Correlation Between Electrical Resistivity and Microstructural Changes in SS316L Under High-Cycle Fatigue

Maryam Izadi
Dr. Ebad Bagherpour
Dr. Shubham Sanjay Joshi
Prof. Zhongyun Fan

Acknowledgement:
Circular Metals Centre funded by an UKRI/EPSRC (EP/V011804/1)

25th February 2025

Brunel University London
WMG THE UNIVERSITY OF WARWICK
UCL THE BARTLETT INSTITUTE FOR SUSTAINABLE RESOURCES
UK Research and Innovation

BCAST
UKRI Interdisciplinary Centre for Circular Metals
NICER PROGRAMME

Famous Cases of Structural Failures

BCAST

UKRI Interdisciplinary Centre for Circular Metals

Tacoma Narrows Bridge Collapse (1940)

The bridge collapsed just four months after opening due to undetected vibrations and fatigue stress.

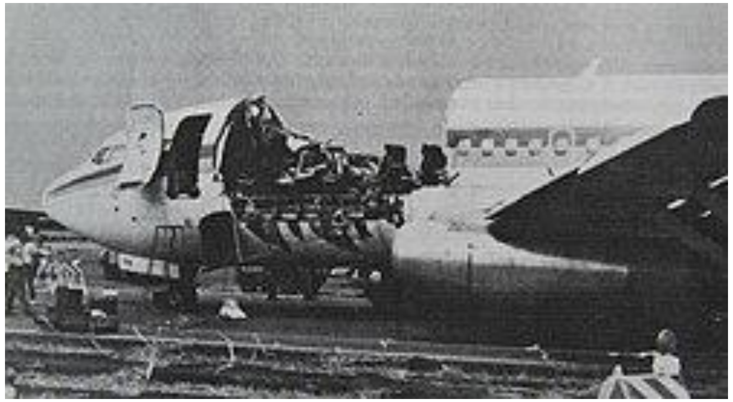
Aloha Airlines Flight 243 (1988)

A fuselage tear caused by undetected metal fatigue.1 death, 65 injuries

Japan Airlines Flight 123 (1985)

A fatigue-related bulkhead failure led to the deadliest single-aircraft accident. 520 deaths

Tacoma Narrows Bridge Collapse of the Tacoma Narrows Bridge, Washington state,



The fuselage of Aloha Airlines Flight 243 after rupturing while in flight.

Japan airlines flight 123 Crash.

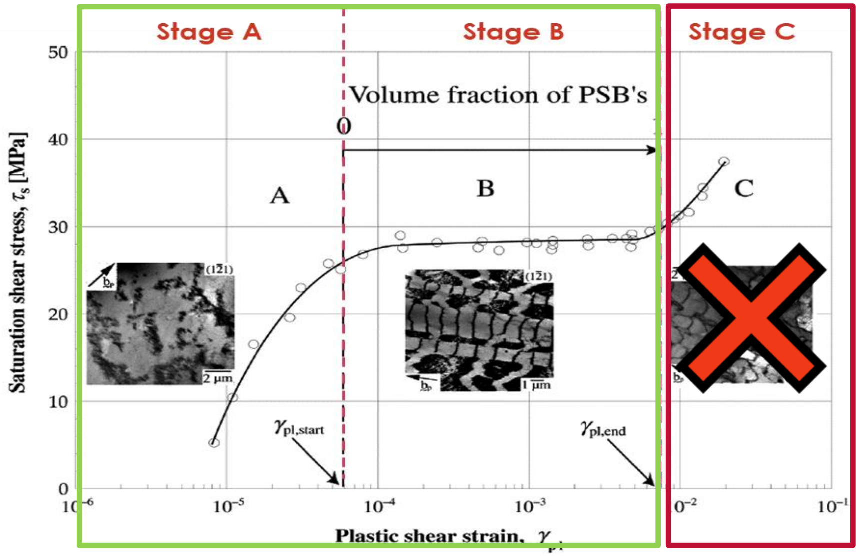
Prevention of Structural Failures

Early detection of fatigue cracks is critical to saving lives and preventing disasters.

Research Focus: Early Fatigue Detection Before Crack Propagation

UKRI Interdisciplinary Centre for Circular Metals

Fatigue stages in a material



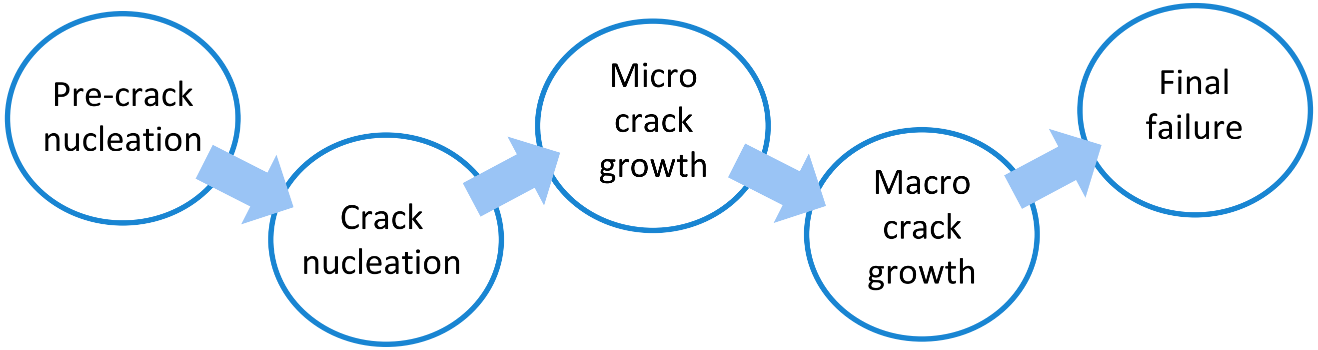
Stage A: Dislocation movement / entanglement

Stage B:Slip line formation

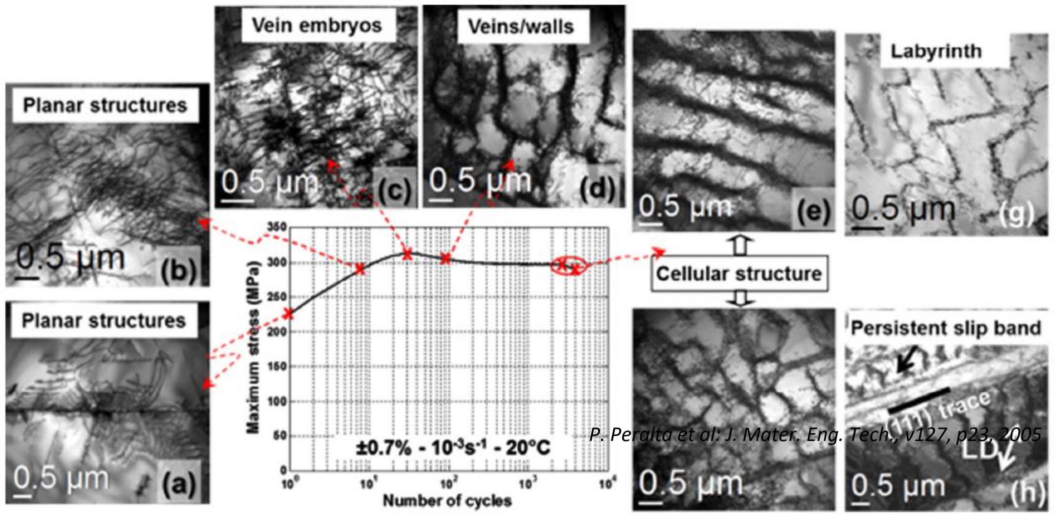
Stage C:Crack initiation /propagation

Key points of this research

1- Focus on pre crack propagation stage.



2- Detection of early-stage fatigue damage and microstructural changes during fatigue through NDT techniques instead of TEM and destructive methods.



P. Peralta et al: J. Mater. Eng. Tech., v127, p23, 2005

Dislocation evolution and the corresponding cyclic deformation behavior of AISI 316L steel

J. Ewing et al ,*Philosophical Transactions of the Royal Society of London. Series A,* 1934

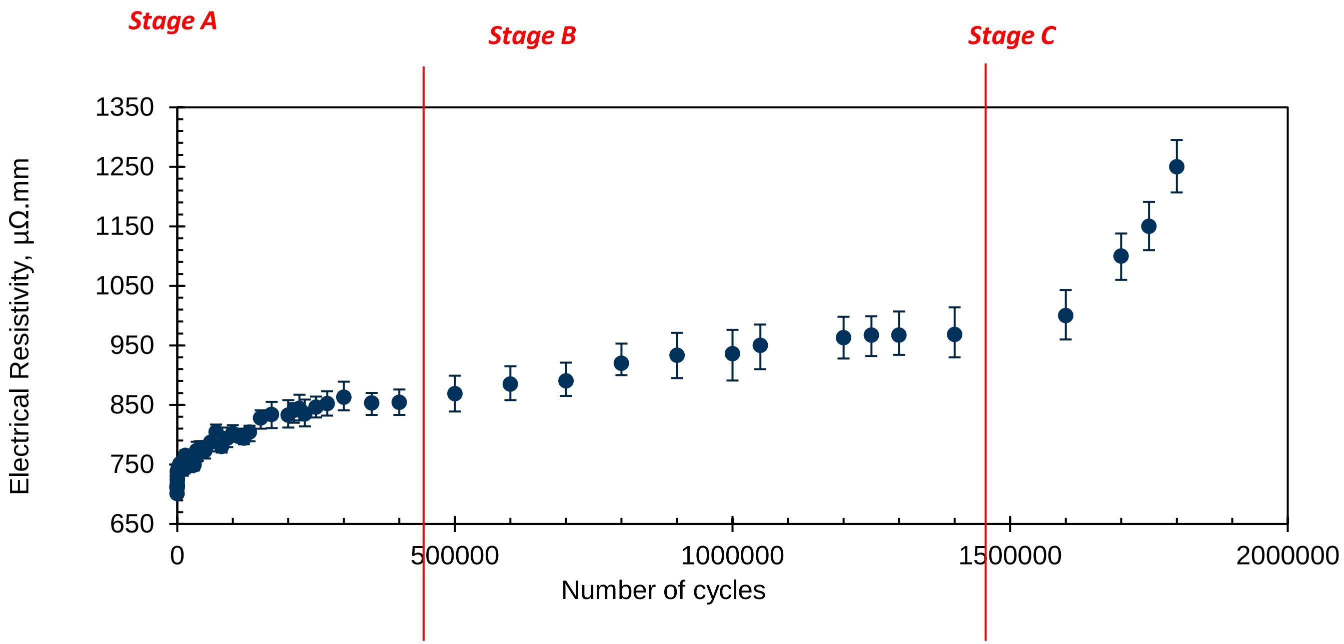
Tracking Fatigue Evolution Using Electrical Resistivity Measurements

UKRI Interdisciplinary Centre for Circular Metals

➢ Principals:

- Ohms law ($R = \frac{V}{I}$) , Structural defects as source of electrons scattering and elevation in electrical resistivity:
  - **Dislocations, Entanglement, Slip bands, Cracks**

Fatigue regime :11.5 kN (400 MPa) load with an amplitude of 3.3 kN and a frequency of 10 Hz- Stainless steel 316 , Fatigue life 2,000,000 cycle



Stage A: Dislocation movement / entanglement → slight resistivity increase

Stage B:Slip line formation → gradual rise in resistivity

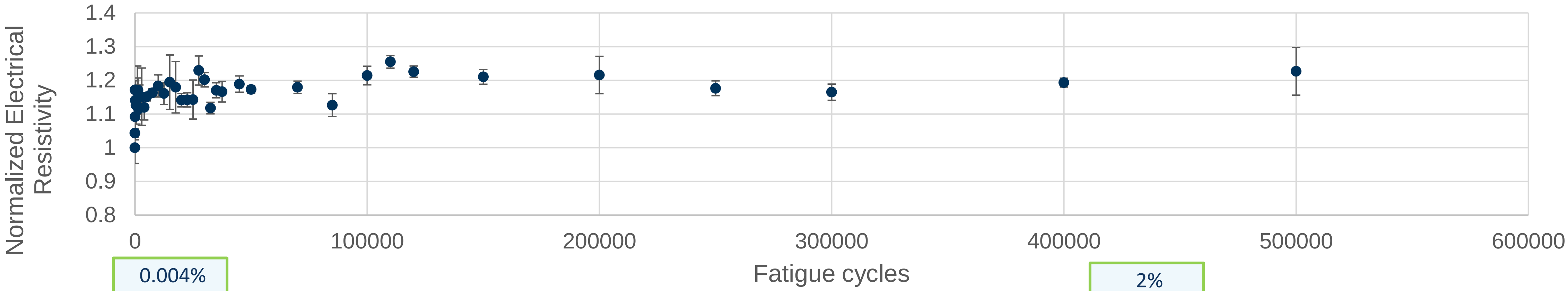
Stage C:Crack initiation /propagation → sharp increase in resistivity

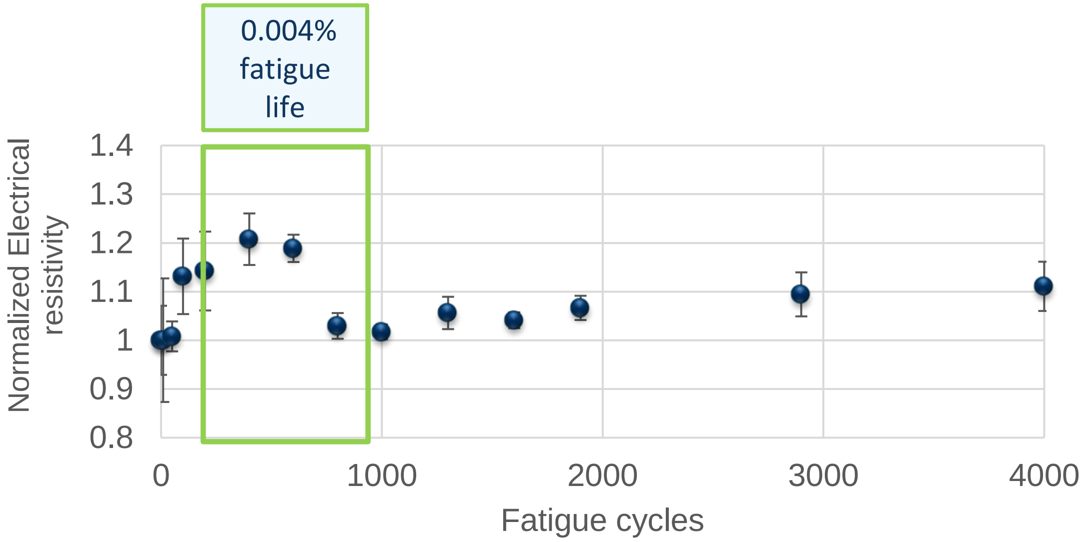
Electrical resistivity is used as an approach to monitor fatigue damage evolution, capturing structural changes in all three fatigue stages.

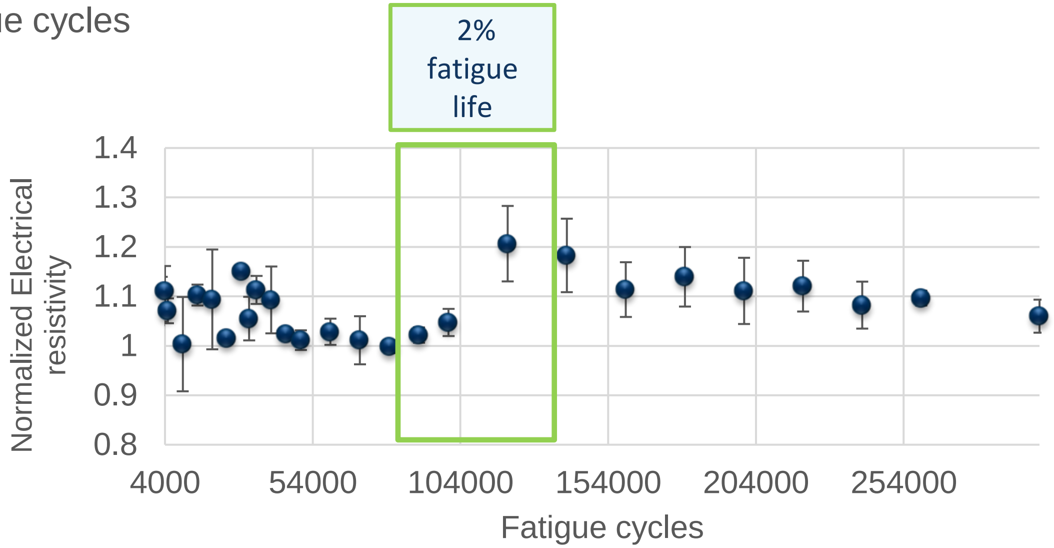
Early-Stage Fatigue Detection:
Electrical Resistivity Reveals Microstructural Changes Before 20% Fatigue Life

UKRI Interdisciplinary Centre for Circular Metals

Fatigue regime : Max stress 260 MPa, R=-0.4 and a frequency of 10 Hz- Stainless steel 316 , Fatigue life 5,000,000 cycle





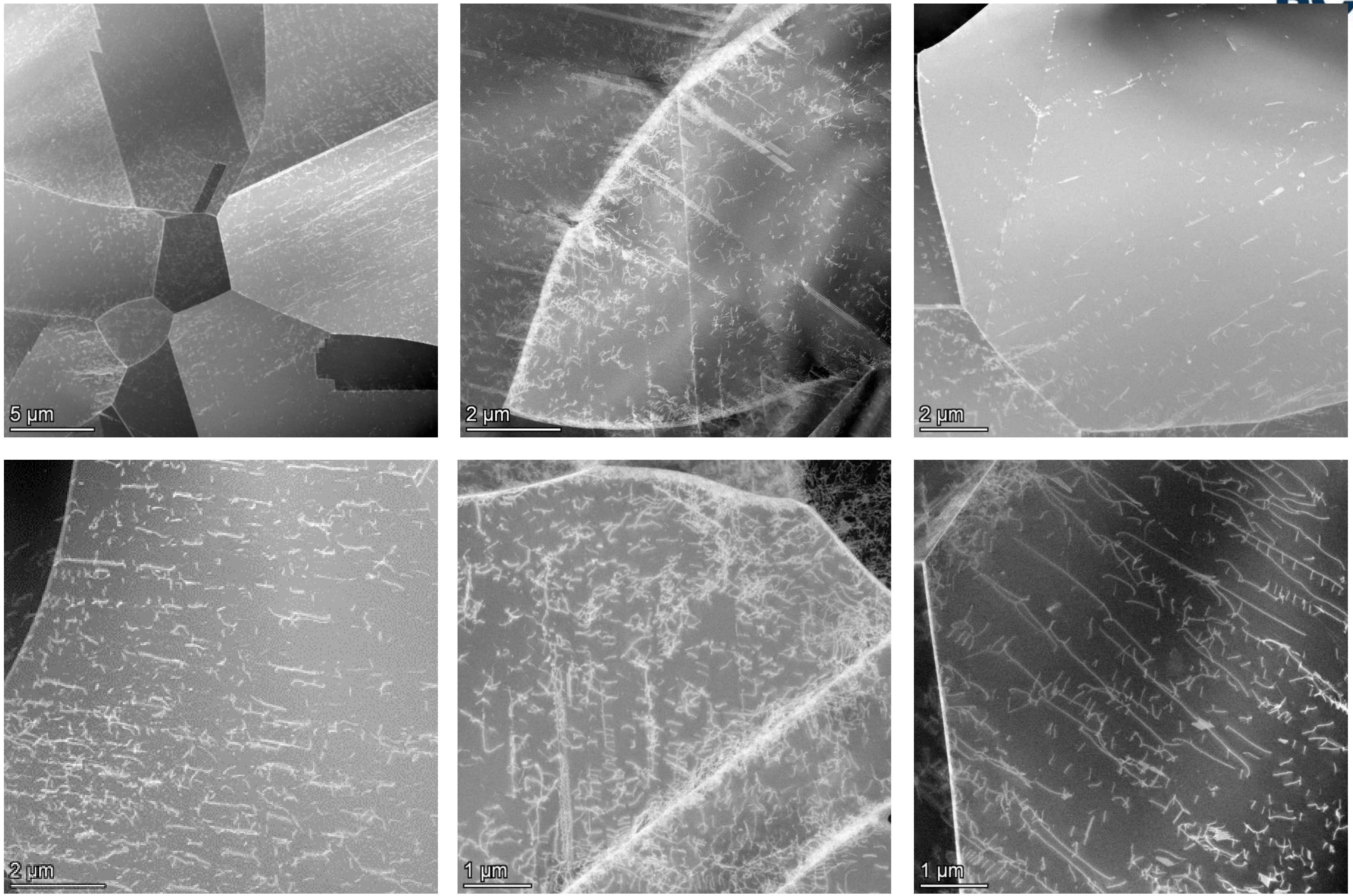


Before reaching 20% of fatigue life, two significant fluctuations in electrical resistivity are observed, indicating key microstructural changes.

Dislocation Evolution in Fatigue: TEM vs. Electrical Resistivity at 0.004% Fatigue Life

BCAST

UKRI Interdisciplinary Centre for Circular Metals

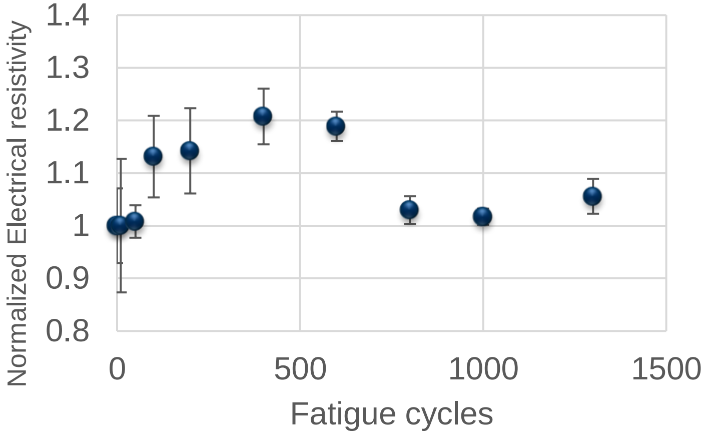


0 cycle
Single dislocations along grains

200 cycle
Dislocation tangles all along grain

1500 cycle
Ordered structures of dislocations

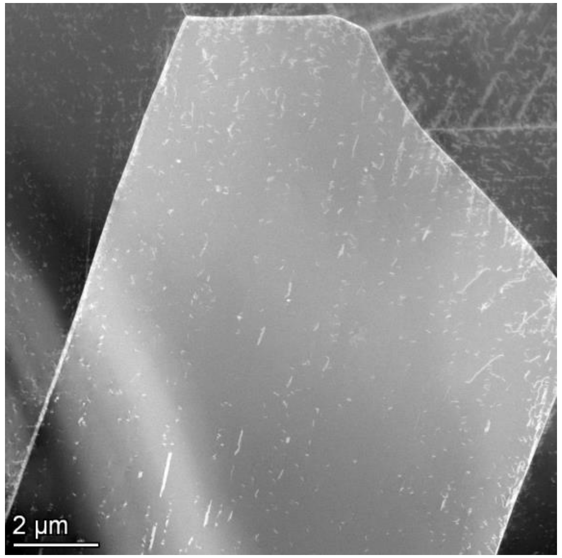
Electrical resistivity measurement by 0.03% fatigue life

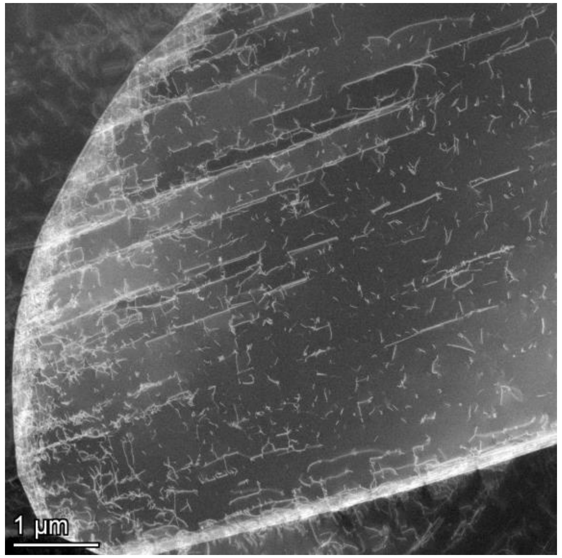


TEM reveals dislocation structure changes, while electrical resistivity tracks corresponding microstructural changes in real time.

Dislocation Evolution in Fatigue: TEM vs. Electrical Resistivity at 2% Fatigue Life

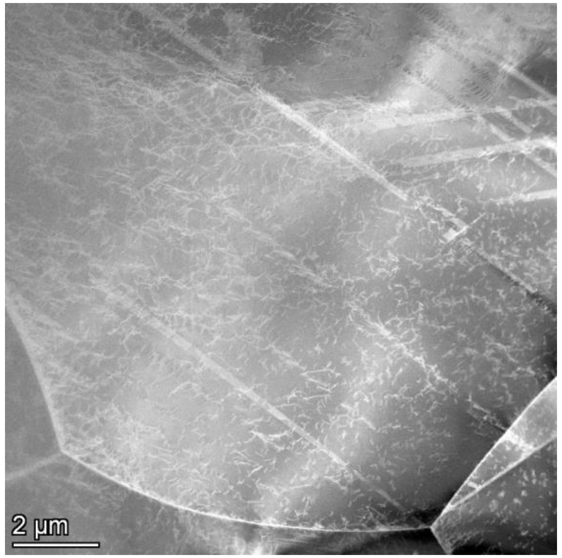
UKRI Interdisciplinary Centre for Circular Metals

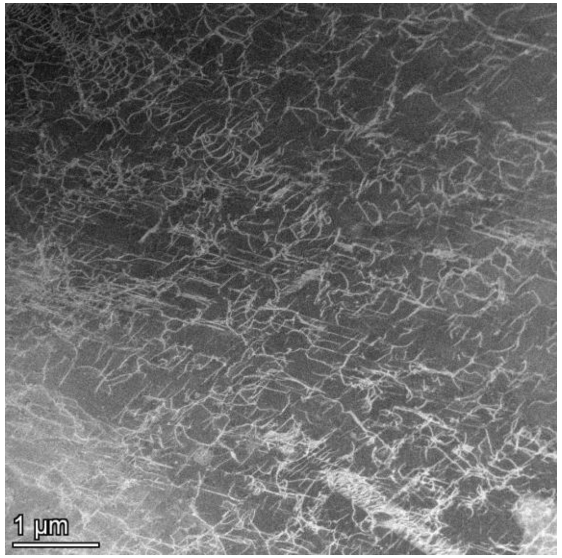




80,000 cycle

Ordered structures of dislocations

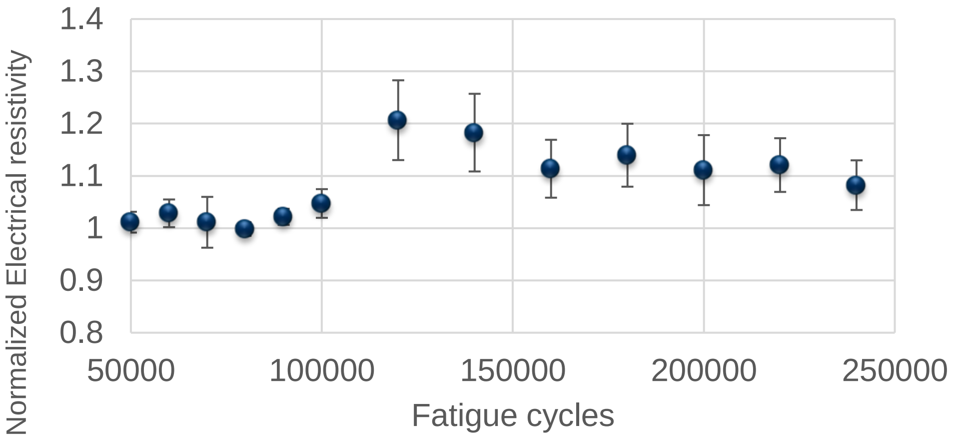




120,000 cycle

Dislocations tangles and formation of cells

Electrical resistivity measurement by 5% fatigue life

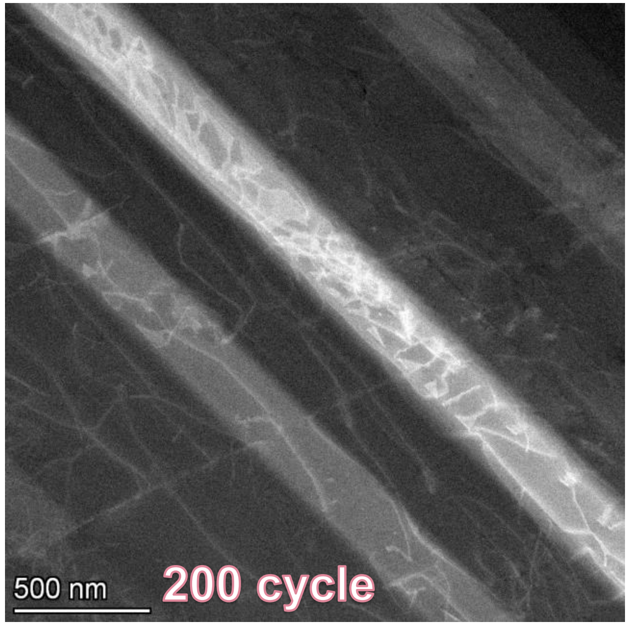


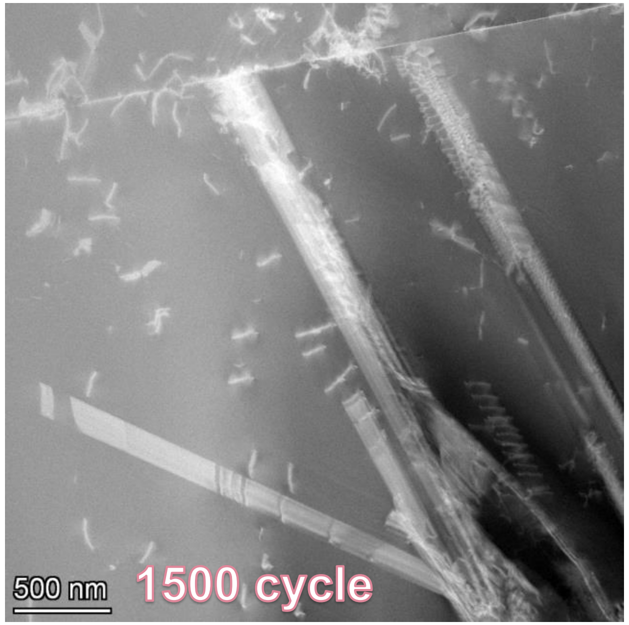
The increasing resistivity trend correlates with the transition from ordered dislocations to dislocation cell formation, increase in dislocation density and more tangled structures of dislocations indicating.

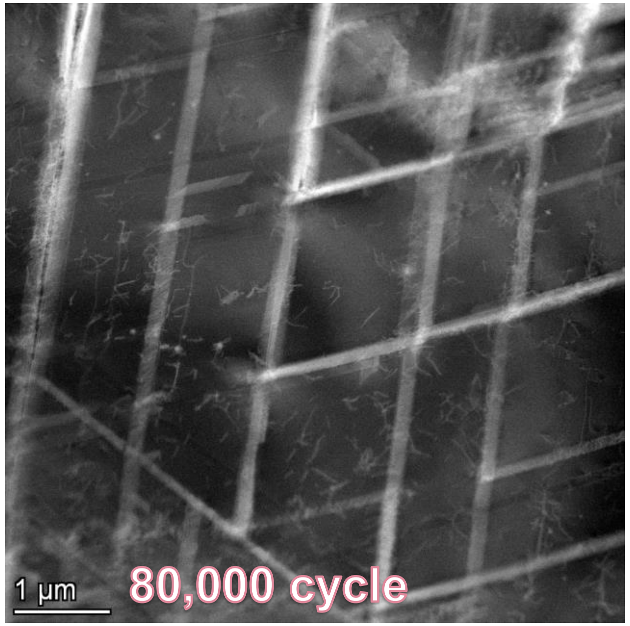
Tracking Slip Band Evolution in before 10% Fatigue Life

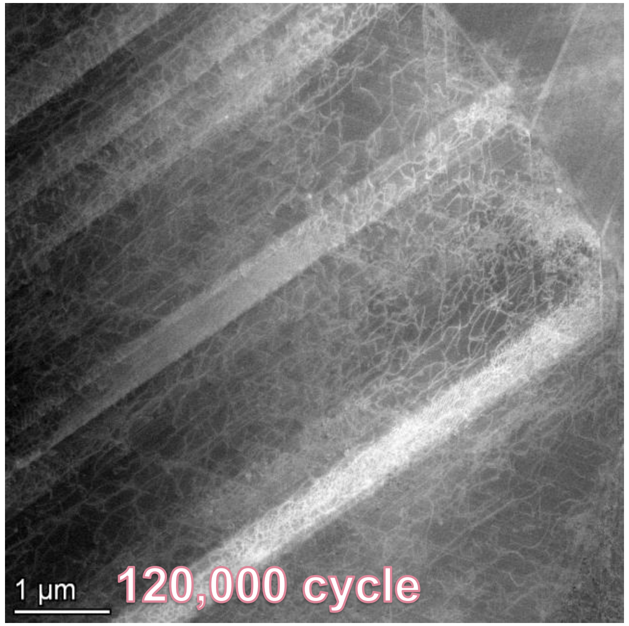
BCAST

UKRI Interdisciplinary Centre for Circular Metals









Cycles (fatigue life percentage)	Slip bands
0 (initial state)	Few or no visible slip bands in the sample
200 (0.002%) First peak	Early formation of slip bands, beginning to appear along grain boundaries
1500 (0.04%)	Slip bands more defined, but still evolving
80,000 (1.6%)	Well-developed slip bands, appearing thicker and more continuous
120,000 (2.4%) second peak	highly structured and dominant across slip bands the sample

Slip bands evolve from early formations (200 cycles) to fully developed structures (120,000 cycles).

Summary

1-Most studies for damage detection focus on crack propagation, while this research explores pre-crack nucleation & propagation.
Investigating early fatigue mechanisms without relying on microscopy and destructive methods, aiming for non-destructive and sensitive approach.
2-Electrical Resistivity as a Fatigue Monitoring Tool:
Successfully tracks microstructural changes across different early fatigue life stages.
Identifies early fatigue damages before 10% fatigue life, providing an early indicator of damage.
3-TEM Analysis of Fatigue Evolution
Demonstrates the correlation between microstructural changes and electrical resistivity measurements.

Future works

- Expanding Electrical Resistivity Measurements

Investigating additional fatigue regimes and different material types (e.g., alloys, composites).
Improving real-time resistivity monitoring systems for practical applications.

- Utilising Other Non-Destructive Techniques (already NLP is approved.)