Effect Of Inter-Layer Dwell Time on Residual Stresses in Directed Energy Deposition of High Strength Steel Alloy

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Abstract

Adoption of metal additive manufacturing by various industries is being hindered by the presence of residual stresses and distortion in the deposited parts. Large thermal gradients during directed energy deposition often led to residual stresses in the final deposit. Parameter optimization is predominantly used for residual stress mitigation. However, the effect of process parameters is material specific. Current research aims to study the effect of inter-layer dwell time on residual stresses in directed energy deposition of high strength steel alloy. Specimens were deposited at three levels of inter-layer dwell time. Surface as well as bulk residual stresses were measured using X-ray diffraction. Both surface as well as bulk residual stresses were found to increase with an increase in the inter-layer dwell time.

Keywords: Directed Energy Deposition; Residual Stress; Inter-layer dwell time; High strength steel alloy

1. Introduction

Additive manufacturing (AM) of metals and alloys plays a significant role in the current manufacturing scenario due to its freedom for design and lower material consumption compared to the conventional subtractive manufacturing methods. Metal AM is being adopted by various industries for aerospace, automotive, and medical applications where customized parts having complex designs are often required [1]. Extensive material development for metal AM during the last decade have resulted in more industries adopting this technology. Various steels, titanium and aluminum alloys, Nickel based super alloys as well metal matrix composites are being used for metal AM [2]. However, wider adoption of metal AM is restricted by various challenges related to the design and manufacturing of parts. Some of these challenges include porosity in the parts, lower surface finish, distortion, and poor dimensional accuracy.

One of the important challenges that hinder the adoption of metal AM parts is the formation of residual stresses. Layer by layer deposition during metal AM causes cyclical heating and cooling of the metal deposit resulting in formation of residual stresses[3]. Presence of residual stresses is often undesirable as it could lead to delamination and cracking of deposited parts. Residual stresses can also cause early failure of a component, which is highly undesirable in critical applications. Different methods are adopted to mitigate residual stresses in metal AM parts. Additively manufactured metal parts are subjected to heat treatment to release the stresses, adding to the cost of manufacturing[4]. Vyatskikh et al. (2023) proposed alloy design having solid state transformations with introduction of soft and hard metallic phases as a method to reduce residual stress formation [5]. Development of digital twins for in-situ monitoring and optimization of process parameters for residual stress mitigation is being investigated [6]. Parameter optimization is often used to reduce the formation of residual stresses. Knowledge of material behavior to different process parameters is required to manipulate quality of final parts [7].

Residual stress evolution in additively manufactured parts has been studied by researchers over the years. Knowledge of influence of different process parameters on the residual stress formation is crucial to improve the properties of final deposit. Denlinger et al. (2015) studied the effect of inter-layer dwell time on distortion and residual stress evolution during directed energy deposition of Ti-6Al-4V and Inconel® 625 [8]. Both alloys exhibited contrasting behavior with change in inter-layer dwell time as shown in Figure 1. Difference in the behavior was attributed to the lack of phase change in Inconel® 625 compared to BCC to HCP change in Ti-6Al-4V. Lee et al. (2023) studied the effect of inter-layer cooling on microstructure and mechanical properties of different titanium alloys. Inter-layer cooling was found to be influencing the microstructure formation and thus the properties of deposited alloys differently [9]. Variation of residual stresses with change in process parameters was observed to be material specific, necessitating the need to study material behaviour for new materials.

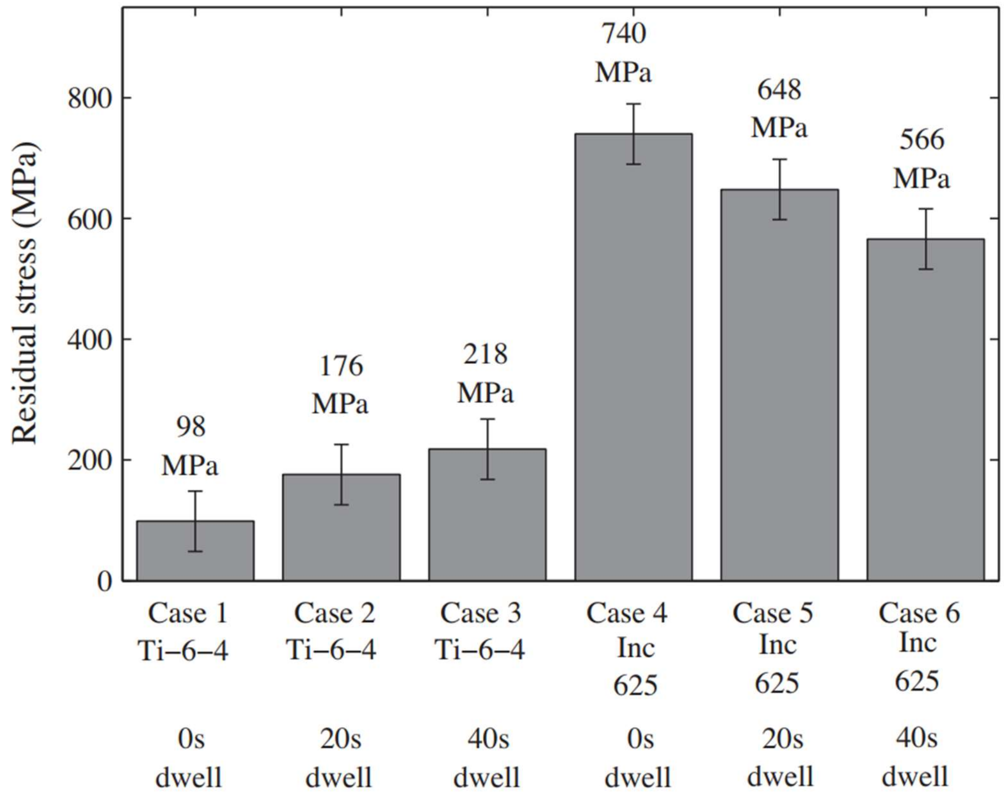

Figure 1. Variation of residual stress evolution with inter-layer dwell time in DED of Titanium and Nickel alloys; with permission from publisher [8]

High strength steel alloy is a recently developed low alloy steel having high strength and toughness and exhibits excellent printability [10]. As the variation of residual stresses to process parameters is material specific, current research aims to investigate the residual stress evolution in high strength steel alloy with varying inter-layer dwell time. Inter-layer dwell time can emulate the time interval between adjacent depositions at a single point of large parts. Following sections of this manuscript describes the materials and methodology of the research, experimental details, results and discussion, and conclusion.

2. Materials and Methods

2.1. Material Characterization

High strength steel alloy powder, manufactured through gas atomization, was supplied by the Powder Alloy Corporation, USA. Elemental composition of the alloy powder as reported by the manufacturer is given in Table 1. As the quality of powder being used in the DED process affects the properties of deposited parts, powder characterization was conducted before sample preparation. Particle size, particle shape and presence of oxidation on the powder particles were analyzed.

Table 1. Chemical composition of High Strength Steel Alloy

Element	Mass %
Iron	Balance
Carbon	0.28
Manganese	0.60
Silicon	1.0
Chromium	2.6
Nickel	1.0
Copper	<0.2
Vanadium	0.15
Molybdenum	0.86
Phosphorous	0.009
Sulphur	0.005
Aluminum	0.004
Titanium	<0.006
Oxygen	0.03
P + Sn + As + Sb	<0.035
Hydrogen	6 ppm

Shape of the High strength steel alloy powder particles was analyzed using a Scanning Electron Microscope (SEM) as shown in Figure 2a. Small, irregular-shaped satellite powder particles were observed to be attached to the large, spherical particles. Particle size distribution of the powder used for deposition was analyzed by Static Light Scattering (SLS). An average size distribution of $D_{10} = 59\ \mu m$, $D_{50} = 76.8\ \mu m$ and $D_{90} = 103.2\ \mu m$ was obtained as shown in Figure 2b. Optical Microscopy (OM) image of the alloy powder is shown in Figure 2Figure 3. Significant oxidation of the powder particles was visible under the microscope as seen by the discoloration.

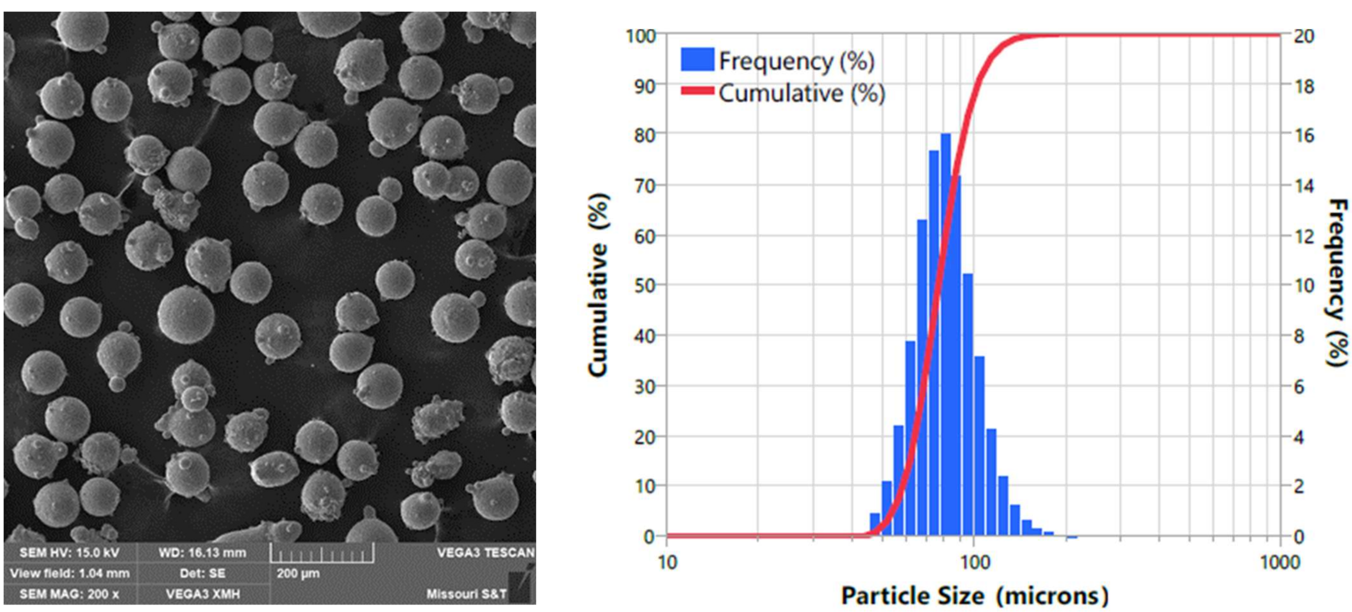

Figure 2. a) SEM image of High Strength Steel Alloy powder. b) Particle size distribution of Alloy powder

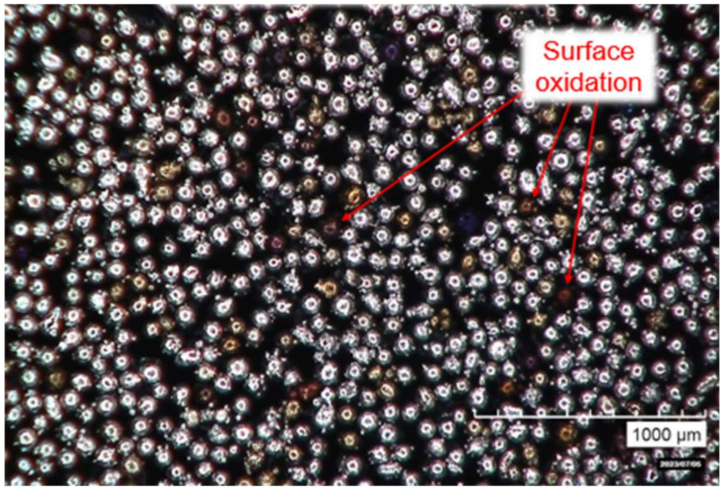

Figure 3.Optical microscope image of High Strength Steel Alloy powder

2.2. Additive Manufacturing

High Strength Steel Alloy powder was deposited onto AISI 1015 carbon steel substrates using an in-house developed Laser-DED system as shown in Figure 5. The laser-DED system employed a 1 KW Nd:YAG laser with a spot diameter of 2 mm. Argon gas was used to provide inert atmosphere in the deposition chamber. Rectangular specimens of $14\ mm \times 10\ mm$ cross-sectional area was deposited with a zig-zag scan pattern as shown in Figure 4. Each specimen was composed of 7 layers without any scan rotation between adjacent layers.

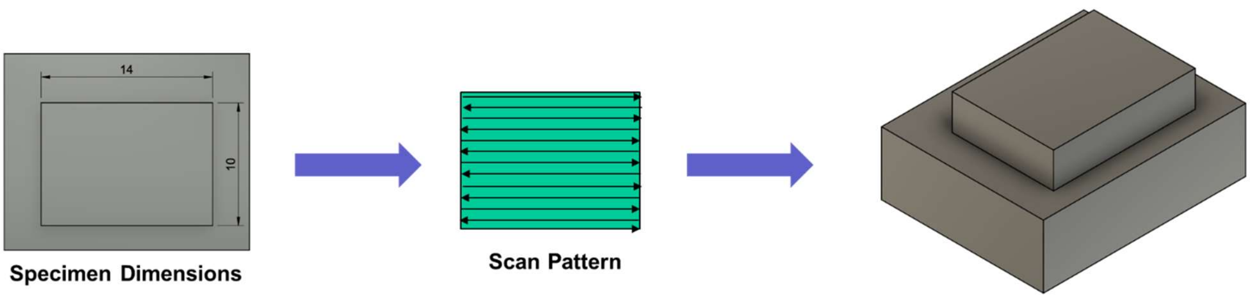

Figure 4. Specimen deposited by Laser DED

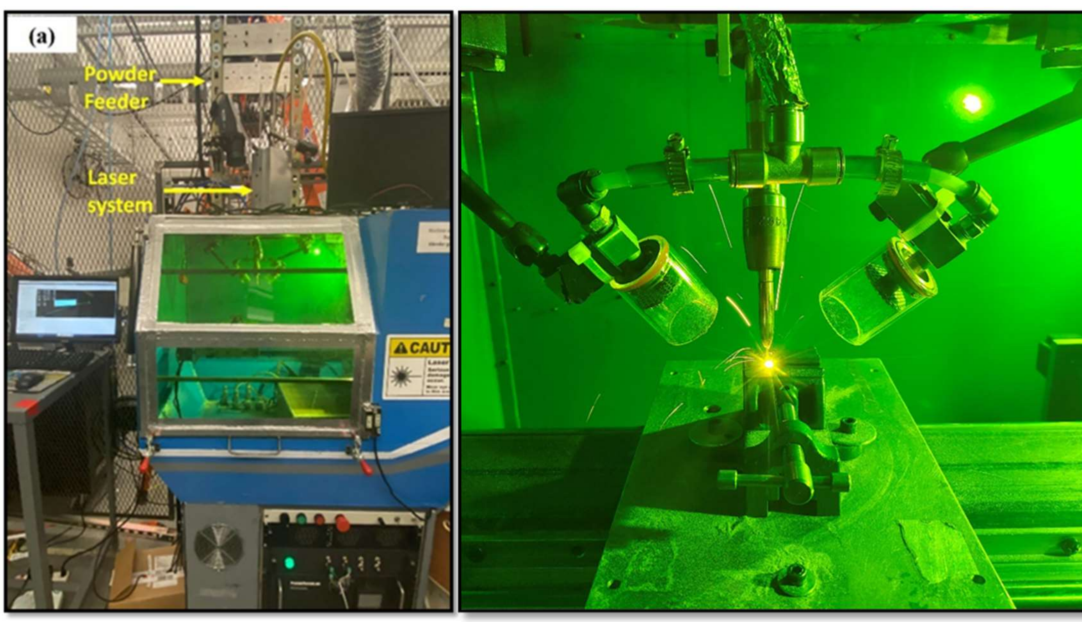

Figure 5. Laser DED system used for deposition.

Trial experiments were conducted to optimize the process parameters for minimum porosity and deposition geometry. Optimized parameters used for deposition are shown in Table 2. To study the effect of inter-layer dwell time on residual stress formation, three levels of inter-layer dwell time at 0 s, 10 s and 30 s were provided in between the deposition of each layer.

Table 2. Optimized Parameters used for deposition.

Laser Power (W)	Scan Speed (mm/min)	Feed Rate (g/min)	Hatch Spacing (%)	Inter-layer Dwell Time (s)
450	500	1.2	60	0
				10
				30

2.3. Residual Stress Measurement

High Strength Steel Alloy specimens prepared by directed energy deposition for this study are shown in Figure 6. X-Ray diffraction followed by uniaxial $\sin^2 \emptyset$ method was used to measure the residual stresses. Initially, stresses were measured on the top surface of As-deposited specimens. To analyze the residual stress variation pattern in the bulk, specimens were mounted and polished using 1200 grit SiC paper to remove material of $500\ \mu m$ thickness from the top surface [5]. Even though polishing could release some of the residual stresses, objective of the study was to analyze the pattern of stress variation. Hence, same polishing conditions were maintained for all the samples. As Deposited surface and bulk surface after polishing are shown in Figure 6.

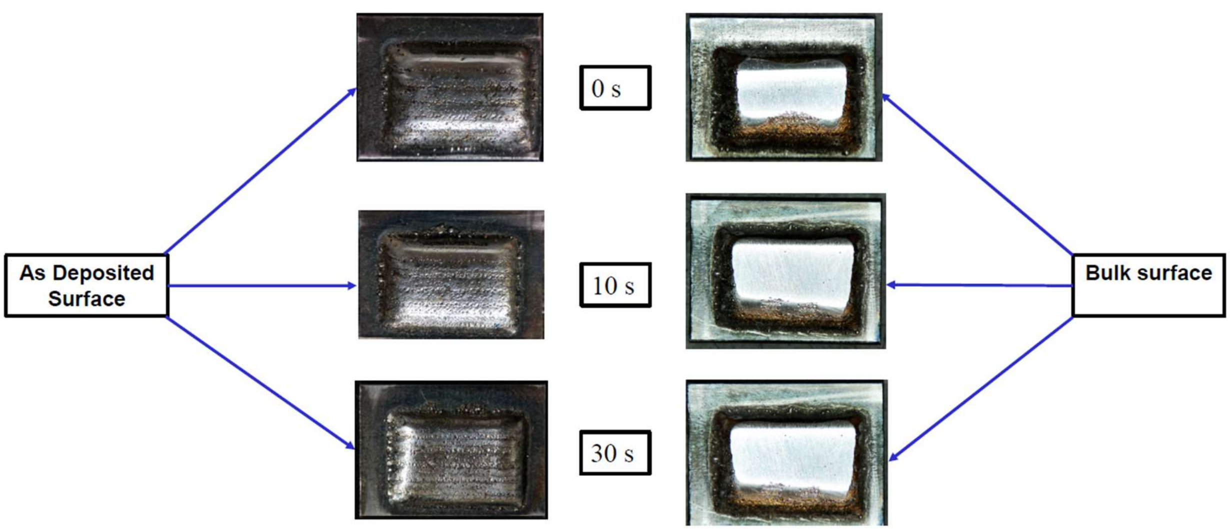

Figure 6. High Strength Steel Alloy specimens deposited by laser DED

3. Results and Discussion

High strength steel alloy deposited by DED process at 3 levels of inter-layer dwell time were subjected to X-ray diffraction. Surface residual stresses of as-deposited specimens measured by uniaxial $\sin^2 \emptyset$ method is shown in Figure 7. Bulk residual stresses on surface obtained by removing material of $500\ \mu m$ thickness from the top surface is shown in Figure 8.

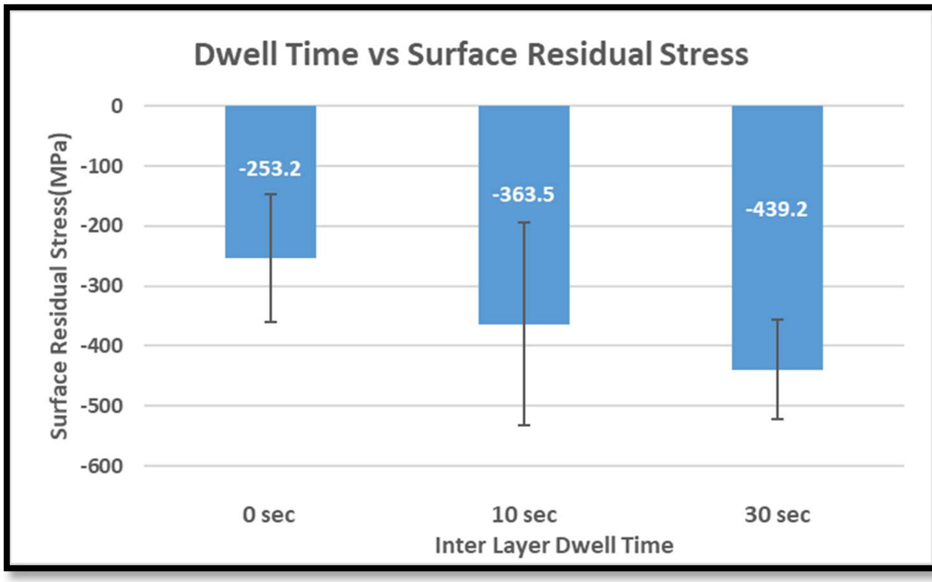

Figure 7. Variation of surface residual stresses with inter-layer dwell time

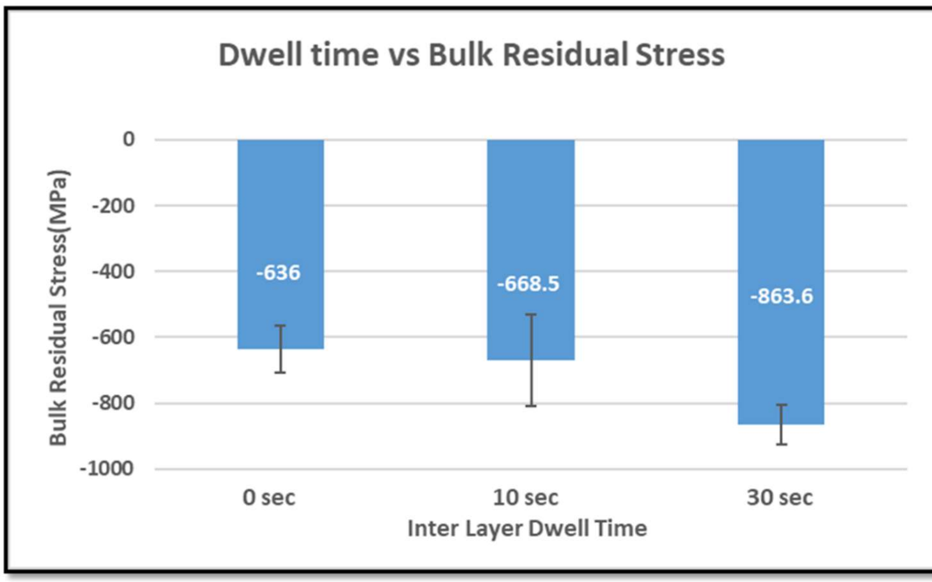

Figure 8. Variation of bulk residual stresses with inter-layer dwell time

Surface residual stresses increased with increasing levels of inter-layer dwell time. Similar trend was observed for bulk residual stresses as well, reiterating the effect of inter-layer dwell time on residual stresses in high strength steel alloy deposition. As the inter-layer dwell time increases, more heat energy can dissipate from the deposited layer towards the substrate. This decreases the peak temperature in the already deposited layers. Hence, a higher thermal gradient is present when a new layer is deposited, leading to higher residual stress formation during the solidification and cooling of top layer. As the inter-layer dwell time increases, higher will be the residual stress formation, which is explained by Thermal Gradient Mechanism [11]. Similarly, compressive nature of bulk stresses can be explained by Cool-down Phase Mechanism which predicts compressive stresses in the bulk layers due to the shrinkage of top layer during cooling [12].

Compressive stresses were also obtained for the top layer, which is contradicting with the common observation of tensile stresses in the top layer. This was due to a small depression in the middle of top surface where the X-ray Diffraction was performed. Residual stress formation in alloys can be affected by the variation of phase formation, owing different values of properties such as thermal expansion coefficient of formed phases

[9]. Further experiments and phase analysis are required to investigate the role of different phases being formed at different inter-layer dwell times.

4. Conclusion

This work investigated the effect of varying inter-layer dwell time on the residual stresses of high strength steel alloy manufactured by directed energy deposition. Based on the results obtained, increasing the dwell time between layers during deposition increases the residual stresses in high strength steel alloy deposits due to higher thermal gradients. Surface residual stresses as well as bulk residual stresses varied similarly with bulk stresses having higher magnitudes due to shrinking of top layer during cooling phase. Further investigation to identify the phase formation at different dwell times is required.

5. Acknowledgment

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6. References

[1] Armstrong M, Mehrabi H, Naveed N. An overview of modern metal additive manufacturing technology. J Manuf Process 2022;84:1001–29. https://doi.org/10.1016/j.jmapro.2022.10.060.

[2] Bandyopadhyay A, Zhang Y, Bose S. Recent developments in metal additive manufacturing. Curr Opin Chem Eng 2020;28:96–104. https://doi.org/10.1016/j.coche.2020.03.001.

[3] Chen S, Gao H, Zhang Y, Wu Q, Gao Z, Zhou X. Review on residual stresses in metal additive manufacturing: formation mechanisms, parameter dependencies, prediction and control approaches. J Mater Res Technol 2022;17:2950–74. https://doi.org/10.1016/j.jmrt.2022.02.054.

[4] Seede R, Zhang B, Whitt A, Picak S, Gibbons S, Flater P, et al. Effect of heat treatments on the microstructure and mechanical properties of an ultra-high strength martensitic steel fabricated via laser powder bed fusion additive manufacturing. Addit Manuf 2021;47:102255. https://doi.org/10.1016/j.addma.2021.102255.

[5] Vyatskikh A L, Wang X, Haley J, Zheng B, Valdevit L, Lavernia EJ, et al. Residual stress mitigation in directed energy deposition. Mater Sci Eng A 2023;871:144845. https://doi.org/10.1016/j.msea.2023.144845.

[6] Tariq U, Joy R, Wu S H, Mahmood M A, Malik A W, Liou F. A state-of-the-art digital factory integrating digital twin for laser additive and subtractive manufacturing processes. Rapid Prototyp J 2023. https://doi.org/10.1108/RPJ-03-2023-0113.

[7] Sames WJ, List F A, Pannala S, Dehoff R R, Babu S S. The metallurgy and processing science of metal additive manufacturing. Int Mater Rev 2016;61:315–60. https://doi.org/10.1080/09506608.2015.1116649.

[8] Denlinger E R, Heigel J C, Michaleris P, Palmer T A. Effect of inter-layer dwell time on distortion and residual stress in additive manufacturing of titanium and nickel alloys. J Mater Process Technol 2015;215:123–31. https://doi.org/10.1016/j.jmatprotec.2014.07.030.

[9] Lee H J, Narayana P L, Kim J H, Park C H, Hong J K, Yeom J T, et al. Effect of interlayer cooling on the microstructure and mechanical properties of titanium alloys fabricated using directed energy deposition. J

Alloys Compd 2023;953:170202. https://doi.org/10.1016/j.jallcom.2023.170202.

[10] Vaughan M W, Elverud M, Ye J, Seede R, Gibbons S, Flater P, et al. Development of a process optimization framework for fabricating fully dense advanced high strength steels using laser directed energy deposition. Addit Manuf 2023;67. https://doi.org/10.1016/j.addma.2023.103489.

[11] Mercelis P, Kruth J P. Residual stresses in selective laser sintering and selective laser melting. Rapid Prototyp J 2006;12:254–65. https://doi.org/10.1108/13552540610707013.

[12] Bastola N, Jahan M P, Rangasamy N, Rakurty C S. A Review of the Residual Stress Generation in Metal Additive Manufacturing: Analysis of Cause, Measurement, Effects, and Prevention. Micromachines 2023;14. https://doi.org/10.3390/mi14071480.