# Generation of a Fatigue Design Curve Suitable for Use on Additive Manufacture Nuclear Plant Components Produced from 316LN Stainless Steel using Laser Powder Bed Fusion

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# Small Bore Globe Valves (½”, 1” & 2” NB)

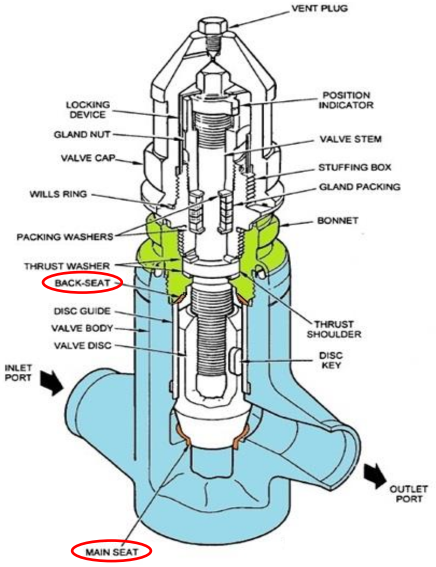
316LN Stainless Steel Body & Bonnet

Tristelle 5183 Main & Back Seats (hard facings)

Method-of-Manufacture includes Hot Isostatic Press (HIP) heat treatment

## Background

- Primary application of AM Laser Powder Bed Fusion (LPBF) technology focused on the production of Small-Bore Globe Valve body and bonnet components.
- Pressure Boundary
- Safety Critical
- High Production Volume




# Background Cont.

## Benefits of AM LPBF Approach

### Lead Time Reduction

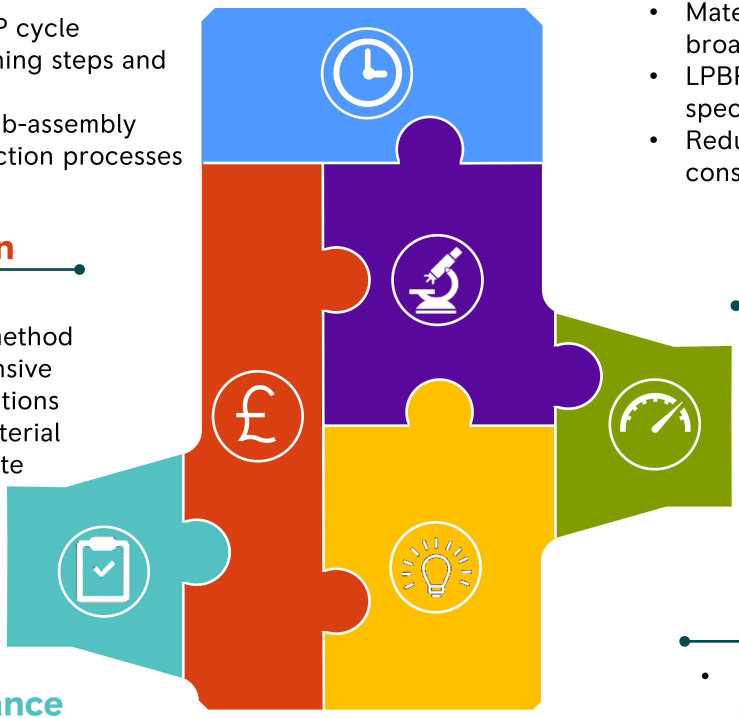
- Removal of a HIP cycle
- Reduced machining steps and timescales
- Elimination of sub-assembly welding & inspection processes

### Cost Reduction

- Simplification of manufacturing method
- Removal of extensive machining operations
- Reduced raw material logistics and waste

### Quality Assurance

- Each metallic powder batch
- Each build plate (control samples/HIP bond specimens)



### Materials & Inspection

- Materials types applicable to broad product range
- LPBF material properties meet specification requirements
- Reduced grain size and consistent microstructure

### Performance Testing

- All valve test requirements met
- Tests exceeded design limits to drive out issues
- Tests on forged valves to enable direct comparison

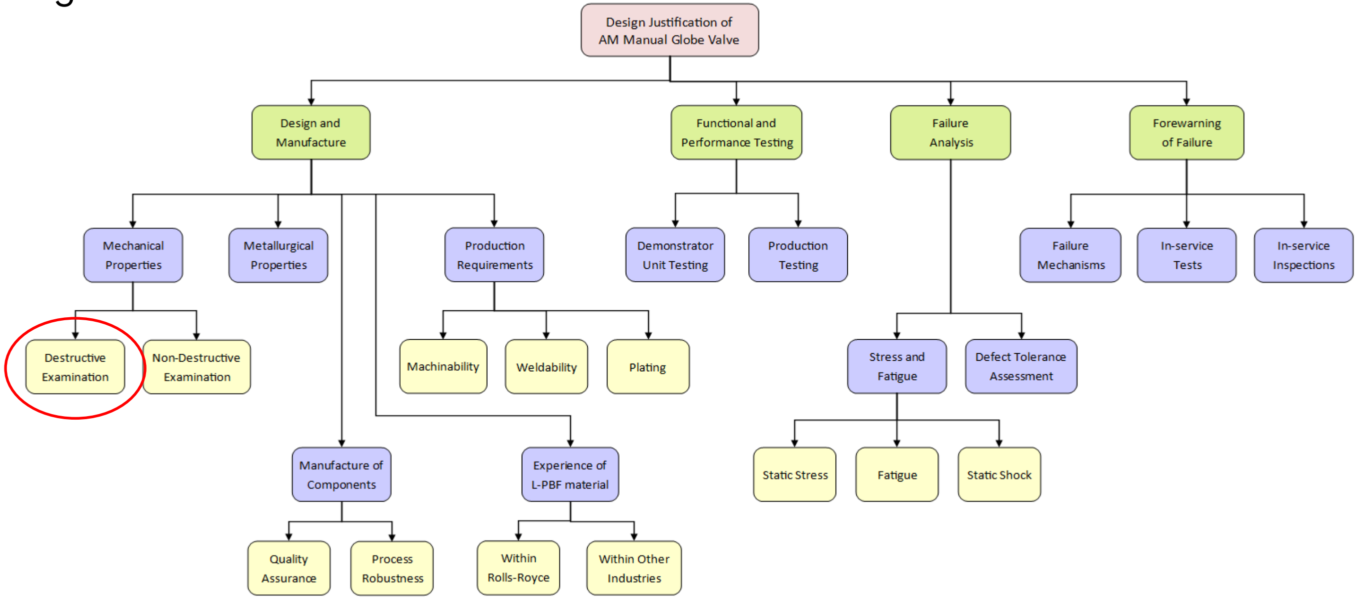
### Innovation

- Encapsulation principle patent filed
- Rolls-Royce leading on AM with key partners
- Application on other product ranges

# Multi-legged Justification Strategy

## Background Cont.

- Multi-legged Justification Strategy set out to demonstrate structural reliability of the material as currently no design basis or code for AM LPBF.
- Leg 1 - Initial in-air fatigue endurance test data on AM LPBF 316LN (single powder batch) was within expected scatter when compared to data on which the NUREG/CR-6909 best-fit is based.
- Following testing on multiple powder batches and builds, a more complex fatigue behaviour was observed.



# Overview of Materials Fatigue Testing & Data

- In-air fatigue data generated by testing material covering four different powder batches of AM LPBF 316LN, five different builds at multiple test houses. All tests carried out post HIP heat treatment.
- Constant-amplitude, strain-controlled fatigue testing carried out in accordance with ASTM E606.
- A strain rate of no greater than 0.4%/s was used during the rising and falling portions of the strain cycle.
- Majority of the testing was conducted at room temperature with four data points generated by testing at 300°C

| | **Test Orientation** | | |
|---|---|---|---|
| | **'X'** | **45°** | **'Z'** |
| Number of Valid Data Points | 45 | 17 | 32 |
| Minimum strain amplitude tested % | 0.18 | 0.20 | 0.18 |
| Maximum strain amplitude tested % | 1.0 | 0.8 | 0.9 |

# Overview of Materials Fatigue Testing & Data

Difference in behaviour of the 'X' and 'Z' orientations

Fatigue lives in the 'X' direction appear lower than the NUREG/CR-6909 data in the low cycle regime (N<~10,000 cycles).

For this reason the Rolls-Royce design curve MP5.1.7 (based on ASME design curve) was not considered suitable.

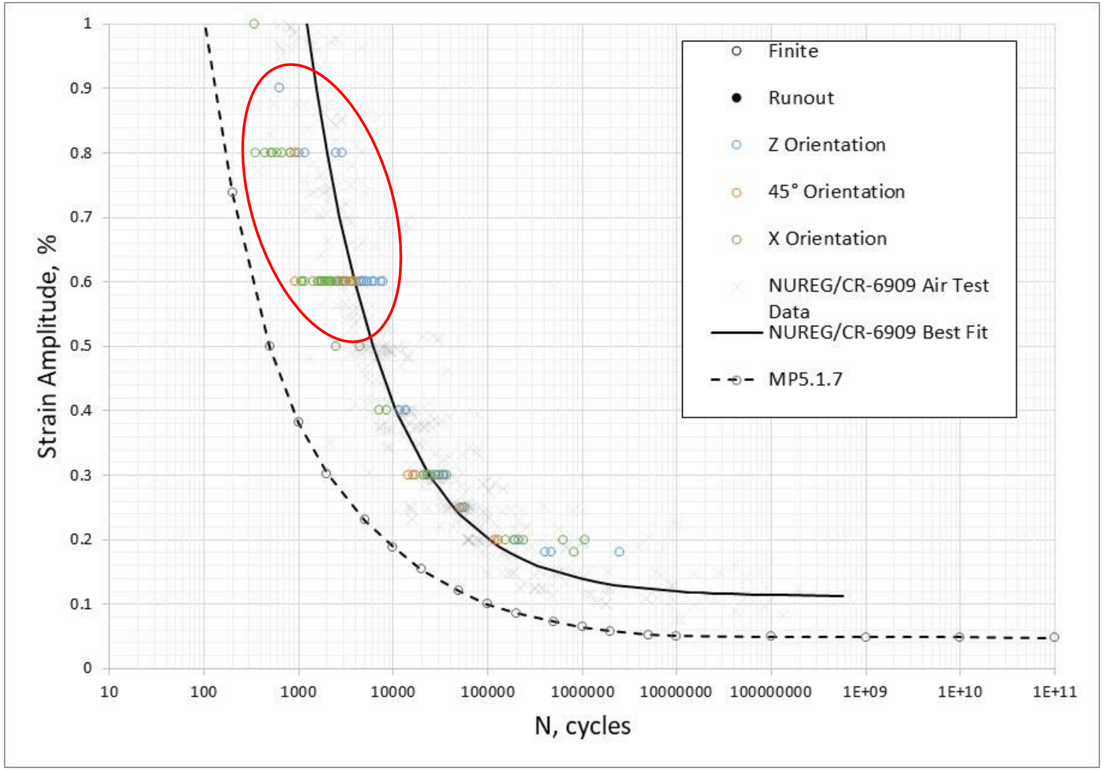
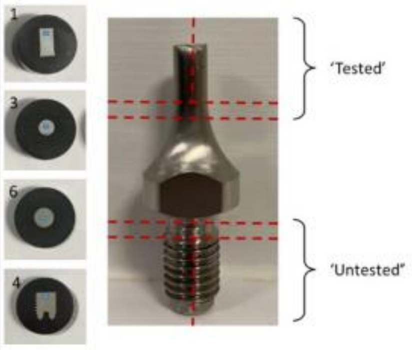


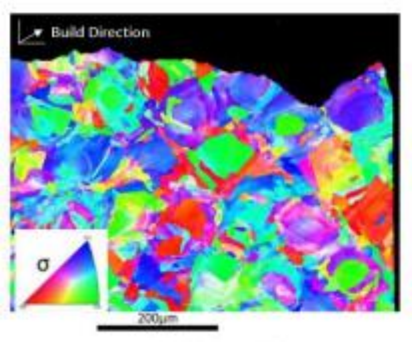

*Fig 2: Fatigue Lives of AM LPBF 316LN Specimens Testing in Air at Ambient Temperature Compared to the Rolls-Royce 'Wrought Design Curve' (MP5.1.7) and Associated Best Fit Curve*

# Microstructural and Failure Characterisation Investigation

## 1. Microstructural Characterisation

- Electron Backscatter Diffraction (EBSD) used to examine the microstructure of various broken fatigue test specimens;
  - Transverse and longitudinal directions
  - Inside and outside the gauge length
- Local EBSD misorientation maps for each section and each specimen broadly comparable.
- The grain size and grain size distributions were seen to be comparable (ASTM 9 to 10.5).
- General observation : crack initiation site most likely to occur in colonies of smaller grains, traversing one or two larger grains prior to transgranular cracking under Mode I loading.



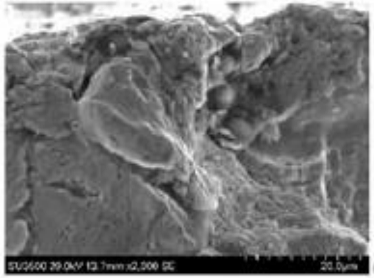



(a) Horizontal

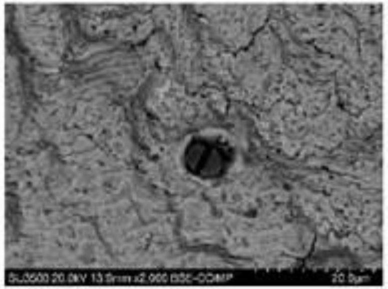
# Microstructural and Failure Characterisation Investigation

## 2. Failure Characterisation

- > 50 tested specimens were examined by SEM.
- Failure exclusively because of fatigue initiation near to or at the outer surface of the specimen gauge.
- Particles were observed and determined by EDS to be Manganese (Mn) rich, near-spherical inclusions - origin more likely via the manufacturing process rather than the powder feedstock.
- Despite their presence, not sufficiently apparent that these particles were active in fatigue initiation and growth, or simply a benign underlying feature.
- In all specimens inspected, secondary cracking was observed on the gauge length near to, but not interacting with, the primary crack. More prevalent in higher strain amplitude test specimens.
- Nothing noted outside of the cracking described, i.e. foreign objects, porosity, etc.



(a) Located at fatigue initiation site



(b) Sheared particle slightly away from failure position

# Microstructural and Failure Characterisation Investigation

Examined fatigue behaviour at the higher strain amplitude of 0.8% (region of concern)

Strain rate reduced by a factor of 10 to limit buckling under compression (0.4 %/$s^{-1}$ to 0.04%/$s^{-1}$)

The 'control' 0.6% tests seen to agree with the previous data carried-out at 0.4%/s.

## 3. Additional Fatigue Testing

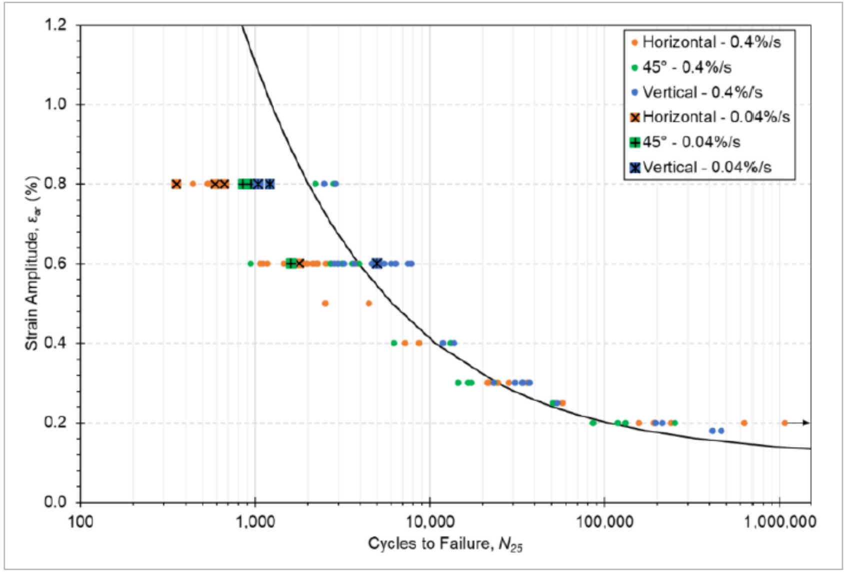



*Fig 7: Additional In-air Fatigue Tests at 0.04%/S Strain rates under Ambient Conditions*

- Investigation concluded no definitive material or mechanistic attribute identified as a cause for the premature failure of the material at high strain amplitudes, other than the textural microstructural differences (directionality).
- More conservative fatigue design curve required for AM LPBF 316L SS.

# Design Curve Derivation

Counter-clockwise rotation of the S-N curve observed in heats of wrought Austenitic SS with increasing tensile strength

AM LPBF 316LN appears to display similar behaviour in the limiting 'X' orientation

- A best fit S-N curve was produced for both the 'X' and 'Z' orientations by using Maximum-Likelihood Estimation (MLE) models fitted to the number of cycles observed.
- In Low Cycle Fatigue (LCF) region the 'X' orientation is clearly limiting. In the medium to high cycle region the 'Z' orientation is considered limiting.

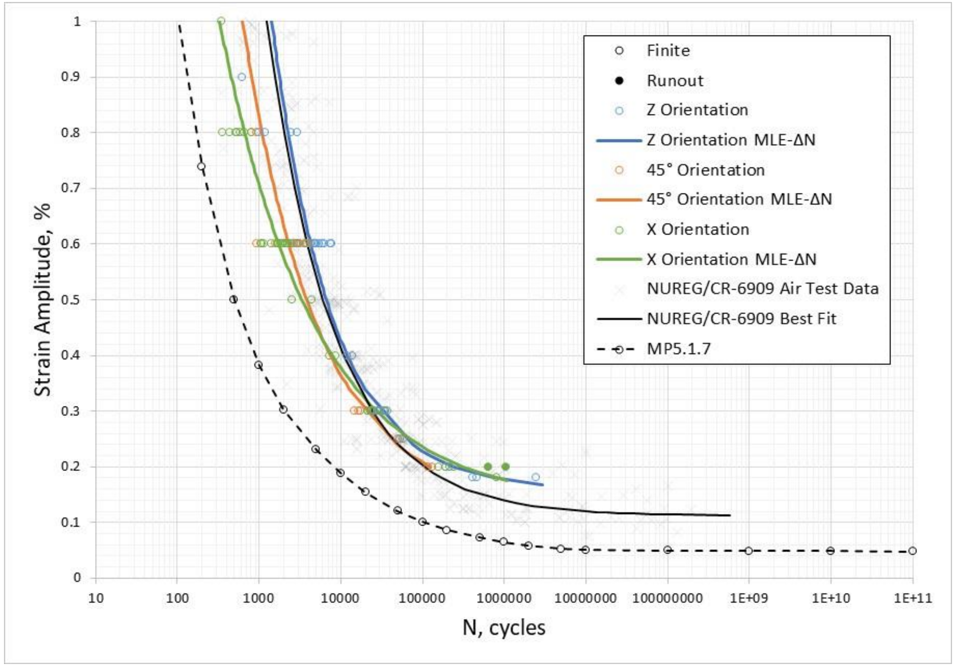



*Fig 9: MLE Fits for each Orientation compared to the NUREG/CR-6909 Best Fit Curve*

# Design Curve Derivation - AM LPBF 316LN St. St.

Combined best fit S-N curve produced by;

- N<20,000 cycles - 'X' orientation best fit
- N>20,000 cycles - NUREG/CR-6909 best fit was used (as bounding of all orientations in region)

Fatigue Design Curve produced from the best fit S-N curve by;

- Applying a bounding mean stress correction
- Factors of 2 on stress
- Factors of 20 on cycles

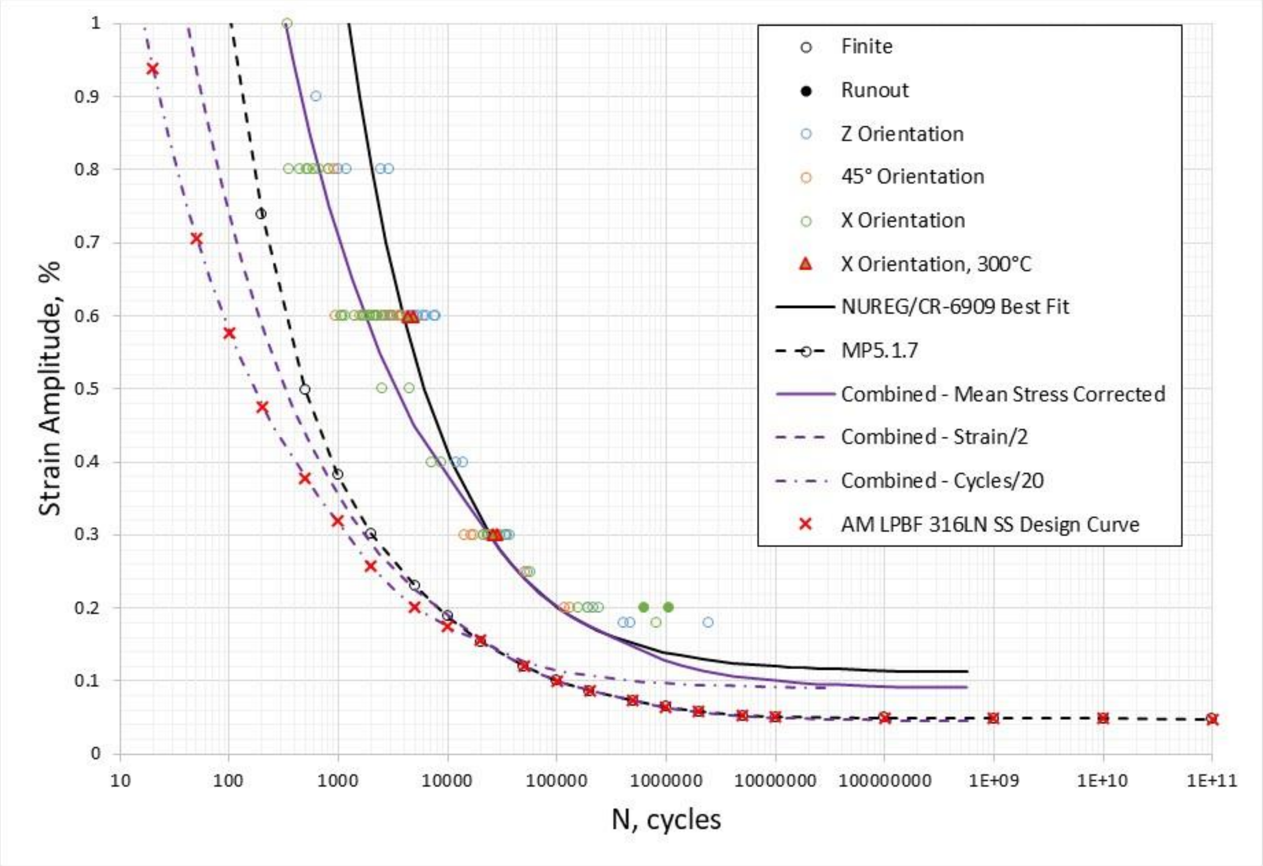
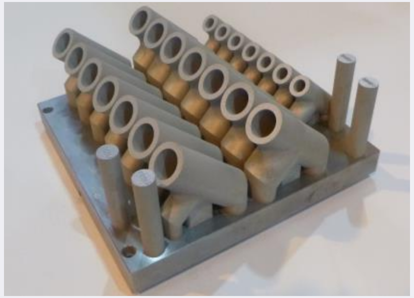



*Fig 11: Construction of the AM LPBF 316LN Stainless Steel In-Air Fatigue Design Position*

# Summary



- In-air fatigue testing on AM LPBF 316LN St. St. on multiple powder batches and builds demonstrated complex fatigue behaviour at high strain amplitude.
- Investigation could not find a definitive material or mechanistic attribute as a cause for the premature failure, other than textural microstructural differences.
- A best fit curve has been constructed by considering each orientation separately and using either a fit to the limiting test orientation, or the NUREG/CR-6909 mean curve at each point across the S-N curve, whichever is lower.
- Fatigue design curve produced from the best fit curve by applying a mean stress correction and then applying conservative transference factors on stress and on cycles.
- AM LPBF 316LN fatigue design curve is judged to be suitably conservative for the assessment of the material on nuclear plant applications, including Small-Bore Globe valves which have also undergone supporting ASME, Section III, Appendix II, thermal cyclic testing.
- Data and approach published externally in ASME PVP 2023 - 106379 *(figure references)*

# Thank you – Any questions?