Residual stress after interlayer shot peening of 316 stainless steel processed by LPBF

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Abstract

Residual stress management is a critical challenge in laser powder bed fusion (LPBF) additive manufacturing, as thermally induced tensile stresses can lead to distortion, cracking, and reduced fatigue performance in objects produced by LPBF. This study investigates the effect of interlayer shot peening frequency on residual stress depth profiles in LPBF-processed 316L stainless steel, comparing specimens peened every 20 layers (P20) and every 60 layers (P60). X-ray diffraction was used to measure residual stress according to ASTM E2860-20 guidelines [6], with layer removal via electrochemical etching. The results show that more frequent peening (P20) induces deeper and more intense compressive stresses, delaying the onset of tensile stress relative to P60. The deeper compressive zone in P20 may offer superior mechanical integrity in AM components for fatigue-sensitive applications. However, depth limitations and potential artifacts from etching introduce uncertainty in deeper measurements. This study contributes to the optimization of mechanical post-processing strategies for residual stress mitigation in metal additive manufacturing.

Keywords: hybrid additive manufacturing, laser powder bed fusion, shot peening, residual stress

1. Introduction

Laser powder bed fusion (LPBF) utilizes a high-powered laser to melt metallic powders. However, the rapid thermal cycles during LPBF can create residual stress build-ups within parts, causing distortion, inaccurate dimensions, and unexpected failure under cyclic loading. With residual stress being introduced during the LPBF process, a key challenge has been identified for structural applications requiring part resilience.

Previous studies have treated part surfaces in hopes to induce compressive stresses to counteract the residual stress introduced into the part during the printing process. Laser shock peening and shot peening are two examples of mechanical surface treatments utilized. Kalentics *et al.* (2017) demonstrated that laser shock peening near the surface of LPBF 316 stainless steel created a compressive stress region improving fatigue life of LPBF parts. Sealy *et al.* (2019) applied a similar concept to direct energy deposition (DED) with interlayer laser shock peening. The results of these studies demonstrate compressive stress regions that are not removed by thermal stress redistribution caused by heat from the melt pool. Despite these successful research experiments, there is a notable gap in literature following the use of interlayer peening during AM processes. That is, the Kalentics *et al.* (2017) and Sealy *et al.* (2019) studies demonstrated two distinct behaviors in terms of residual stress that have not been explained. Specifically, Kalentics *et al.* (2017) showed a single compressive residual stress hook after interlayer peening while Sealy *et al.* (2019) demonstrated two distinct compressive residual stress hooks after interlayer peening. While the AM process parameters within these studies caused vastly different thermal histories, the resulting mechanism that results in singular versus dual compressive hooks is poorly understood as well as the final surface residual stress.

Therefore, the objective of this study was to test the hypothesis that increasing the frequency of interlayer shot peening induces multiple compressive stress regions ("hooks") by redistributing melt pool-driven thermal stresses, in order to evaluate the impact of sub-surface treatment on the magnitude of surface residual stress in LPBF 316L stainless steel. Multiple configurations of interlayer peening intervals and thermal cycles were compared to determine whether interlayer mechanical treatments can positively enhance the structural integrity of LPBF parts. Surface residual stress was measured to assess the effects of these treatments. Residual stress at the surface was quantified using X-ray diffraction (XRD) in accordance with ASTM E2860-20 [6], providing high-resolution, non-destructive evaluation of stress states. This method allowed for comparison of compressive and tensile stress magnitudes across different processing conditions.

2. Literature Review

Residual stress is a well-documented challenge in metal additive manufacturing (AM), particularly in laser powder bed fusion (LPBF), due to steep thermal gradients and rapid solidification. Several studies have investigated mechanical surface treatments, such as laser peening and shot peening, to mitigate these stresses. The following review highlights relevant findings in residual stress manipulation through multilayer and subsurface peening strategies, particularly their depth-dependent characteristics and implications for LPBF part performance.

2.1. Multilayer Laser Peening in AlSi10Mg

Madireddy et al. [1] explored the use of multilayer laser peening to reduce residual stress in LPBF-fabricated AlSi10Mg parts. By varying the peening interval and employing the hole-drilling method for stress analysis, the study found that peening every 10 layers (equivalent to 500 μm intervals) produced the most favorable compressive stress profile. The stress-depth curve revealed two distinct compressive "hooks"—secondary compressive stress regions—which were notably absent in specimens treated at other intervals. However, the underlying mechanism for these hooks remains unclear, and their inconsistent appearance suggests a knowledge gap in how layer-wise mechanical treatments influence residual stress redistribution. These findings raise important considerations for enhancing surface integrity, particularly in applications such as biomedical implants, where corrosion resistance and fatigue life are critical.

2.2. Subsurface Versus Surface Peening in LPBF 316L

Kalentics et al. [2] investigated the comparative effects of surface and subsurface laser peening in LPBF-manufactured 316L stainless steel. Using the hole-drilling method, residual stress was measured to a depth slightly over 1 mm. Subsurface peening, applied 10 layers below the surface, induced more pronounced compressive stresses than surface-only treatments across the measured depth. Despite this, a second compressive hook was not detected, which may be attributable to limited measurement depth. These results support the hypothesis that additional compressive regions could exist beyond 1 mm and underscore the need for deeper stress profiling in subsurface-treated specimens. This has implications for optimizing peening strategies where deeper stress modulation is desirable.

2.3. Interlayer Peening Effects in Directed Energy Deposition

In a study focused on directed energy deposition (DED), Sealy et al. [3] applied laser peening every five layers during the fabrication of 420 stainless steel components. Residual stresses were measured using hole-drilling to a depth of 3 mm. The results demonstrated the presence of a second compressive stress hook in peened samples—an effect not seen in untreated controls. These findings suggest that while the DED process's thermal cycles partially offset the benefits of peening, they do not eliminate them entirely. The occurrence of multiple compressive regions highlights the complex interplay between mechanical and thermal phenomena in AM processes. However, the possibility of additional compressive features beyond the explored depth remains an open question and a potential avenue for future research.

2.4. Residual Stress Characterization Techniques

A comparative study by Bobzin et al. [4] evaluated two primary residual stress measurement techniques: X-ray diffraction (XRD) and incremental hole-drilling (IHD). While XRD offers a non-destructive means for assessing surface stress, its depth penetration is limited to a few microns. In contrast, IHD allows for deeper, depth-resolved stress profiles but is semi-destructive. Both methods successfully detected stress relaxation following heat treatments. In the context of LPBF-fabricated components with thin, mechanically treated layers, XRD—especially when paired with electrochemical layer removal—emerges as a suitable method for characterizing surface and near-surface residual stress. This informs the experimental approach of the present study, which utilizes XRD to investigate the effects of interlayer shot peening on residual stress distribution.

3. Experimental Procedure

3.1. Sample Fabrication Using LPBF

All samples in this study were fabricated using a Matsuura Lumex Additive Manufacturing System employing the Laser Powder Bed Fusion (LPBF) technique with 316L stainless steel powder.

Figure 1. Matsuura Lumex Avance-25 laser powder bed fusion system.

LPBF involves the selective melting of fine metal powders using a high-power laser layer-by-layer to build parts directly from CAD models (Figure 2). Each powder layer, typically 50 µm thick, is spread across the build plate, then selectively melted by a laser beam following sliced cross-sectional data [5].

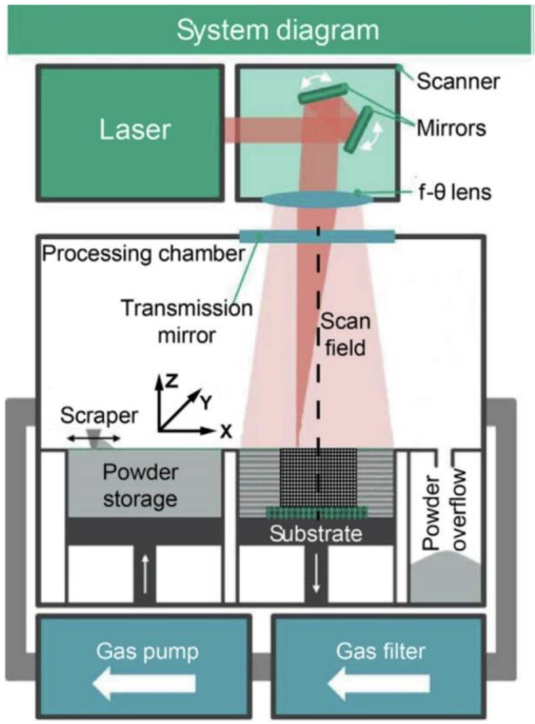

Figure 2. Laser powder bed fusion (LPBF) process [5].

To ensure consistent build conditions and minimize process variability, the same machine, material batch, and LPBF parameters were maintained across all builds. Eighteen total specimens were fabricated, divided across six unique configurations, with each configuration printed on its own build plate. Each configuration consisted of three Almen strip samples (19 × 76 × 8 mm) arranged as shown in Figure 3. The six configurations studied are listed in Table 1. A schematic showing the layers targeted for interlayer peening is provided in Figure 4. After printing, samples were separated from the build plate using wire electrical discharge machining (EDM). Part labeling followed the naming convention above with numeric suffixes (*e.g.*, AP, P60, TC60).

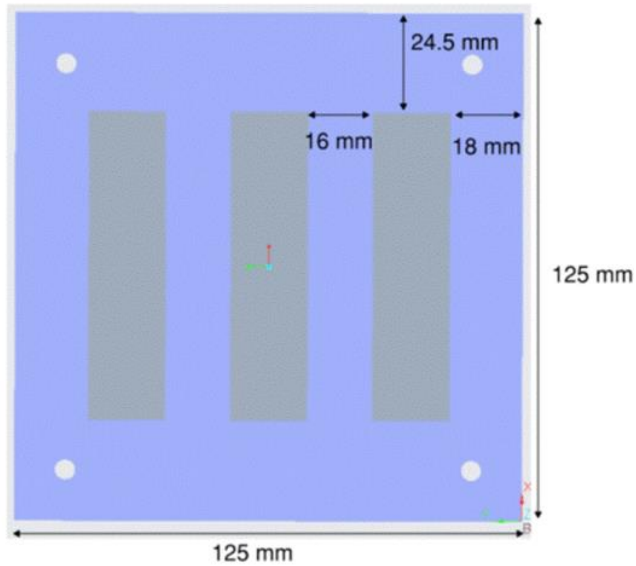

Figure 3. Sample arrangements on build plate.

Table 1: Sample nomenclature for hybrid additive manufacturing of 316 stainless steel

	Sample nomenclature	Definition:
1.	As Printed (AP):	Continuous print, no surface treatment
2.	As Printed – Top Peened (APTP):	Continuous print, surface shot peened post-print
3.	Thermally Cycled Layer 20 (TC20):	60-minute pause every 20 layers, no peening
4.	Shot Peened Layer 20 (P20):	Interlayer shot peening every 20 layers
5.	Thermally Cycled Layer 60 (TC60):	60-minute pause every 60 layers, no peening
6.	Shot Peened Layer 60 (P60):	Interlayer shot peening every 60 layers

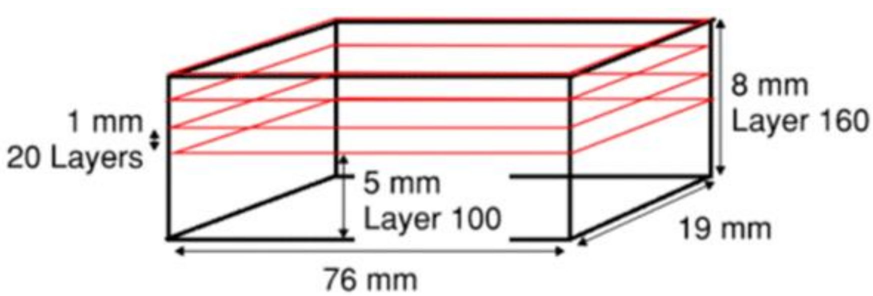

Figure 4. Print shape with red layers indicating interlayer peening layer.

3.2 Interlayer Shot Peening Procedure

Shot peening was performed manually between designated layer intervals using cut wire 32 media and the Sentenso ProcessMaster shot peening system. In shot peening, compressed air delivered peening media at a constant set of parameters (*e.g.*, gas pressure, speed, coverage) across all peened samples. Each interlayer peening session consisted of ten passes before reinstalling the build plate into the LPBF system for continued fabrication. Table 2 outlines the controlled peening parameters. A piece of scrap aluminum was used to mask off non-target samples during shot peening, ensuring no unintentional surface modification. After each shot peening session, build plates were promptly returned to the LPBF machine to resume the printing process.

Table 2 Shot peening process parameters

Parameter	Value
Process Speed	40 mm/s
Peening Pressure	1.5 bar
Peening Angle	76°
Media Feed Rate	2 kg/min
Time Spent Peening	20 sec/layer

Figure 5. Sentenso ProcessMaster shot peening system.

3.3 X-Ray Diffraction Testing

Residual stresses were evaluated using x-ray diffraction (XRD), Pulstec micro-X360, following ASTM E2860-20 guidelines [6]. While hole-drilling methods (ASTM E837-13a) are standard for surface measurements, XRD was chosen for its suitability in analyzing layered structures [7]. To access subsurface layers corresponding to peened intervals, electrochemical etching was performed. This setup employed a DC power supply connected to a platinum wire auxiliary electrode, which was suspended in an electrolyte-filled tube clamped to the sample surface. Each etching session removed approximately 100 μm of material depth, verified by a depth gauge, enabling progressive exposure of specific layers for stress measurements.

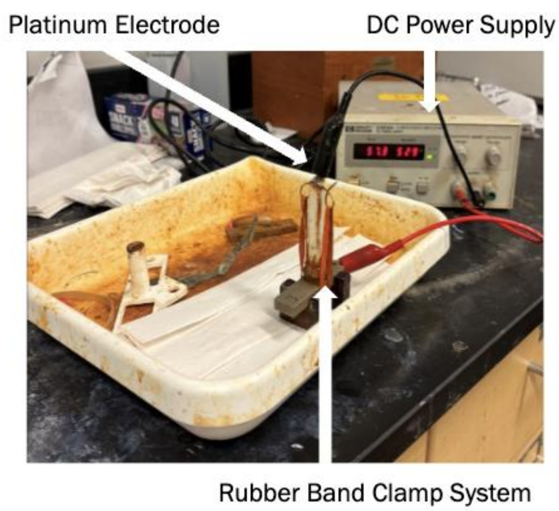

Figure 6. Electrochemical etching setup.

After each etch, samples were repositioned into the XRD system. Residual stresses were measured based on Bragg's Law, with the instrument calibrated for austenitic steel at a diffraction angle of 35°. Sample alignment was achieved using laser and optical sensor systems integrated within the XRD setup.

Figure 7. Pulstec micro-X360 x-ray diffraction system to measure residual stress in hybrid AM.

4. Results

4.1. Surface Residual Stress

Figure 8 displays surface residual stress measurements (MPa) for six LPBF-processed 316L stainless steel configurations. Each configuration was comprised of three replicates to ensure minimal variability. Shot-peened configurations – APTP (as printed-then peened), P60 (peened every 60 layers), and P20 (peened every 20 layers) – all exhibited high-magnitude compressive residual stresses. In contrast, untreated and thermally cycled configurations – AP (as printed), TC60, and TC20 – retained low tensile stress states.

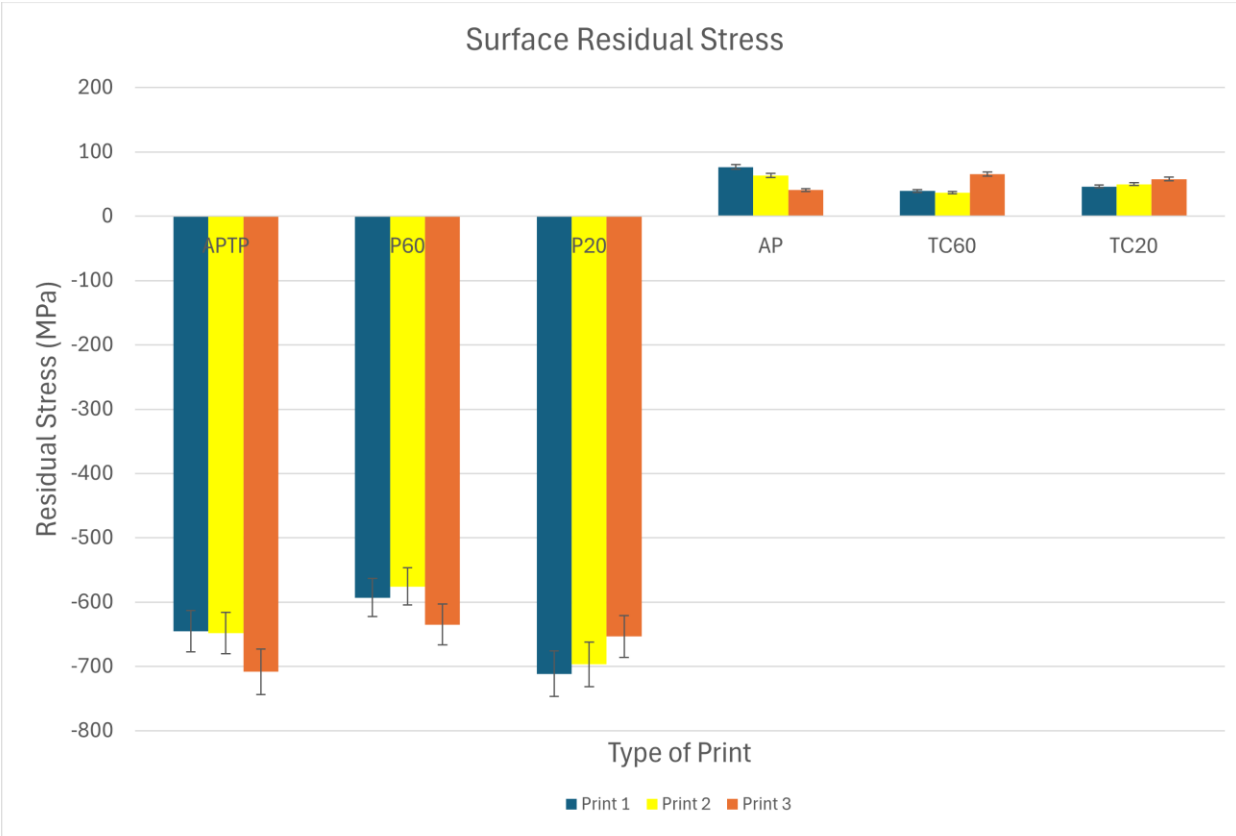

Figure 8. Surface residual stress of LPBF-processed samples with varying shot peening.

Shot peening, both post-process (APTP) and interlayer (P60, P20), consistently resulted in residual stresses between −600 MPa and −750 MPa, reflecting strong compressive surface stress development. On the other hand, the AP, TC60, and TC20 samples exhibited low-magnitude tensile residual stresses ranging from +20 to +80 MPa.

4.2. Depth Residual Stress

Figure 9 illustrates the residual stress distribution as a function of depth for samples subjected to interlayer shot peening every 20 layers (P20) and every 60 layers (P60). Both conditions exhibit an initial compressive residual stress near the surface, gradually transitioning to a tensile regime as depth increases. The P20 configuration consistently maintains higher compressive stresses near the surface, reaching values below –800 MPa, compared to approximately –740 MPa in the P60 conditions.

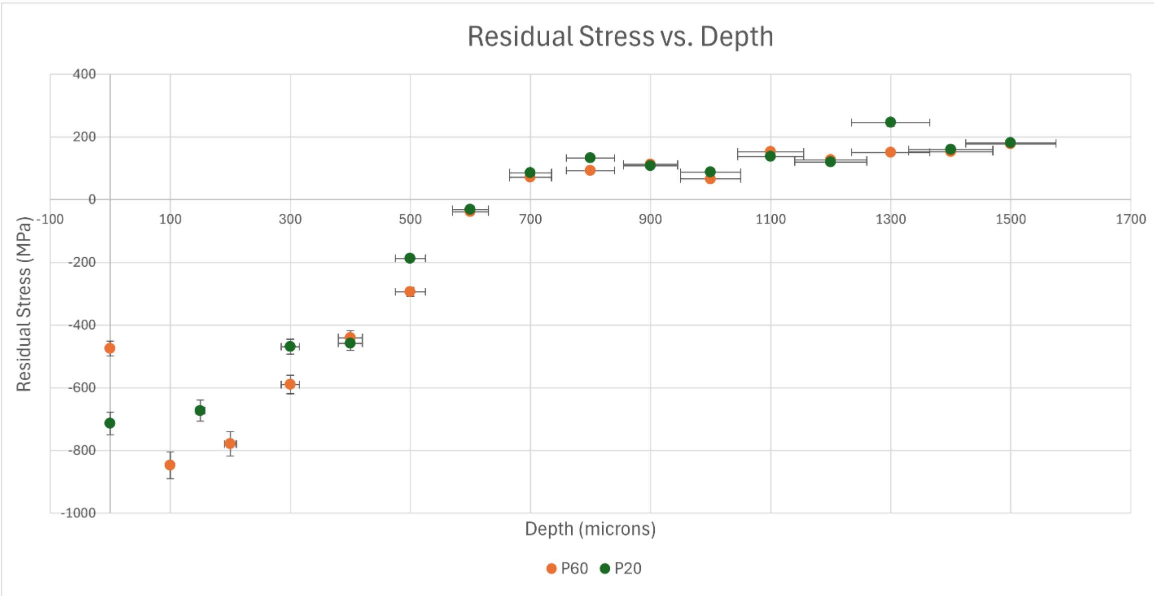

Figure 9. Residual stress and depth comparison between 20-layer and 60-layer interlayer shot peening intervals.

At depths of 600 µm and beyond, both configurations begin to exhibit a transition from compressive to tensile stress. Both the P20 and P60 configurations follow a similar tensile stress trend through a depth of 1500 microns.

5. Discussion

5.1. Surface Residual Stress

Shot peening imparts compressive residual stress by plastically deforming the surface and generating a stress profile counteracting thermally induced tensile stresses from LPBF solidification. The above observations are in alignment with the previous findings on interlayer and multilayer laser peening, where peening has mitigated residual stress and reduced distortion during additive manufacturing [1]. The greater compressive stress observed in P20 samples relative to P60 is likely due to the more frequent peening intervals, which accumulate greater surface plastic deformation.

The appearance of induced compressive stress as seen in the APTP samples, although reduced from the P20 and P60 samples is significant as it demonstrates the viability of post-process peening, even as interlayer peening offers in-situ stress control. Kalentics et al. [2] introduced the concept of 3D laser shock peening and demonstrated how peening during manufacturing significantly enhances fatigue resistance, supporting the above findings.

The AP sample retained tensile stress consistent with standard LPBF processing behavior for stainless steels, where rapid solidification and constrained cooling often induce tensile stresses [5]. The TC60 and TC20 samples showed the thermally cycled pauses do not meaningfully neutralize tensile stress development, outlining the need for interlayer mechanical intervention such as peening to effectively control and mitigate stress.

Although the measurements were limited to surface stress, Sealy et al. [3] demonstrated the broader integrity benefits of asynchronous laser processing methods, which also emphasize control of residual stress throughout the part. The compressive values in this study fall within the expected range for 316L stainless steel subjected to similar plastic deformation modes.

The observed stress patterns have important implications for AM part quality. Residual tensile stress in untreated builds is a known cause of warping, cracking, and reduced fatigue life. Conversely, compressive residual stress, such as that achieved via shot peening, is beneficial for fatigue performance and dimensional stability [2], [5]. The results underscore the value of interlayer peening as an in-process strategy for residual stress management in LPBF. Future work should include depth-resolved stress measurements and investigate the trade-offs between peening frequency, energy input, and surface integrity.

5.2. Depth Residual Stress

The dual-hook compressive profile observed in P20 is consistent with findings by Madireddy et al. [1], who reported a similar phenomenon when laser peening was applied at 10-layer intervals in LPBF AlSi10Mg. Their study suggested that periodic peening introduces cyclic stress redistribution zones, resulting in multiple compressive regions. The appearance of a second compressive "hook" in our P20 data confirms this theory and suggests that more frequent interlayer mechanical treatment can compound compressive effects across depth.

Kalentics *et al.* [2] also supports this behavior, showing that laser peening within LPBF builds significantly improves fatigue performance by generating subsurface compressive stress zones. However, their measurements did not capture deep enough regions to conclusively observe a secondary compressive hook. The current study, using electrochemical etching paired with XRD per ASTM E2860-20 [6], extends these measurements and confirms the existence of such deeper compressive zones.

In contrast, the P60 profile demonstrates a less complex distribution. Although it achieves considerable compressive stress at the surface, the absence of a second compressive hook suggests that less frequent treatment may not sufficiently modify the stress accumulation and redistribution driven by thermal cycling. Sealy et al. [3], working with DED and asynchronous laser processing, similarly identified the formation of a second compressive hook only under specific peening intervals – underscoring the importance of tuning peening frequency.

The broader and deeper compressive zone observed in P20 could be explained through the mechanical impact of peening intervals applied frequently (e.g., every 20 layers) modifying the stress evolution trajectory at each treated interval. This is supported through the idea that shot peening, particularly interlayer treatments, plastically deforms the surface and near-surface zones to introduce compressive stress to counteract tensile stress implemented through LPBF's rapid thermal gradients and constrained solidification process. Furthermore, the emergence of a second compressive hook around 1300 µm in P20 implies stress redistribution over multiple build stages. This phenomenon may arise from partial thermal relaxation of previously peened layers being reintroduced into the melt pool environment – a mechanism discussed by Sealy et al. [3] and Madireddy *et al.* [1].

Although the data trends are clear, certain limitations exist. Residual stress was measured using X-ray diffraction, which has sensitivities to surface quality, sample tilt, and crystallographic texture [4], [6]. Depth profiling relied on repeated electrochemical etching, which introduces surface roughness and alignment inconsistencies into the analysis. However, care was taken during the analysis process to align samples using built-in XRD laser sensors and to maintain etching depth accuracy of ±10 µm.

In future work, the use of incremental hole drilling (ASTME837-13a [7]) could improve confidence in subsurface measurements, particularly in identifying the exact depth and shape of the second compressive hook. This could also help speed up the time the analysis process took, as the electrochemical etching process took over 2 minutes per ±10 µm. Additionally, replicating these findings across other geometries or alloys would help assess generalizability.

6. Summary & Conclusions

This study aimed to evaluate the effect of interlayer shot peening frequency on the residual stress distribution in laser powder bed fused (LPBF) 316L stainless steel, with the goal of understanding how mechanical surface treatments influence subsurface stress profiles and structural integrity. By comparing specimens peened at two different intervals—P20 (every 20 layers) and P60 (every 60 layers)—this work assessed how varying peening frequency redistributes melt pool-induced thermal stresses. Residual stress measurements were performed using X-ray diffraction (XRD) in accordance with ASTM E2860-20 [6], providing quantitative insight into stress depth and magnitude across different treatment conditions.

This work demonstrates that interlayer shot peening significantly alters residual stress distribution in LPBF-fabricated stainless-steel components. P20 specimens, subjected to more frequent peening, exhibit a deeper and more pronounced compressive residual stress field compared to P60 specimens, suggesting a greater potential for enhancing fatigue performance and mitigating surface tensile stresses. These results support the hypothesis that increasing interlayer peening frequency induces multiple compressive stress regions by redistributing thermal stresses from the melt pool. The findings align with previous studies showing improved fatigue behavior through aggressive peening strategies in AM parts [1], [2], and confirm trends observed in both LPBF and directed energy deposition (DED) systems [3].

However, limitations such as reduced depth resolution and surface roughness artifacts during etching [4] introduce uncertainty beyond 1 mm depth. Future work should incorporate complementary methods such as hole-drilling (ASTM E837-13a) [7] and neutron diffraction to validate deeper stress measurements. Ultimately, this study highlights the potential of in-situ mechanical treatments like interlayer peening to enhance the mechanical reliability of AM components, particularly in critical applications where fatigue resistance is paramount.

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