Effect of liquid metal environment on nucleation and propagation of fatigue cracks

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Introduction

The novel MYRRHA project under development at SCK CEN is an accelerator-driven system where the fast reactor is cooled by a lead-bismuth eutectic (LBE) melt. Structural materials of the reactor need to be qualified to perform under this environment ensuring the integrity and safety of systems. Effect of environments on materials mechanical performance is an emerging issue for nuclear systems, and the underlying mechanisms are still being investigated to incorporate their effects in design rules. In SCK CEN, the performance of MYRRHA's candidate structural materials, such as 316L austenitic stainless steel, is studied through mechanical testing in LBE environmental conditions similar to the ones which will be present during reactor operation. This research project aims to study the influence of LBE environment on the fatigue properties of candidate structural material 316L, and the nature of the deformation mechanism which governs them.

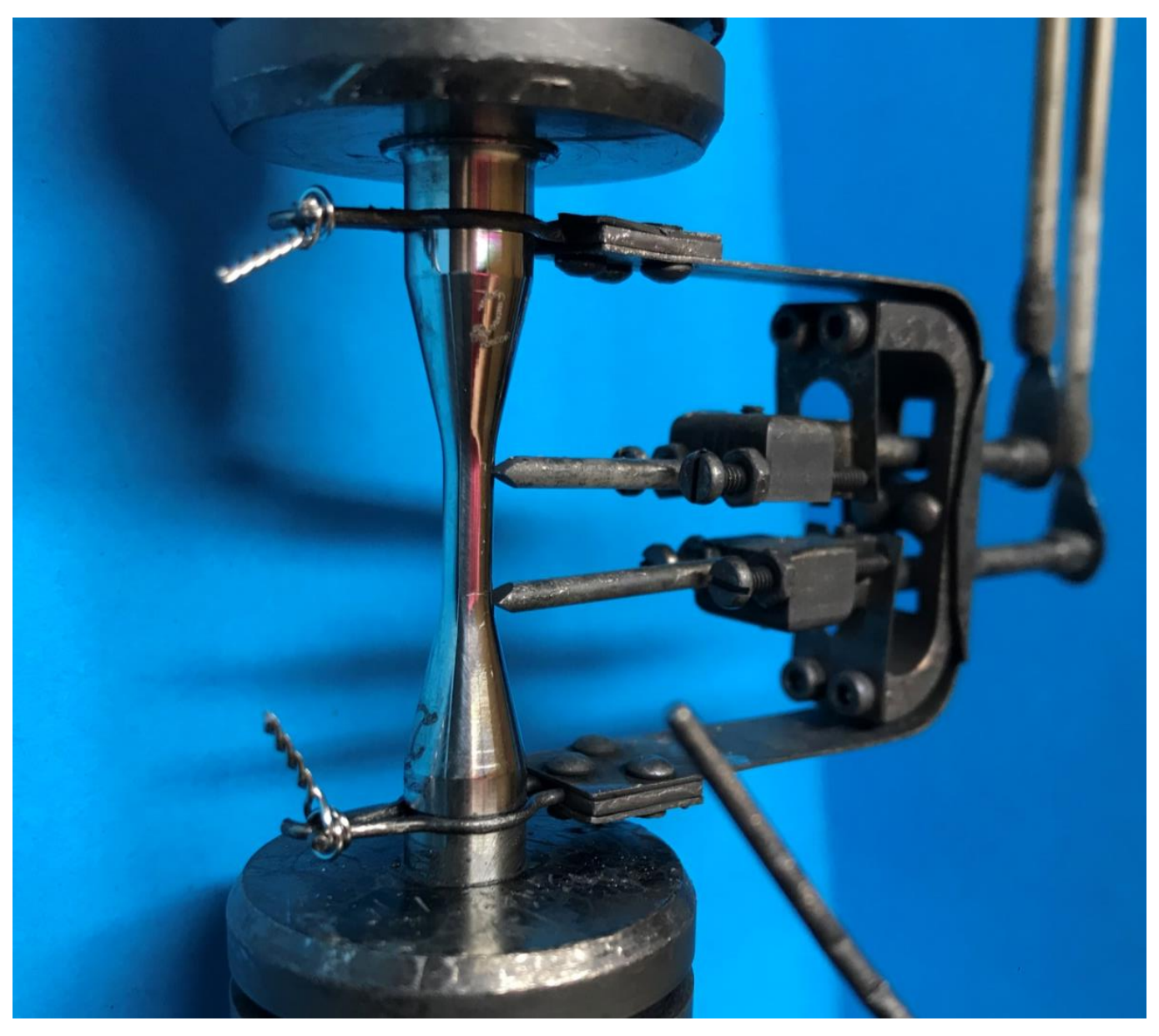
Objectives

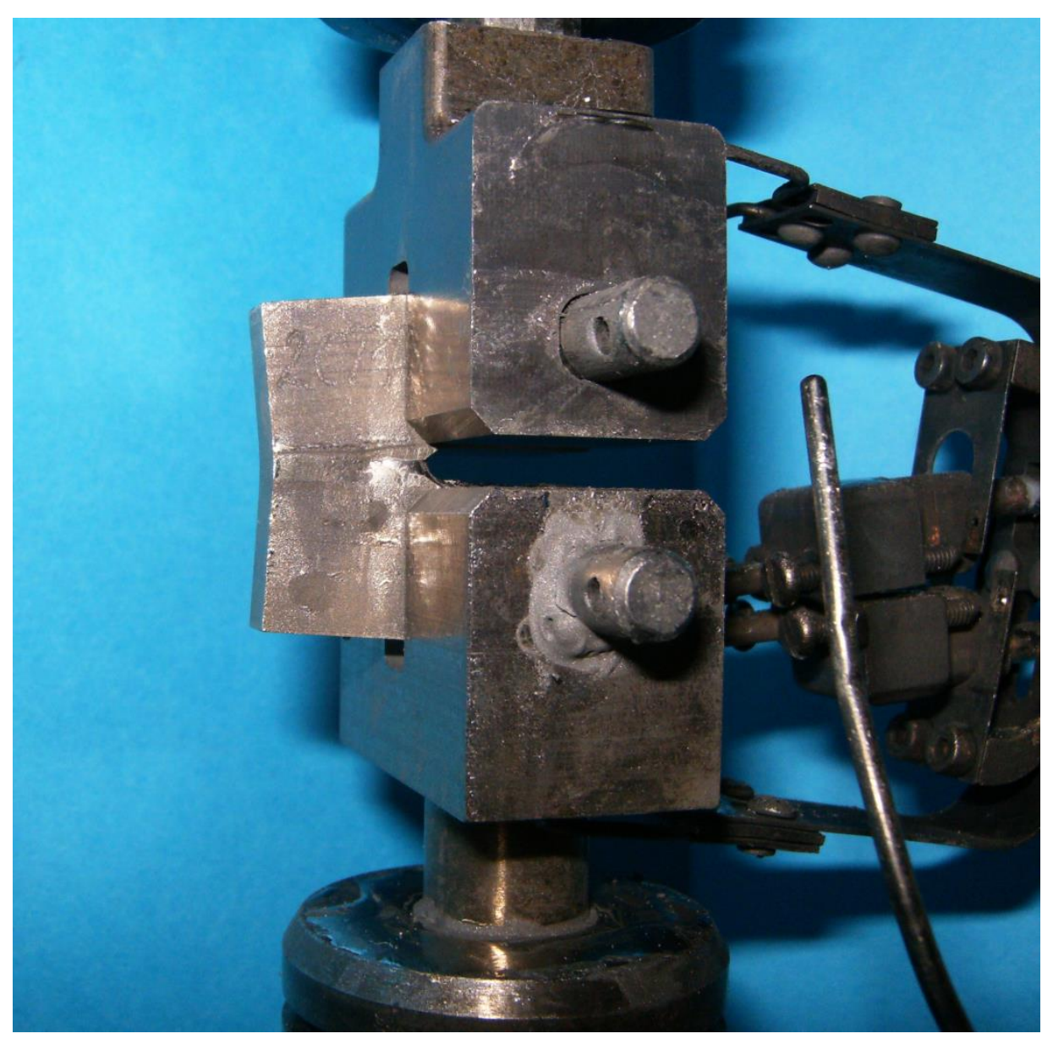
Determine the critical loading and environmental conditions in which LBE effects on fatigue life and fatigue crack propagation (FCG) are significant.

Propose a model for the deformation mechanism that governs nucleation and propagation of cracks in LBE environments.

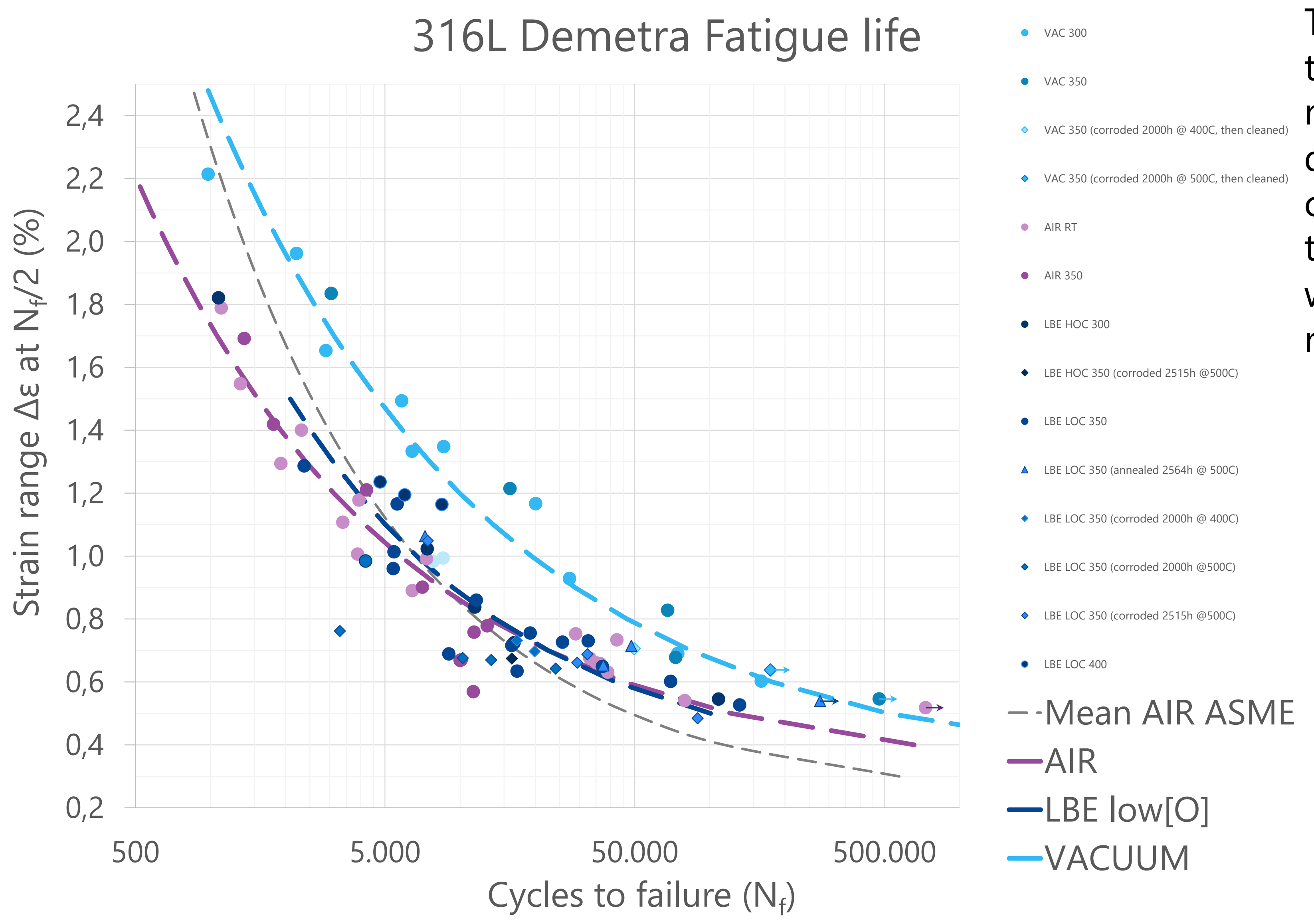
Methodes

The LIMETS3 testing machine, developed at SCK CEN, comprises a load-line and frame which can be submerged in an autoclave filled with LBE at controlled oxygen and temperature conditions. The setup is able to carry out tensile, fatigue, and fatigue crack propagation tests in LBE, air, and vacuum environments.
Nucleation of fatigue cracks is investigated through strain-controlled low-cycle fatigue tests on solid cylindrical specimens, in four different environments: LBE at low oxygen concentration (low[O]); LBE with high oxygen concentration (high[O]), vacuum, and air. Comparison of test results and microstructure is therefore possible among different environments.
Propagation of fatigue cracks is investigated through fatigue crack growth (FCG) tests on CT specimens, also tested in the four different environments enabling comparison of test results and fracture surfaces.



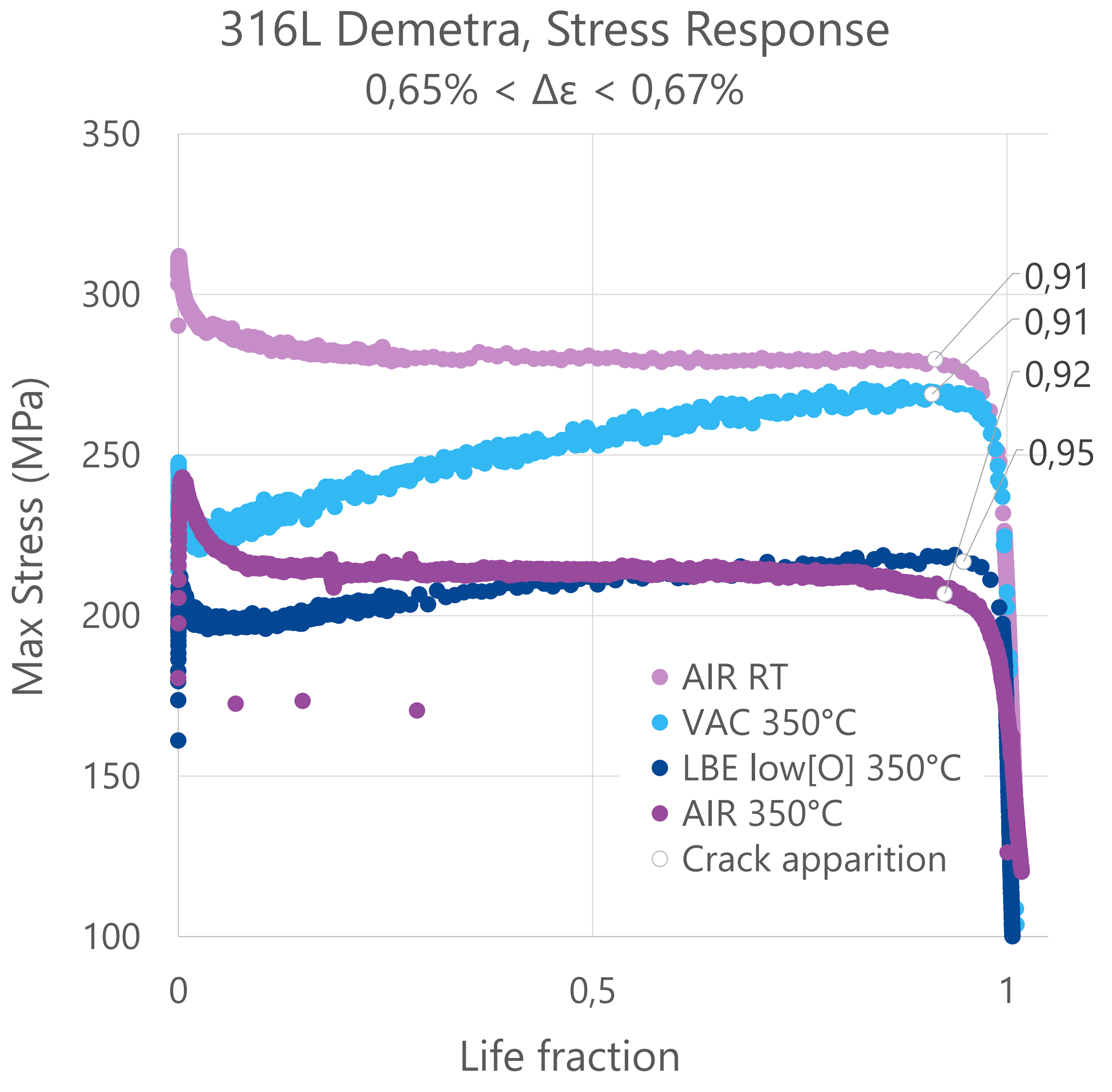


Results



The available results of numerous tests performed at different strain ranges (Δε) in the environments described before, have allowed the construction of the fits shown on the strain-life (ε-N) plot on the left, which can be compared to reference mean air curves.

Direct comparison of material response is possible for samples tested in different environments at similar strain ranges, for example stress response (plotted on the right) and hardening or softening, and number of cycles for crack nucleation (indicated on the plot).

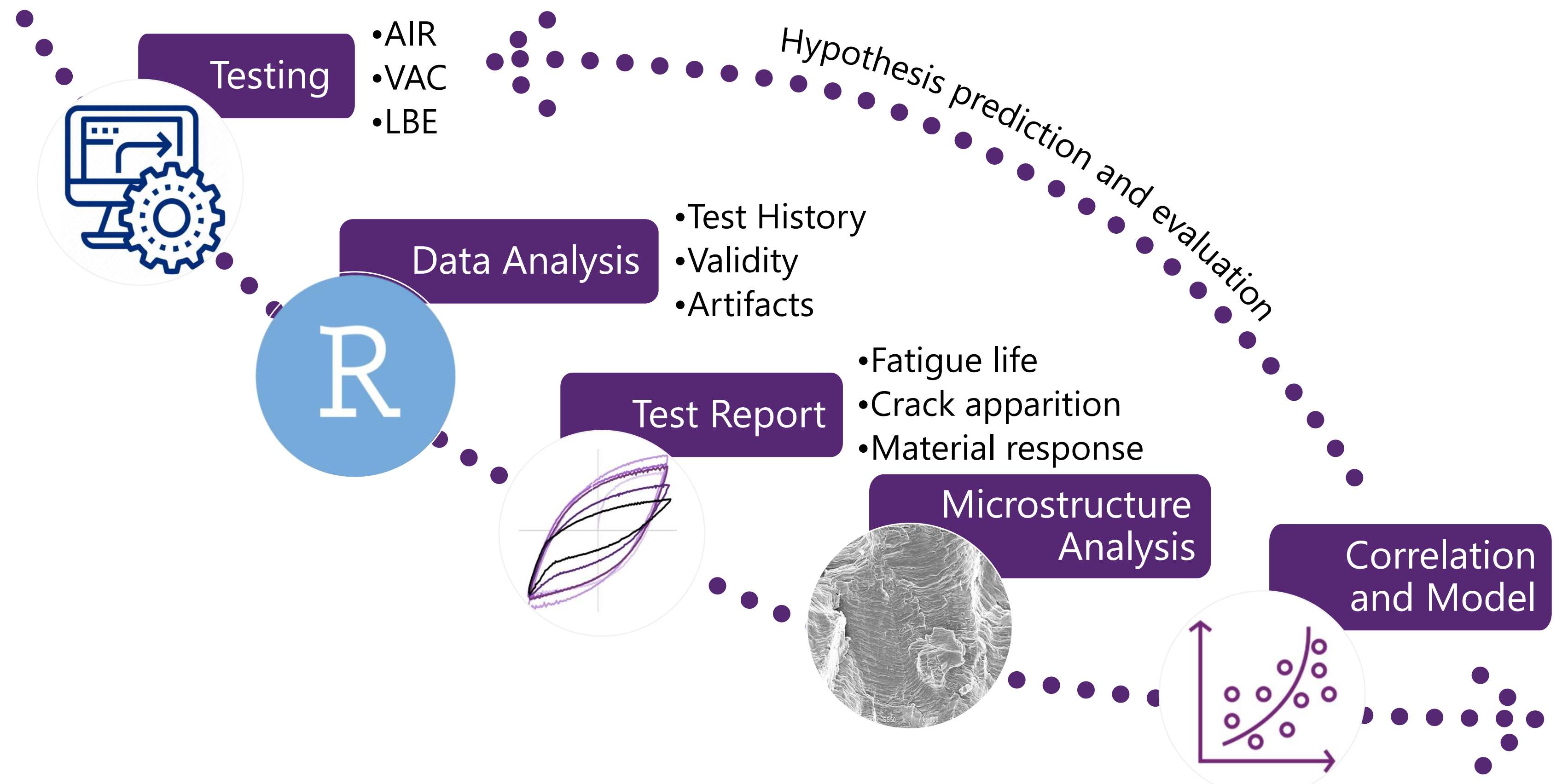


Discussion

The fatigue life air data from this research show good agreement with the reference mean air curve for austenitic stainless steels used in design codes. In contrast, higher fatigue lives are observed in the vacuum environment, where the absence of oxygen or other interacting elements delay the nucleation of cracks. Fatigue lives in LBE low[O] environment also show good agreement with the reference curve in air. Moreover, the calculated fits for air and LBE low[O] show even better agreement, specially at lower strain ranges.

Comparison of stress responses of tests performed at similar strain ranges suggests that specimens tested in LBE and vacuum undergo a second hardening, whereas specimens tested in air apparently don't. However, hardening is an indicator of the specimen's bulk behaviour, which in principle should not be affected by its environment besides the test temperature. Detailed inspections of every test history could help identify and correct possible artifacts introduced during setup.

An indicator of the speed at which the crack propagates once nucleated is the difference in cycles between the crack apparition Na and the failure of the specimen Nf. Comparison of the propagation at similar strain ranges suggests that cracks propagate faster in LBE than they do in air or vacuum. Weakening of atomic bonds or enhancement of dislocation sources are two possible explanations that dedicated FCG tests and microstructure analysis will further investigate and evidence.



Hypothesis prediction and evaluation

Testing
- AIR
- VAC
- LBE

Data Analysis
- Test History
- Validity
- Artifacts

Test Report
- Fatigue life
- Crack apparition
- Material response

Microstructure Analysis

Correlation and Model

Conclusion

Currently available fatigue data suggests that crack nucleation requires a similar number of cycles in both LBE and air, but that once a crack is present, it might propagate faster in LBE environments.

Additional testing at higher strain ranges is necessary to determine if the agreement of LBE and air lives is present all throughout the strain-life curve. Additional testing at certain selected strain ranges is necessary to directly compare material response. Standardized procedures for data analysis will allow to confirm trends and discard artifacts due to machine setup, sample preparation, or mounting. Microstructure analysis of fractured surfaces and crack fronts will provide insight on the deformation mechanism in presence of LBE.

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