Simulation of the residual stress field and evaluation of tensile strength in thin-walled components fabricated by metal 3D printing

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Abstract: Residual stresses significantly influence the mechanical performance and dimensional accuracy of metal components fabricated via additive manufacturing. This study investigates the residual stress fields and tensile properties of thin-walled specimens produced by metal 3D printing using stainless steel SS316L. Residual stresses were characterized through both numerical simulations and experimental measurements employing the hole-drilling method. Tensile testing was conducted to evaluate the effect of residual stresses on mechanical strength. Results indicate a strong correlation between the residual stress distribution and tensile behavior of SS316L specimens. The difference between the residual stress simulation and the measured experiment is 10%. The findings provide valuable insights for optimizing additive manufacturing parameters to enhance the structural integrity and reliability of metal 3D printed parts.

Keywords: 3D printing, residual stress, numerical method, thin-walled components.

1. Introduction

Direct Laser Metal Deposition (DLMD) is an advanced additive manufacturing technique employing a high-power laser to fabricate metal components layer by layer directly from metal powders within an inert gas atmosphere. This method enables the production of complex parts with high dimensional accuracy and is widely applied for both manufacturing and repair of critical components. The DLMD system comprises a laser source, powder feeder, multi-axis motion system, and an inert gas shielding arrangement. Figure 1 illustrates the schematic diagram of the DLMD system and the deposition head assembly (Khoa et al, 2024).

Key advantages of DLMD include:

- High precision meeting aerospace, automotive, and energy industry standards;
- Compatibility with a wide range of metals, including stainless steel, titanium alloys, and nickel-based alloys;
- Efficient material use reducing waste compared to conventional machining;
- The ability to repair damaged components such as turbine blades and molds, minimizing cost and downtime;
- Integration with CAD software allowing customized design and optimized process parameters (Morville et al, 2012).

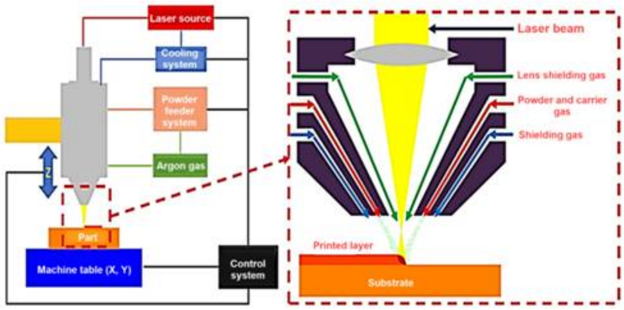

Figure 1. Schematic diagram of the DLMD system and deposition head assembly

The process involves rapid melting and solidification of powder layers, generating steep thermal gradients and contraction that induce residual stresses within the fabricated parts. These residual stresses can cause deformation, surface cracking, delamination, and deterioration of mechanical properties, thus affecting product quality and lifespan (Toyserkani, 2022).

To analyze residual stresses, numerical simulations based on finite element methods (FEM) are extensively used, employing platforms such as ANSYS and COMSOL Multiphysics. These tools facilitate prediction of temperature distribution and residual stress fields during additive manufacturing, helping optimize process parameters efficiently (Toyserkani, 2022; Alimardani, 2007; White, 1984). For instance, Alimardani (Alimardani, 2007) modeled temperature and stress distributions in multilayer LSFF of SS304L, while Morville *et al.* examined heat transfer and fluid flow effects on geometry and surface quality in DLMD.

Experimentally, residual stress measurement often employs the semi-destructive hole-drilling technique. Non-destructive methods, including X-ray diffraction (XRD), have gained attention due to their accuracy, although equipment cost and complexity limit widespread adoption (White, 1984; Mase et al, 1999).

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This study presents a finite element simulation of residual stress in thin SS316L plates fabricated via DLMD, validated by residual stress measurements using the hole-drilling method on printed samples under identical processing parameters. Tensile tests comparing 3D-printed SS316L and base material specimens evaluate the influence of residual stresses on mechanical properties (Noda et al, 2003; Chepkoech et al, 2024).

2. Modeling of the multi-layer dlmd process

The article uses ANSYS Workbench software to build a 3D metal printing model using DLMD technology with process parameters, material, and part geometry fully corresponding to the actual printed sample. Different thin plate layers in 3D printing are simulated to investigate residual stress, including: 1 layer, 5 layers, 10 layers, 15 layers, and 20 layers. Each printed layer has a thickness of 2 mm, a width of 2 mm, and a length of 120 mm, created sequentially from 2×2×2 mm cubic elements, with the element creation process controlled by the G-code, simulating the actual printing process. The 3D printed part model with 20 layers (thin-walled plate type) is described as shown in Figùe 2, with dimensions of 120×40×2 mm.

The SS316L material model with temperature-dependent physical properties is used, as specified in the reference (Li, 2023).

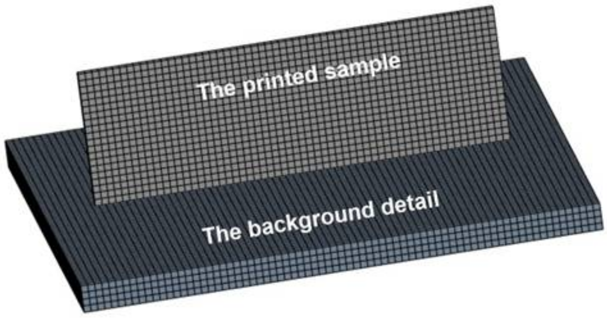


Figure 2. 3D printing simulation with 20 layers

The process parameters for the 3D printing process using the DLMD method selected for investigation are shown in Table 1 (Khoa et al, 2024).

Table 1. Process parameters for 3D metal printing of SS316L

Printing speed	Powder feed rate	Initial temperature	Printing temperature	Cooling time
8 mm/s	1920 mm^3/s	80°C	1200°C	7200 s

The moving heat source during the printing process consists of elements that are sequentially generated according to the printing speed and have a temperature equal to the melting zone temperature of 1200°C. After the printing process, the part is cooled to the ambient temperature of 25°C.

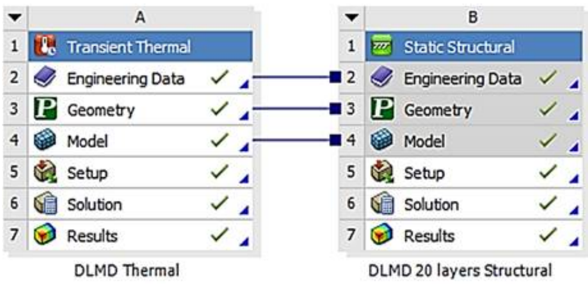


Figure 3. 3D metal printing simulation process

The simulation of the residual stress field for the 3D printed metal part is carried out through two processes as shown in Figure 3. The first is the simulation of heat transfer within the part during the printing process, and the second is the calculation of the residual stress field based on the temperature distribution data. The simulation results for the residual stress field of the layers are shown in Figure 4.

From the simulation results, several observations can be made:

For components printed with varying numbers of layers (1, 5, 10, 15, and 20 layers), the regions of residual stress occurrence are similar. The residual stress in the printed part is typically high near the interface with the substrate and low in the regions farther from the substrate. This reflects the uneven thermal process of the printed part.

Due to the high temperatures during the printing process, when printing multiple layers, the part undergoes several consecutive thermal cycles, similar to the annealing and hardening processes. As a result, the residual stress tends to concentrate at the two corners of the last layer near the substrate, as this region is fixed and experiences a significant transition in cross-sectional area.

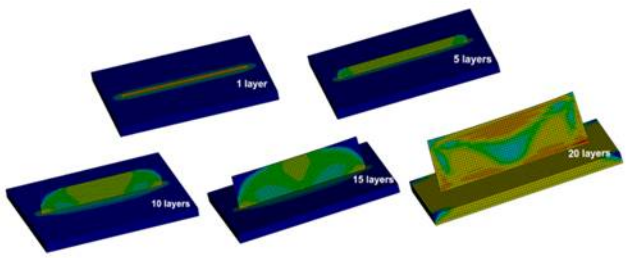


Figure 4. Simulation of residual stress field after 3D printing

To validate the simulation results, the paper proceeds with printing the sample according to the exact dimensions, material, and process parameters as in the simulation. The material composition of SS316L is shown in Table 2.

Table 2. Composition by percentage of SS316L material powder (Ebrahimi et al, 2022)

Cr	Ni	Mo	Mn	Si	N	O	P	C	S
18.2	10.2	2.57	1.1	0.8	0.07	0.02	0.009	0.013	0.001

The sample is printed using the DLMD technology with 20 printed layers, and the process parameters are selected as specified in the simulation in Section 3.2. The image of the printed sample is shown in Figure 5.

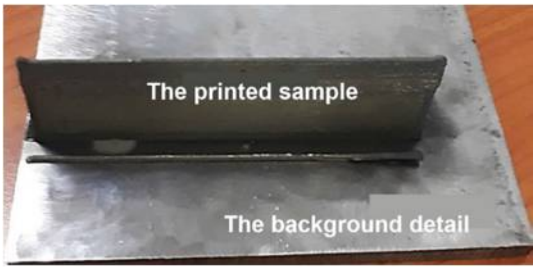


Figure 5. 3D printed SS316L metal sample using DLMD technology

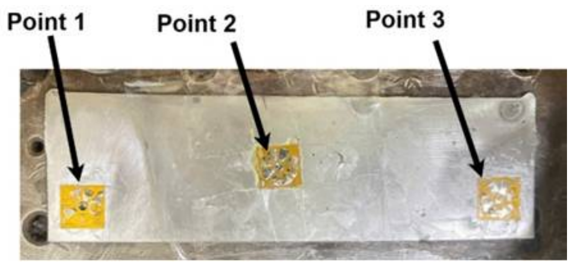


Figure 6. Sample with residual stress measurements on the RS-200 device

The residual stress of the sample is measured according to the ASTM 837 standard using the RS-200 measurement device. Figure 6 shows the sample with residual stress measurements taken at the center and the lower corner of the printed sample.

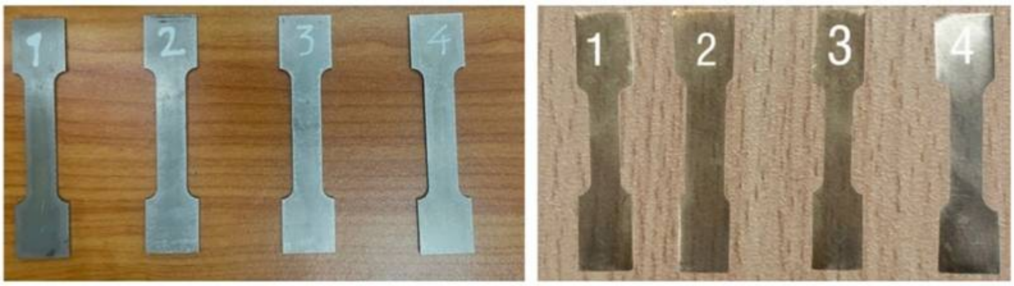
The residual stress measurement results are presented in Table 3.

Table 3. Residual stress measurement results on the RS-200 device

No.	Measurement point	Residual stress value (MPa)
1	Point 1	215
2	Point 2	45
3	Point 3	201
	Average	***153***

3. Tensile strength testing of 3d-printed and base material specimens

Tensile specimens were fabricated from both 3D-printed sheets and base material sheets. The specimens were designed identically according to the TCVN 1971:2014 standard. The material details are provided in Table 2. The specimen shapes are shown in Figure 7. The tensile test results are presented in Table 4.



a) Base material SS316L tensile specimen; *b) 3D-printed SS316L tensile specimen.*

Figure 7. Tensile test specimens

Table 4. Tensile strength test results of specimens

Sample No.	3D-Printed specimens		Base material specimens	
	Yield strength σ_C (MPa)	*Tensile strength σ_B* (MPa)	*Yield strength σ_C* (MPa)	*Tensile strength σ_B* (MPa)
1	414	596	239	581
2	447	564	253	657
3	462	557	268	596
4	433	604	246	638
Avg	***439***	***580***	***251***	***618***

The results obtained from the two samples indicate that, although the material used (SS316L) is the same, the 3D printed material exhibits different yield strength and tensile strength compared to the base sample. Specifically, the yield strength of the 3D printed material is higher due to the presence of residual stresses. These residual stresses, along with the tree-like internal structure formed by the boundaries between the printed layers, contribute to the increased yield strength. In contrast, the tensile strength of the 3D printed part is lower than that of the base sample. This can be attributed to the presence of internal voids and defects at the layer interfaces, which reduce the material's load-bearing capacity before failure. Furthermore, the anisotropic microstructure and rough surface morphology of the 3D printed material exacerbate stress concentration, thus lowering its tensile strength compared to the base material.

Residual stresses, both at the micro and macroscopic levels, play a significant role in reducing the tensile strength of the 3D printed sample when compared to the base material. These residual stresses are primarily responsible for the reduced tensile strength of the 3D printed part. The layer-by-layer construction process and rapid cooling inherent to 3D printing result in uneven residual stress distribution within the material, leading to internal strain variations. These stresses weaken the structure, reducing the material's ability to withstand load before failure, which consequently lowers the tensile strength of the 3D printed sample relative to the base material (Li, 2023).

4. Conclusion

The results of the residual stress simulation and the measured results are summarized and presented in Table 5.

Table 5. Simulation and measured residual stress results for the sample

No.	Measurement method	Computational simulation	Measurement from RS-200 device	Error (%)
1	Residual stress at the center of the thin plate (MPa)	49	45	8.889%
2	Residual stress at the corner of the thin plate (MPa)	237	215	10.232%

From the summary of results, several observations can be made:

Firstly, the numerical simulation of the DLMD process provides the clearest visualization of the residual stress distribution pattern when 3D metal printing is performed layer by layer. The simulation results show that the residual stress distribution pattern for different sample types with varying numbers of layers is almost identical.

Secondly, experimental validation shows that the numerical simulation method for residual stress distribution in the DLMD process has a high degree of accuracy (the error compared to the experimental results is 8.889% at the center of the thin plate and 10.232% at the corner of the thin plate). This error could be reduced if the material model, printing parameters, and heat exchange conditions are more accurately represented.

Thirdly, the results from tensile testing demonstrate that the mechanical properties of 3D printed materials are adversely affected by various factors. Residual stress is one of the primary factors contributing to the reduction of overall mechanical properties, particularly the fatigue strength.

Fourthly, the simulation results can also be utilized to investigate and optimize process parameters and boundary conditions, aiming to achieve high-quality 3D printed products.

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