

Effect of HIP and Laser Shock Peening Sequence on the Fatigue Behavior of Laser Powder Bed Fused Ti6Al4V

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Abstract

The fatigue performance of laser powder bed fused Ti-6Al-4V is influenced by process-induced defects, surface condition and the stress state generated by manufacturing and post-processing. This study examined whether reversing the order of hot isostatic pressing (HIP) and laser shock peening (LSP) altered the fatigue response of a deliberately defect-rich LPBF condition. Specimens were subjected to LSP followed by HIP or HIP followed by LSP. X-ray computed tomography was used to quantify the internal defect populations, stress-life testing was conducted between 210 and 380 MPa at $R = 0$ and 50 Hz, and scanning electron microscopy was used to examine post-test surface features associated with crack initiation. The two hybrid routes exhibited similar defect counts and mean sphericity values, while the HIP + LSP condition contained the largest measured defect and the greatest detected defect volume. Nevertheless, HIP + LSP produced the stronger fatigue response, including two right-censored run-outs at 10^6 cycles, compared with no run-outs for LSP + HIP. The CT descriptors therefore did not account for the observed sequence effect. The results are consistent with, but do not directly prove, the hypothesis that applying LSP after HIP preserves the beneficial final surface state generated by peening, whereas subsequent HIP exposure may modify or relax part of that state. Because residual stress was not measured, this mechanism is presented as a literature-supported interpretation rather than a measured causal relationship. The findings demonstrate that post-processing order can influence fatigue performance even when conventional CT defect metrics do not indicate a superior internal defect population.

1 Introduction

Laser powder bed fusion (LPBF) enables the manufacture of geometrically complex Ti6Al4V components for aerospace, biomedical and high-value engineering applications. Its wider use in fatigue-critical service is nevertheless constrained by surface roughness, lack-of-fusion defects, entrapped gas porosity and the variability of local defect populations [1–4]. These discontinuities can initiate fatigue cracks, particularly when they intersect a highly stressed surface or contain sharp, crack-like features [5–8]. Consequently, high relative density alone is not sufficient to establish fatigue reliability.

Defect-based approaches, including the Murakami square-root-area concept, have been used to relate the projected size of a critical discontinuity to fatigue strength [9, 10]. For additively manufactured alloys, however, fatigue behaviour is also affected by defect morphology, orientation, distance from the surface, surface texture and local residual stress [11–14]. Two specimens with comparable total porosity may therefore exhibit different fatigue lives when their largest defects occupy different mechanical environments.

Hot isostatic pressing and laser shock peening address different aspects of this problem. HIP combines elevated temperature and isostatic gas pressure to reduce or modify internal porosity and is widely used to improve the fatigue performance and consistency of additively manufactured titanium alloys [15–17]. LSP is a mechanical surface treatment in which laser-generated shock waves plastically deform the

near-surface region. Studies on conventional and additively manufactured Ti6Al4V have associated LSP with near-surface compressive residual stress, surface hardening and changes in fatigue performance [18–22]. LSP does not, however, provide a general means of closing deep internal lack-of-fusion defects.

The two processes may therefore be complementary, but their order is unlikely to be mechanically neutral. When HIP is conducted after LSP, the material is exposed to a prolonged thermal cycle after peening. Experimental and modelling studies on Ti6Al4V show that the magnitude and distribution of LSP-induced residual stress can change during thermal exposure, with the extent of relaxation depending on temperature, time and the initial material state [23, 24]. Conversely, when LSP is applied after HIP, the final operation modifies the surface after the high-temperature cycle has been completed.

Direct experimental comparisons of HIP followed by LSP and LSP followed by HIP remain limited. The present study therefore addresses the following question: does the order of HIP and LSP alter the fatigue behaviour of defect-rich LPBF Ti6Al4V when the final CT-measured internal defect populations are broadly comparable? The study combines CT, stress-life testing and SEM surface examination. Residual stress was not measured; accordingly, the discussion distinguishes the measured sequence effect from the proposed residual-stress-based mechanism.

2 Experimental Methods

2.1 Material and specimen manufacture

Miniature notched fatigue specimens were manufactured from reused Ti-6Al-4V extra-low-interstitial powder by LPBF using an EOS M290 system under an argon atmosphere. The laser power was 280 W, scan speed was 1.2 m s^{-1} , layer thickness was 0.03 mm and the interlayer scan rotation was 67 degrees. The present manuscript focuses on the deliberately defect-rich batch designated Sample E, produced using a hatch pitch of 162 micrometres while the remaining build parameters were held constant. Specimens were built vertically in a single build to minimise inter-build variability. Following manufacture, the specimens were stress relieved at 650 degrees C for 3 h under vacuum and removed from the build plate by wire electrical discharge machining.

The specimen was 22 mm long and 5 mm wide and contained a notch with a radius of 2 mm. The test surface and specimen dimensions are shown in Fig. 1. All specimens retained the as-built surface condition except for the changes produced by the assigned post-processing route.

2.2 Post-processing sequences

The primary comparison involved two hybrid post-processing sequences: LSP followed by HIP and HIP followed by LSP. An as-built/stress-relieved condition was used as a CT reference. Twelve fatigue specimens were tested for each hybrid condition. The treatments were the same in both hybrid routes; only their order was reversed.

Table 1
Experimental conditions used in the sequence comparison.

Condition	Processing sequence	Role in this study
As-built reference	LPBF + stress relief	CT reference for the initial defect population
LSP + HIP	LPBF + stress relief + LSP + HIP	Hybrid fatigue condition in which HIP was the final process
HIP + LSP	LPBF + stress relief + HIP + LSP	Hybrid fatigue condition in which LSP was the final process

2.3 Laser shock peening

LSP was performed using a frequency-doubled Nd:YAG laser operating at 532 nm, with a pulse duration of 4–8 ns, repetition rate of 10 Hz, nominal peak power density of approximately 15 GW cm^{-2} , a 1 mm spot diameter and 60% spot overlap. A flowing water layer provided confinement. The indicated flat test surface was peened. The processing parameters and treated region were kept constant for the LSP + HIP and HIP + LSP routes so that treatment order was the principal experimental variable.

2.4 Hot isostatic pressing

HIP was conducted using Quintus Purus technology at 820 degrees C and 170 MPa for 2 h under an inert atmosphere, followed by controlled cooling. The same HIP cycle was used for both hybrid sequences.

2.5 X-ray computed tomography

Internal defects were characterised using a GE Phoenix v|tome|x L240 X-ray CT system operated at 120 kV and 100 microamperes, with a reconstructed voxel size of 14 micrometres. The reconstructed volumes were analysed using VGSTUDIO MAX 2025.1. A common analysis workflow was applied to all reported conditions. The quantities considered here were detected defect count, total detected defect volume, equivalent defect diameter, mean sphericity and the fraction of the total defect volume associated with the largest defects.

The CT values are interpreted as resolution- and threshold-dependent descriptors of the detected population. Total detected volume is not treated as an intrinsic porosity fraction unless normalised by the corresponding analysed material volume. Because individual defects were not registered and tracked in the same specimen before and after treatment, population differences are not described as direct transformation of specific pores.

2.6 Fatigue testing and treatment of run-outs

Stress-controlled fatigue tests were conducted at room temperature using a TP Engineering MINI FP2 bending fatigue system. The maximum corrected stress ranged from 210 to 380 MPa, the stress ratio was $R = 0$ and the loading frequency was 50 Hz. Twelve specimens were tested for each hybrid condition. A test was terminated when the predefined force-response criterion was reached or when the

specimen attained 10^6 cycles. Specimens reaching 10^6 cycles without satisfying the failure criterion were classified as right-censored run-outs.

Stress-life diagrams are used to show the individual observations. The reported arithmetic mean cycles are retained only as a descriptive summary of the observed test records. Run-outs are not treated as failures at 10^6 cycles, and the capped descriptive mean is not used to estimate a population mean fatigue life or a percentage improvement. Formal estimation of an S-N relationship and characteristic life requires the specimen-level stress, cycle and censoring records in a censored regression model.

2.7 Scanning electron microscopy

Post-test surfaces were examined using a JEOL IT300 scanning electron microscope operated at 10 kV. The examination focused on cavities, surface-connected discontinuities and crack-like features close to the test surface. Because the specimens did not exhibit complete macroscopic fracture, the images are interpreted as evidence of local initiation and short-crack development rather than conventional fracture-surface fractography.

3 Results

3.1 CT-measured defect populations

Representative CT reconstructions for the as-built reference and the two hybrid routes are shown in Fig. 2. The as-built condition contained numerous irregular defects consistent with a deliberately defect-rich LPBF condition. Both hybrid routes contained substantial residual defect populations after HIP exposure. The reconstructions are population-level comparisons; they do not demonstrate the evolution of an individually tracked defect.

Table 2

CT descriptors for the as-built reference and hybrid post-processing conditions. Detected volume is reported as an absolute value and should not be interpreted as porosity fraction without normalisation to the analysed material volume.

Condition	Detected defect count	Mean sphericity	Largest equivalent diameter (mm)	Detected defect volume (mm3)
As-built	71,073	0.570	0.568	31.94
LSP + HIP	42,131	0.568	0.509	36.77
HIP + LSP	39,936	0.564	0.669	62.64

The defect count decreased from 71,073 in the as-built reference to 42,131 after LSP + HIP and 39,936 after HIP + LSP. However, mean sphericity did not increase: values were 0.570, 0.568 and 0.564, respectively. The available mean sphericity data therefore do not support a claim of general defect rounding. Similarly, the HIP + LSP condition contained the largest equivalent diameter, 0.669 mm, and the

largest detected defect volume. These conventional descriptors do not identify HIP + LSP as the least severe defect population.

The largest 1%, 5% and 10% of defects accounted for 27.17%, 58.57% and 73.40% of detected defect volume in HIP + LSP, compared with 21.62%, 51.90% and 68.74% in LSP + HIP. The better fatigue response of HIP + LSP therefore occurred despite a defect population with a greater concentration of detected volume in its largest defects. This observation motivates consideration of factors not captured by the reported CT summary metrics, including defect location relative to the stressed surface and the final surface state.

3.2 Sequence-dependent fatigue response

The individual stress-life observations are shown in Fig. 4. HIP + LSP produced two run-outs at 10^6 cycles, whereas no run-outs occurred in the LSP + HIP group. The corresponding observed, capped mean cycles were 595,167 and 152,583 cycles, respectively. These values provide a descriptive indication of the magnitude of the sequence effect but are not uncensored population means.

Table 3
Descriptive fatigue summary for the two hybrid sequences. The capped mean includes run-outs at their termination cycle and is not an estimate of mean failure life.

Parameter	LSP + HIP	HIP + LSP
Number of specimens	12	12
Observed capped mean cycles	152,583	595,167
Maximum recorded cycles	264,000	1,000,000
Right-censored run-outs at 10^6 cycles	0	2
Mean corrected maximum stress (MPa)	299.2	303.9
Maximum corrected stress (MPa)	374.4	377.4

The mean corrected stresses were similar, differing by approximately 4.7 MPa, and the maximum corrected stresses were also comparable. Nevertheless, the full comparison must ultimately be based on specimen-level censored S-N regression because fatigue life is strongly stress dependent. The present results establish a descriptive sequence effect; they do not, by themselves, quantify a stress-independent percentage improvement or prove that the two S-N relationships have different slopes.

3.3 SEM observations

Representative post-test SEM images are shown in Fig. 5. HIP + LSP specimens contained subsurface cavities and local crack-like features that appeared short and spatially confined in the examined fields. LSP + HIP specimens showed open, surface-connected discontinuities, partially fused particles and geometrically irregular surface features. These observations are consistent with different local initiation

environments, but the selected micrographs do not constitute a statistical comparison of crack density or crack length.

4 Discussion

4.1 What is directly demonstrated

Three conclusions follow directly from the measurements. First, reversing the order of HIP and LSP changed the observed fatigue response: HIP + LSP produced longer recorded lives and two run-outs, whereas LSP + HIP produced no run-outs. Second, the available CT descriptors do not explain this difference. HIP + LSP did not possess the smallest maximum defect, the lowest detected defect volume or the highest mean sphericity. Third, the SEM examination identified local crack-like features and surface-connected discontinuities, but it did not quantify a treatment-specific crack-growth rate or residual-stress field.

4.2 Residual-stress relaxation as a mechanistic hypothesis

A plausible interpretation is that treatment order altered the final near-surface mechanical state. In HIP + LSP, the high-temperature, high-pressure operation was completed before peening. The final LSP operation could therefore establish a beneficial near-surface stress and deformation state without subsequent exposure to the HIP thermal cycle. In LSP + HIP, by contrast, the peened surface was exposed to 820 degrees C for 2 h. Previous studies have shown that LSP-induced residual stresses in Ti-6Al-4V can relax or redistribute during thermal exposure and that the magnitude of the change increases with temperature [23, 24].

This interpretation is consistent with the sequence-dependent fatigue data, but it is not directly verified here. The phrase "retained compressive residual stress" should therefore be understood as a hypothesis rather than a measured material property. The results do not exclude contributions from LSP-induced hardening, surface roughness, local plastic deformation, HIP-related microstructural changes, defect position or specimen-to-specimen variability.

4.3 Relationship between internal defects and the final surface state

The CT results illustrate why fatigue performance should not be ranked using one bulk defect descriptor. The condition with the strongest observed fatigue response also contained the largest equivalent defect and the greatest detected defect volume. A large internal defect may be less damaging than a smaller surface-connected defect if its orientation, distance from the maximum-stress region and local stress-intensity contribution are less severe. Conversely, surface roughness or an open lack-of-fusion feature near the notch can dominate crack initiation even when total porosity is comparatively low [6, 11–14].

The present sequence effect is therefore best interpreted as an interaction between the inherited LPBF defect population and the surface state produced by the final manufacturing operation. This

interpretation is broader and more defensible than attributing the entire effect to pore closure or residual stress alone.

4.4 Statistical interpretation of the fatigue data

The two run-outs in the HIP + LSP group contain useful survival information but do not provide known failure lives. Treating them as failures at 10^6 cycles biases an arithmetic mean and obscures the censoring mechanism. For final inferential analysis, the specimen-level records should be fitted by maximum likelihood using a lognormal or Weibull censored fatigue-life model. A suitable formulation is a regression of $\log_{10}(N)$ on $\log_{10}(\text{corrected maximum stress})$, treatment condition and, if supported by the sample size, a stress-by-condition interaction. This would permit comparison at a common reference stress and estimation of survival probability at 10^6 cycles.

4.5 Limitations

Residual stress was not measured, so thermal relaxation remains an inferred mechanism and the SEM assessment was qualitative and did not quantify crack density, crack length or defect-to-crack correspondence.

4.6 Implications for process design

For fatigue-critical LPBF Ti-6Al-4V, the results caution against treating HIP and LSP as commutative operations. When both treatments are specified, completing HIP before LSP avoids exposing the final peened surface state to the HIP thermal cycle. This recommendation is supported by the present fatigue observations, although qualification for component design should include residual-stress measurement, surface characterisation and validation using the relevant component geometry and loading spectrum.

5 Conclusions

1. Reversing the order of HIP and LSP produced a substantial descriptive difference in the fatigue response of the defect-rich LPBF Ti-6Al-4V condition.
2. HIP + LSP produced two right-censored run-outs at 10^6 cycles, whereas LSP + HIP produced no run-outs. The corresponding capped mean cycles are descriptive and should not be interpreted as uncensored mean failure lives.
3. The available CT descriptors did not explain the superior response of HIP + LSP. This condition contained the largest equivalent defect and the greatest detected defect volume, while mean sphericity was similar across the reported conditions.
4. The results are consistent with the hypothesis that applying LSP after HIP produces a more favourable final surface state, whereas subsequent HIP exposure may modify or relax the LSP-induced state..
5. Post-processing order should be treated as a process-design variable. HIP followed by LSP is the preferred sequence within the conditions examined, subject to confirmation through censored S-N modelling and direct surface-state characterisation.

Declarations

Acknowledgements

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Conflict of Interest

The authors declare no financial conflict of interest. In-kind HIP processing support from Quintus Technologies AB is disclosed in the Acknowledgements.

Data Availability

The data supporting the findings of this study are available from the corresponding author on reasonable request, subject to institutional and collaborator agreements.

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Figures

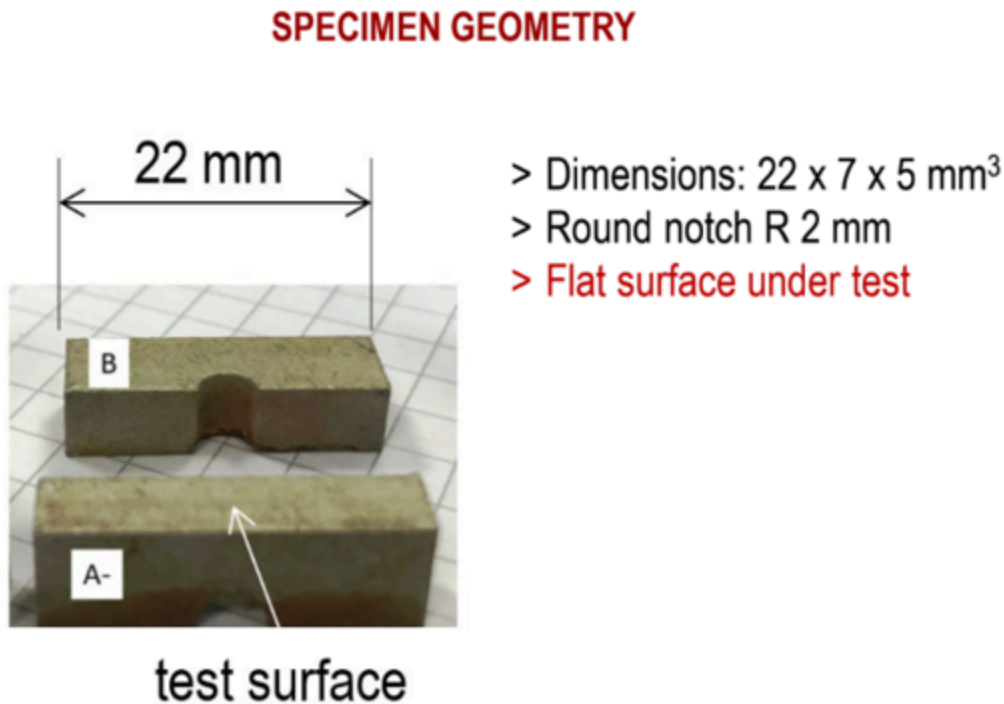


Figure 1

Miniature notched fatigue specimen and identification of the test surface. Dimensions are in millimetres.

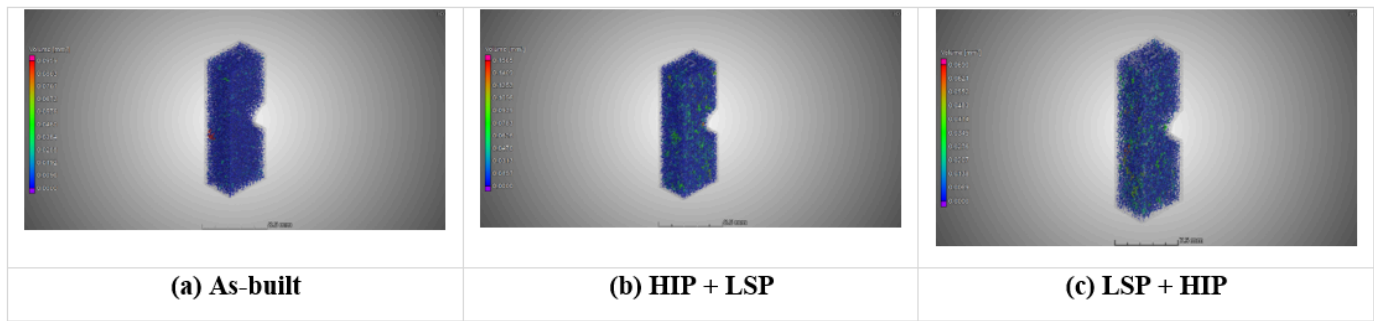


Figure 2

Representative three-dimensional CT reconstructions of the detected defect populations: (a) as-built reference, (b) HIP + LSP and (c) LSP + HIP. The conditions in panels (b) and (c) have been ordered according to the treatment sequence identified in the source image records.

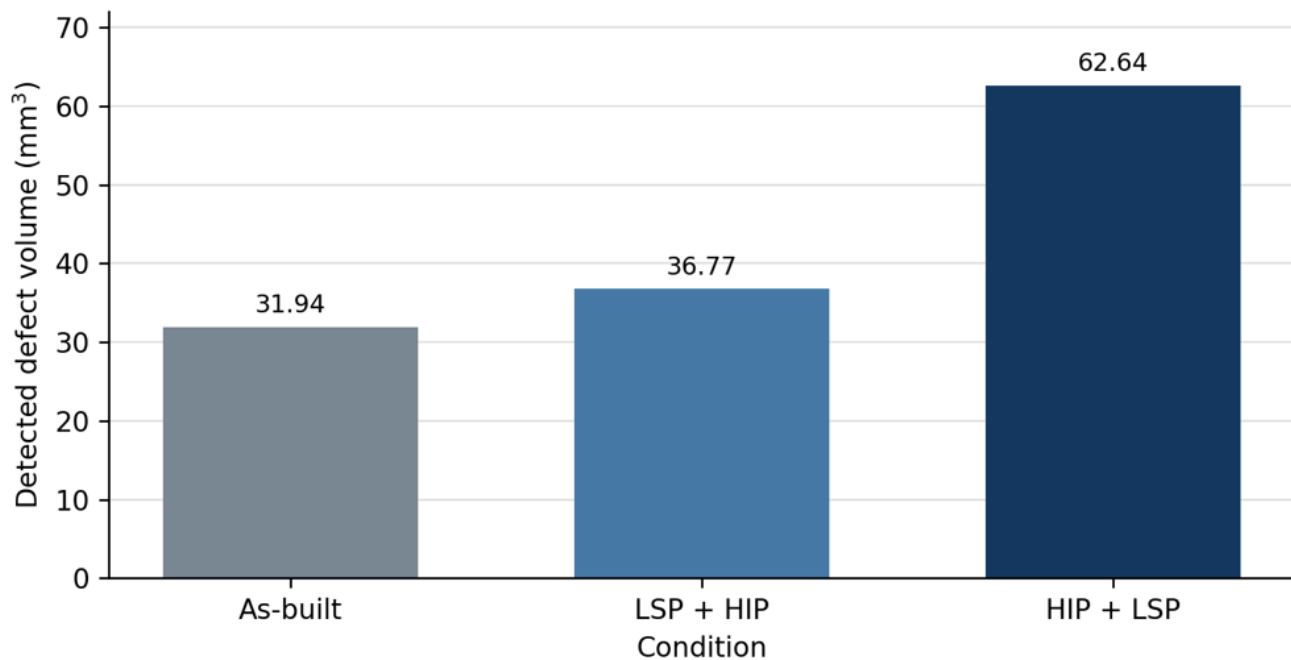


Figure 3

Total detected defect volume for the reported CT regions. The values are not normalised porosity fractions and may be influenced by analysed volume, segmentation and the spatial sampling of different specimens.

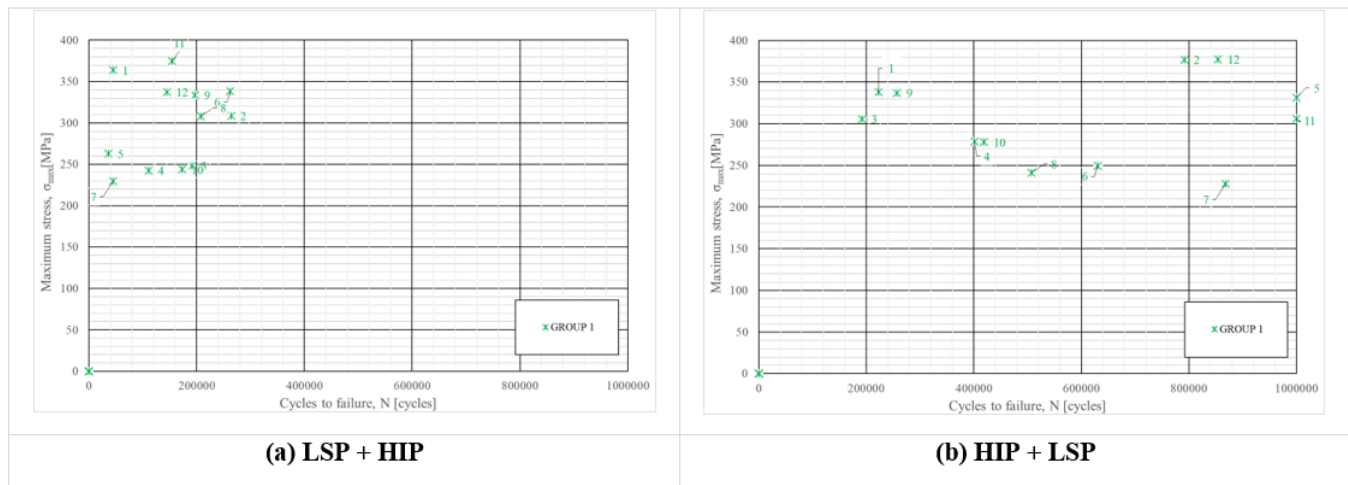


Figure 4

Stress-life observations for (a) LSP + HIP and (b) HIP + LSP. Observations at 10^6 cycles are right-censored run-outs and should be distinguished from fatigue failures in subsequent statistical modelling.

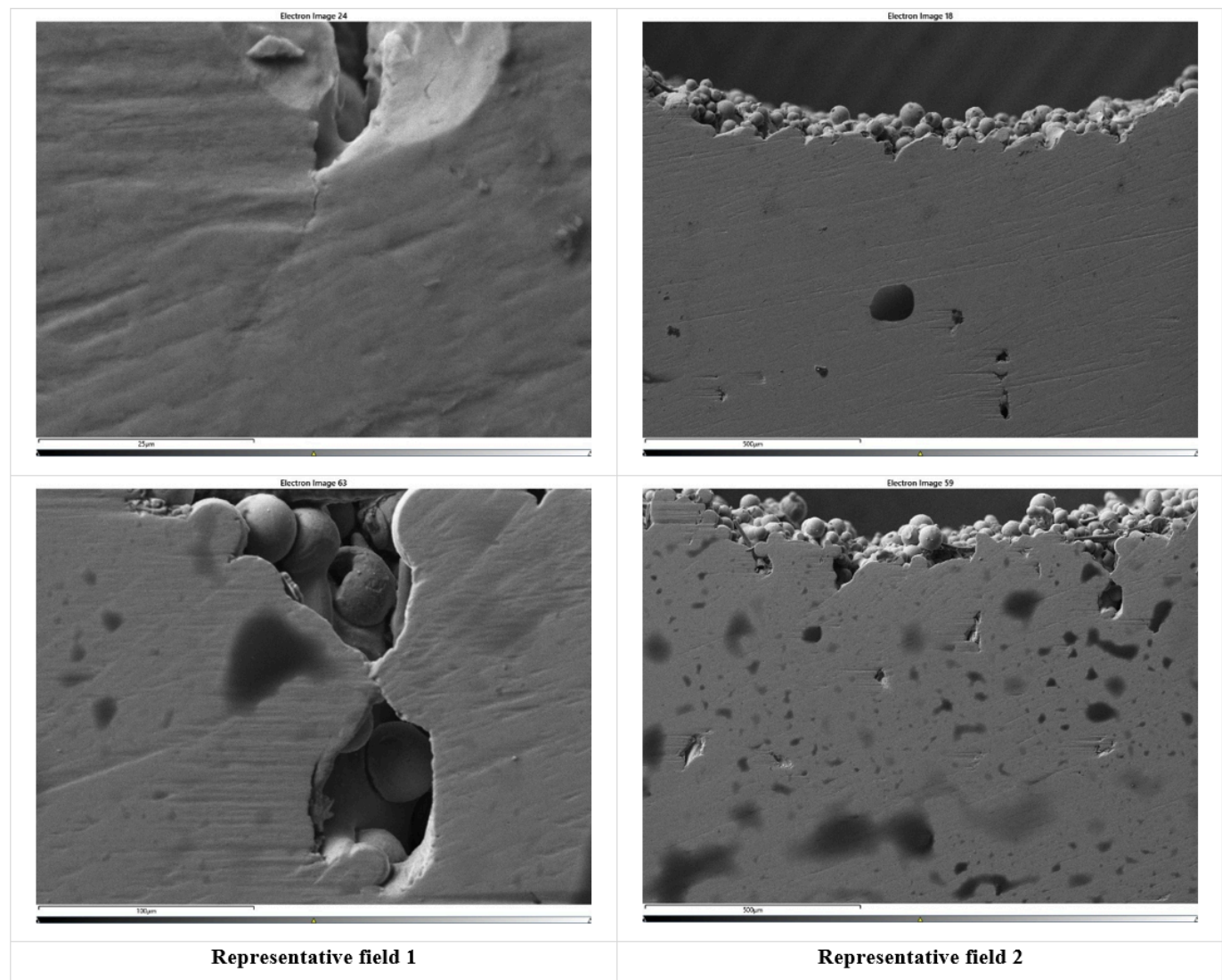


Figure 5

Representative post-test SEM fields. Top row: HIP + LSP. Bottom row: LSP + HIP. Interpretation is restricted to cavities, surface discontinuities and local crack-like features visible in the examined fields; residual stress was not measured.