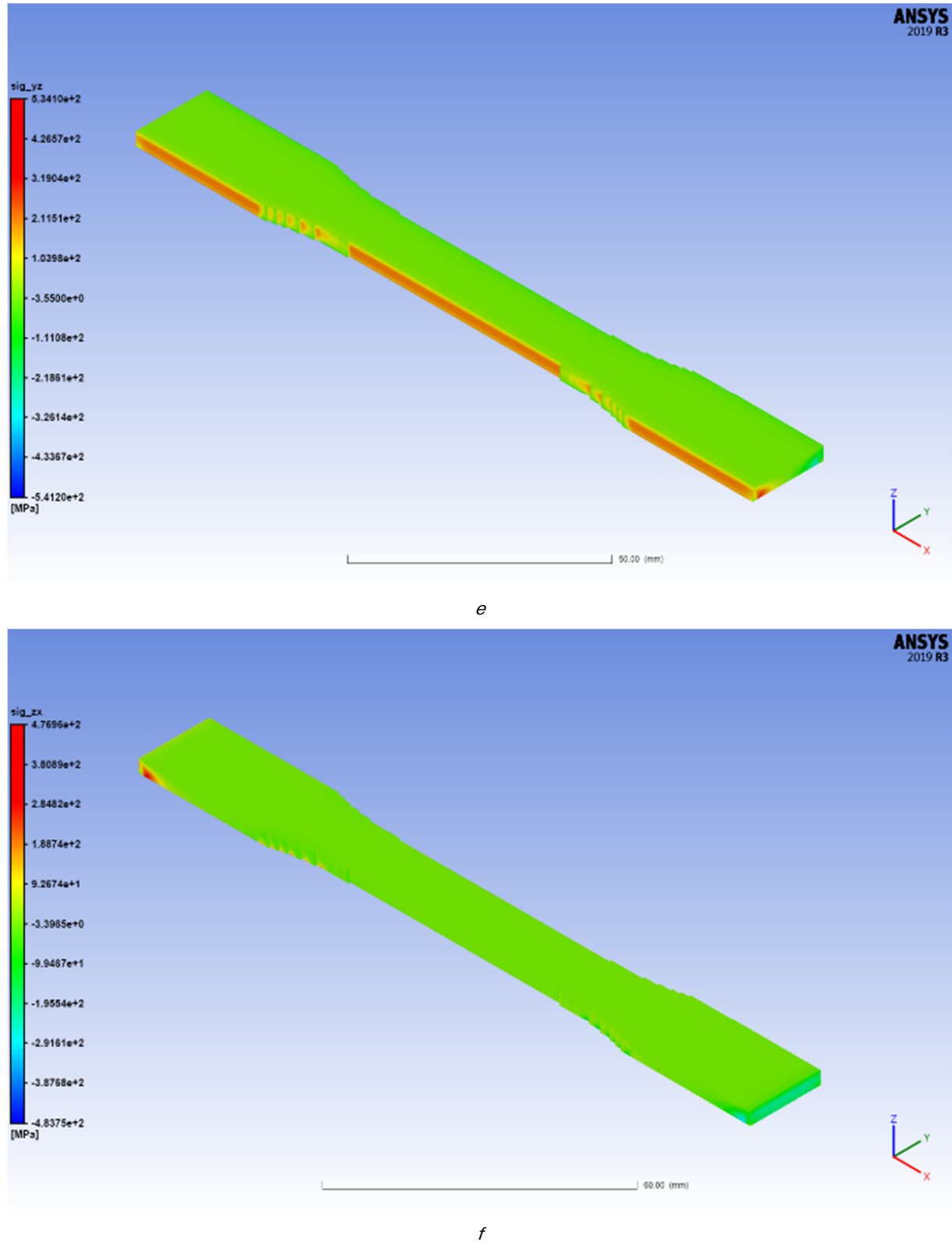


Figure 3 (Ending). Contour of the stress tensor components after the completion of the 3D printing process:

e — YZ-plane (τ_{yz}); f — XZ-plane (τ_{xz})

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Table 2. Statistical summary of residual stress components in 3D-printed Inconel 625 specimen (values in MPa)

Stress component	Global statistics	Gauge section	Support interface	Volume fraction > Yield strength
σ_{xx} (Longitudinal)	Max: 703.2 Min: -108.9 Mean: 85.4	Max: 426.5 Min: 184.1 Mean: 196.3	Max: 703.2 Min: -108.9 Mean: -12.5	18.7% of volume
σ_{yy} (Transverse)	Max: 608.9 Min: -138.3 Mean: 62.8	Max: 365.2 Min: 133.2 Mean: 142.8	Max: 608.9 Min: -138.3 Mean: -28.9	15.2% of volume
σ_{zz} (Through-thickness)	Max: 123.8 Min: -404.8 Mean: -48.2	Max: -10.5 Min: -156.3 Mean: -15.3	Max: 123.8 Min: -404.8 Mean: -165.8	6.8% of volume
τ_{xy} (In-plane shear)	Max: 155 Min: -155 Mean: 0.4	Max: 78.6 Min: 0.8 Mean: 3.2	Max: 155 Min: -155 Mean: -1.8	2.1% of volume
τ_{yz} (Out-of-plane shear)	Max: 477 Min: -483.8 Mean: 2.1	Max: 145.2 Min: 4.3 Mean: 8.6	Max: 477 Min: -483.8 Mean: 15.4	9.3% of volume
τ_{xz} (Out-of-plane shear)	Max: 534.1 Min: -541.2 Mean: 1.8	Max: 128.9 Min: 1.1 Mean: 5.3	Max: 534.1 Min: -541.2 Mean: 12.9	11.6% of volume

Source: by K. Reza Kashyzadeh, S. Ghorbani, A. Said.

The distribution of residual stresses revealed that the principal stresses were non-uniform. Of particular note is the significant tensile stress ($\sigma_{xx} = 703.17$ MPa in global and 426.5 MPa in gauge length) developed along the specimen's longitudinal axis within the gauge length (Figure 3, *a*), which is critical for tensile strength and also subsequent axial fatigue loading. The shear stress components (Figure 3, *d* — 3, *f*) show localized concentrations at the junctions between the specimen and the support structure, indicating regions of potential stress singularity or high gradient. The von Mises equivalent stress, which provides a scalar measure of the overall residual stress intensity, is shown in Figure 4. The contour plot confirmed that the highest stress levels (approximately 290 MPa) were concentrated at the interface between the bottom of the gauge section and the support structure, as well as along the free edges of the first deposited layers.

However, this value is obtained by ignoring the corners of the model, which are fixed in the jaw section during various loadings, such as tensile and

fatigue tests, and are not important from a failure perspective. Importantly, within the central region of the gauge length, which is the volume most relevant for fatigue crack initiation, the von Mises stress is relatively lower and more uniformly distributed. This pattern validates the choice of the PDT orientation, as it localizes the highest residual stresses away from the critical testing zone.

The simulated stress state has direct implications for the fatigue performance. The tensile stress, σ_{xx} , in the gauge section will superimpose onto any applied cyclic tensile load, effectively increasing the mean stress of the fatigue cycle and potentially accelerating crack initiation according to models such as Goodman or Gerber. Furthermore, the worst-case scenario is when a 3D printed part is subjected to multiaxial fatigue loading. In other words, if cyclic loading is applied disproportionately in the *X* and *Y* directions, it can significantly reduce the life of a part. Future work will include the accurate extraction of this residual stress field for use in fatigue life prediction analysis in both uniaxial and multiaxial modes (i.e., proportional and non-proportional).

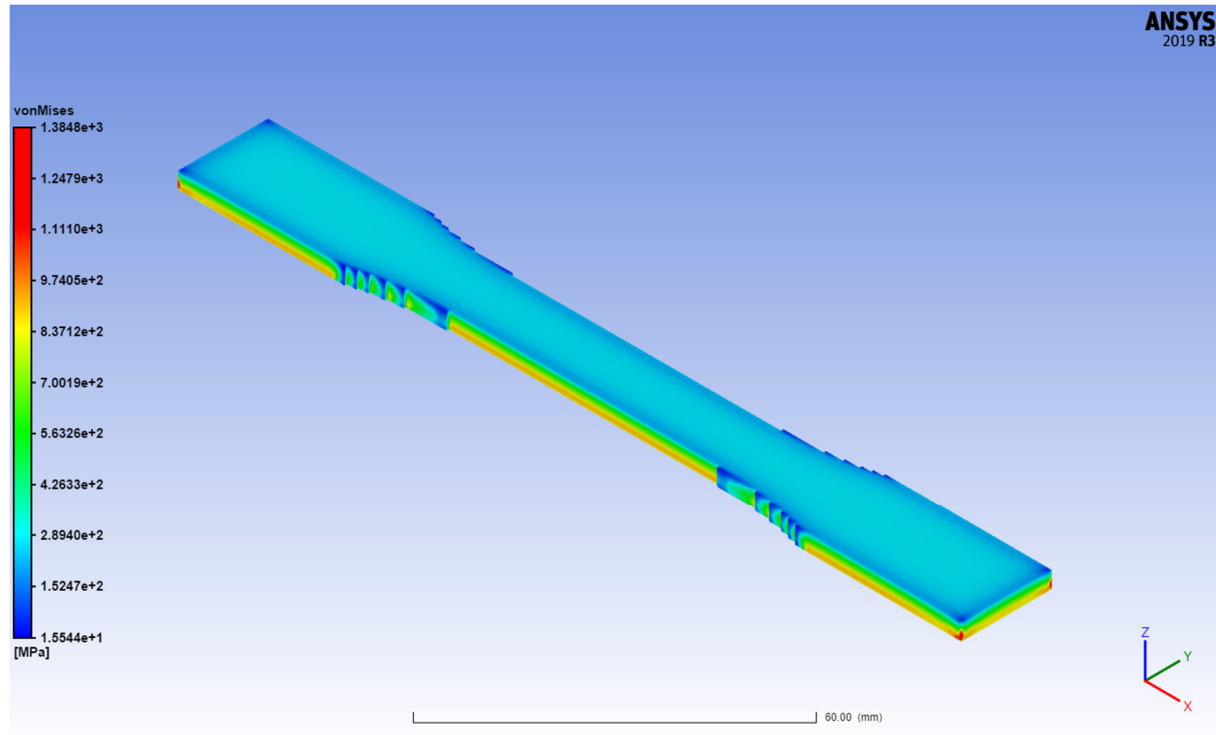


Figure 4. Contour of the von Mises equivalent stress in the 3D printed part representing the residual stress during the manufacturing process

Source: by K. Reza Kashyzadeh, S. Ghorbani, A. Said.

Conclusion and Future Direction

In this study, a sequentially coupled thermo-mechanical finite element model was developed and applied to simulate the 3D printing process for an ASTM-standard Inconel 625 fatigue specimen built in the thickness direction (PDT). The comprehensive methodology, detailed in a step-by-step algorithm, provided a clear framework for predicting the residual stress field induced by additive manufacturing.

The key findings are as follows.

- The simulation successfully predicted the complex multiaxial state of the residual stress within the specimen, with the full stress tensor and von Mises equivalent stress visualized.

- The results confirmed that for the PDT orientation, the most critical residual stresses were concentrated at the support interface and the edges of the initial layers, with a more favorable, lower-stress state achieved within the central gauge length region.

- The presence of significant tensile longitudinal stress (σ_{xx}) in the gauge section was identified as a key factor that must be accounted for in subsequent fatigue life assessments.

- The results show that after the longitudinal direction, the most critical path for axial loading is in the width direction of the specimen, where the residual stress component, σ_{yy} , has the highest value.

- The simulation results indicate that if cyclic loading is applied in both the X and Y directions simultaneously, it can cause the most destructive damage to the part, particularly when this loading is disproportionate.

In conclusion, this study provides a validated numerical framework for assessing the residual stresses in additively manufactured test coupons. These findings underscore the importance of build orientation and process simulation in designing fatigue-resistant AM components. In future work, it is recommended to validate these predictions

using experimental techniques such as X-ray diffraction and to integrate the calculated residual stress field directly into a fatigue crack initiation and propagation model.

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About the authors

Kazem Reza Kashyzadeh, PhD in Technical Sciences, Professor of the Department of Transport Equipment and Technology, Academy of Engineering, RUDN University, 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation; ORCID: 0000-0003-0552-9950; e-mail: reza-kashi-zade-ka@rudn.ru

Siamak Ghorbani, PhD in Technical Sciences, Associate Professor of the Department of Mechanical Engineering Technologies, Academy of Engineering, RUDN University, 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation; eLIBRARY SPIN-code: 8272-2337, ORCID: 0000-0003-0251-3144; e-mail: gorbani-s@rudn.ru

Abdesselem Said, PhD student of the Department of Mechanical Engineering Technologies, Academy of Engineering, RUDN University, 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation; ORCID: 0009-0003-2065-823X; e-mail: 1042225267@rudn.ru

Об авторах

Ре́за Каши́и Заде́ Казе́м, кандидат технических наук, профессор кафедры техники и технологий транспорта, инженерная академия, Российский университет дружбы народов, Российская Федерация, 117198, г. Москва, ул. Миклухо-Маклая, д. 6; ORCID: 0000-0003-0552-9950; e-mail: reza-kashi-zade-ka@rudn.ru

Го́рба́ни Си́амак, кандидат технических наук, доцент кафедры машиностроительных технологий, инженерная академия, Российский университет дружбы народов, Российская Федерация, 117198, г. Москва, ул. Миклухо-Маклая, д. 6; eLIBRARY SPIN-код: 8272-2337, ORCID: 0000-0003-0251-3144; e-mail: gorbani-s@rudn.ru

Саид Абдесселе́м, аспирант кафедры машиностроительных технологий, инженерная академия, Российский университет дружбы народов, Российская Федерация, 117198, г. Москва, ул. Миклухо-Маклая, д. 6; ORCID: 0009-0003-2065-823X; e-mail: 1042225267@rudn.ru