Fatigue properties of tungsten from different processing routes

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LUND UNIVERSITY

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Objectives

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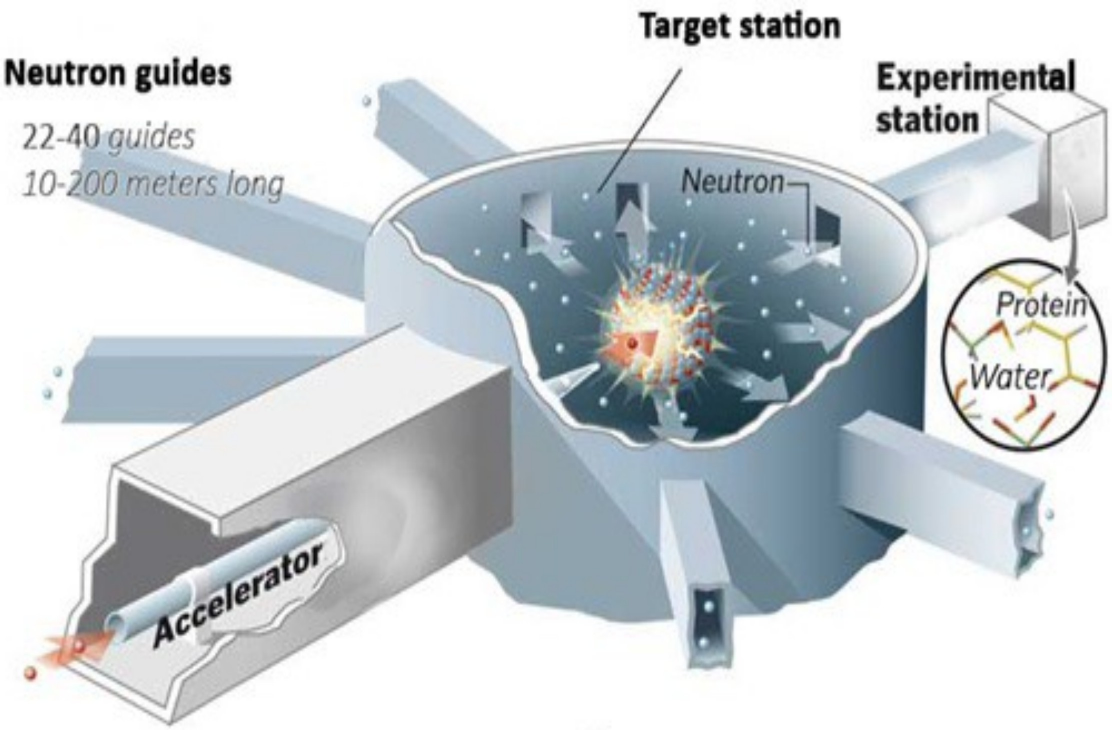
Study the fatigue behaviour of pure tungsten processed through two different routes and check their suitability as spallation target material.

- Characterize fatigue and tensile properties at room temperature (Low Plasticity – similar to irradiation embrittlement)
- Compare the fatigue and tensile properties of tungsten

  (i) Rolled and Annealed (ii) Sintered and HIPed
- Examine the importance of surface quality

The European Spallation Source

- 5 MW (2 GeV) proton beam
- Tungsten target



Thermomechanical Fatigue

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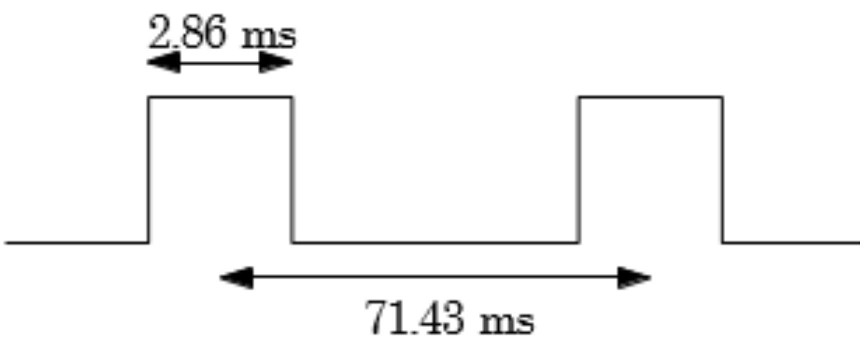
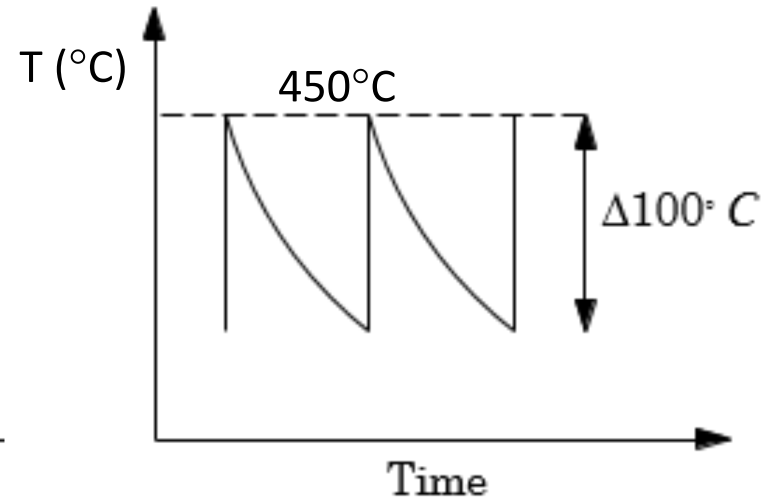
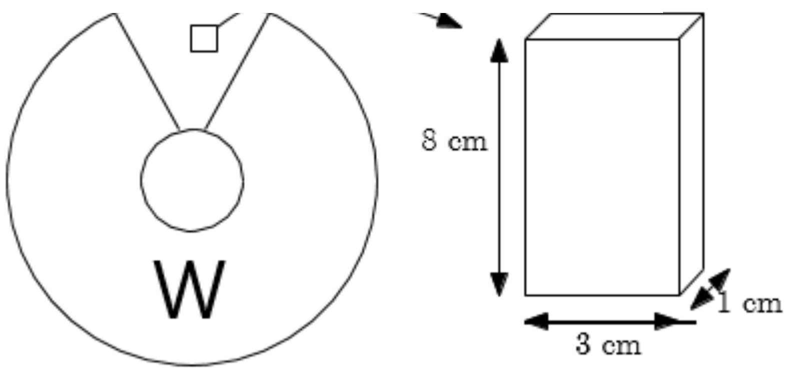
Proton Beam Pulse





Stresses generated have been Calculated to be in the range 44 to 110 MPa.

F. Sordo et al, ESS-Bilbao, September 2016.



Target wheel, 36 sectors
Around 7000 W-bricks

Tungsten Specimens

Process Route:

W-Powder

↓

Pressed into a green compact

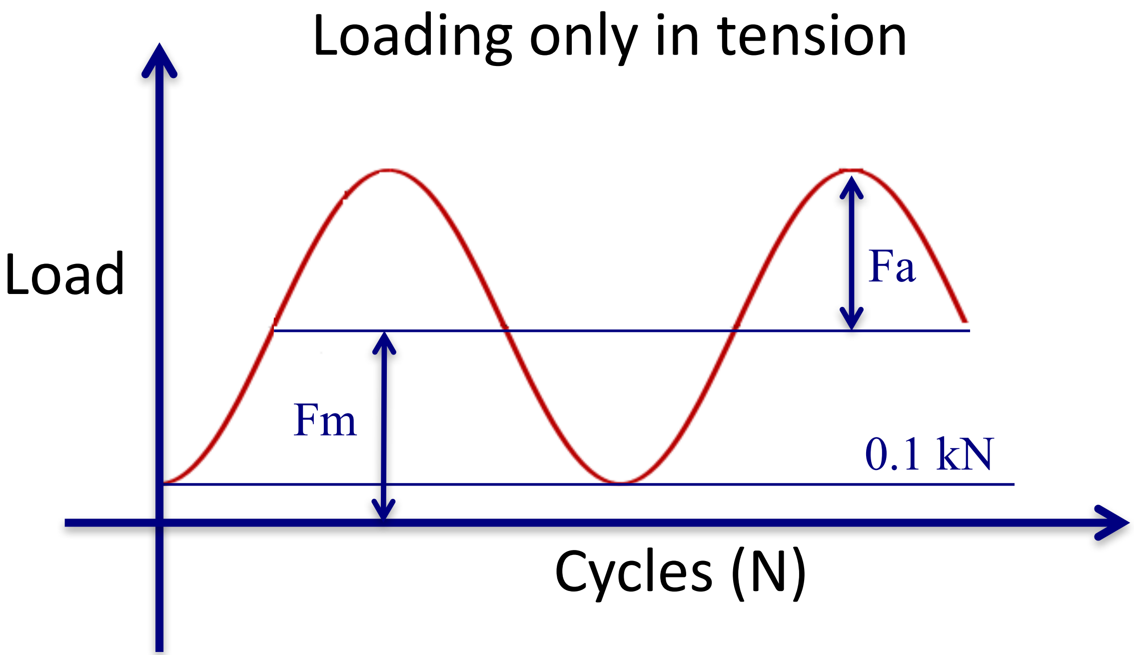
↓

1. Sintered and HIPed
2. Rolled and Annealed

Impurity elements in tungsten

Element	Typical max. value [ppm]	Guaranteed max. value [ppm]
Al	1	15
Cr	3	20
Cu	1	10
Fe	8	30
K	1	10
Mo	12	100
Ni	2	20
Si	1	20
C	6	30
H	0	5
N	1	5
O	2	20
Cd	1	5
Hg	0	1
Pb	1	5

Fatigue Testing (Stress-controlled)



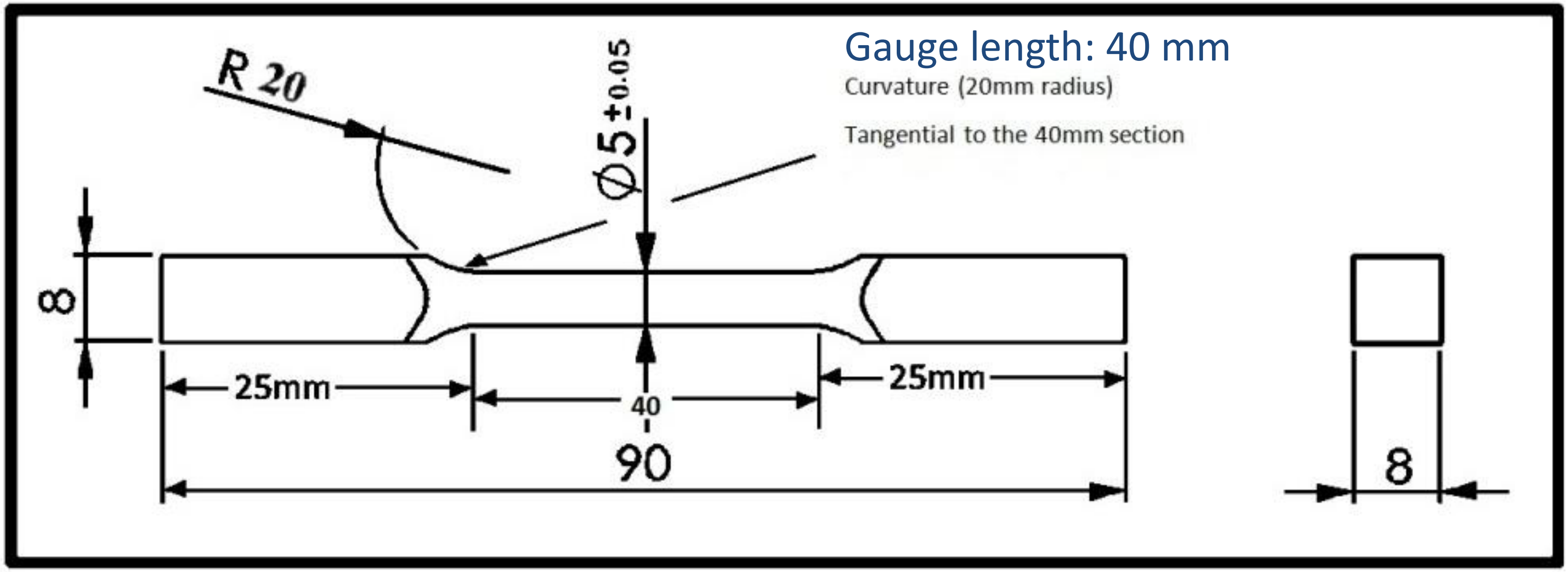
Fatigue testing with a sinusoidal load of 25 Hz.

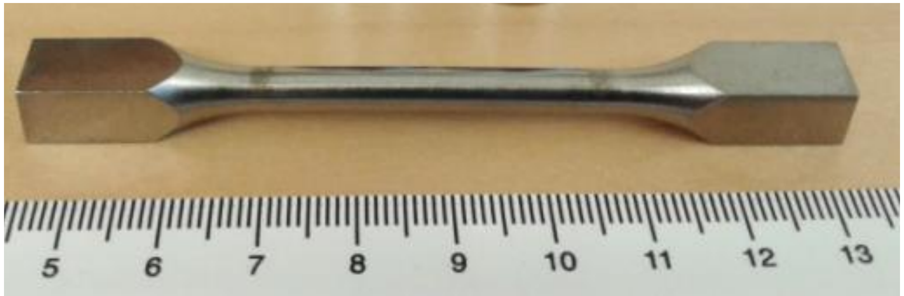
Minimum load at 0.1 kN

Runout limit = 2×10^6cycles

Up and Down method was used to find the fatigue limit, starting at ~$0.3\times$UTS

Tungsten Specimen Dimensions





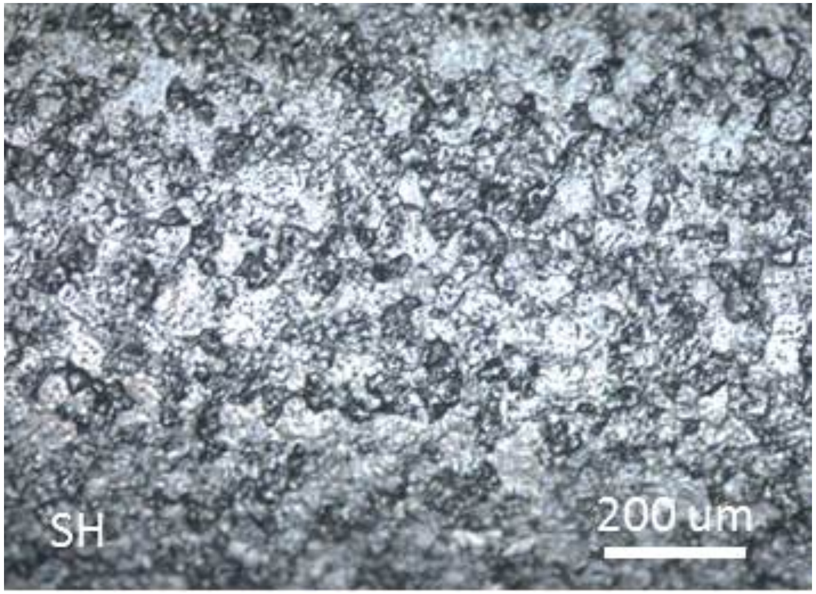
Experimental Set-up

MTS max load :250 kN, Control system: INSTRON, servo-hydraulic

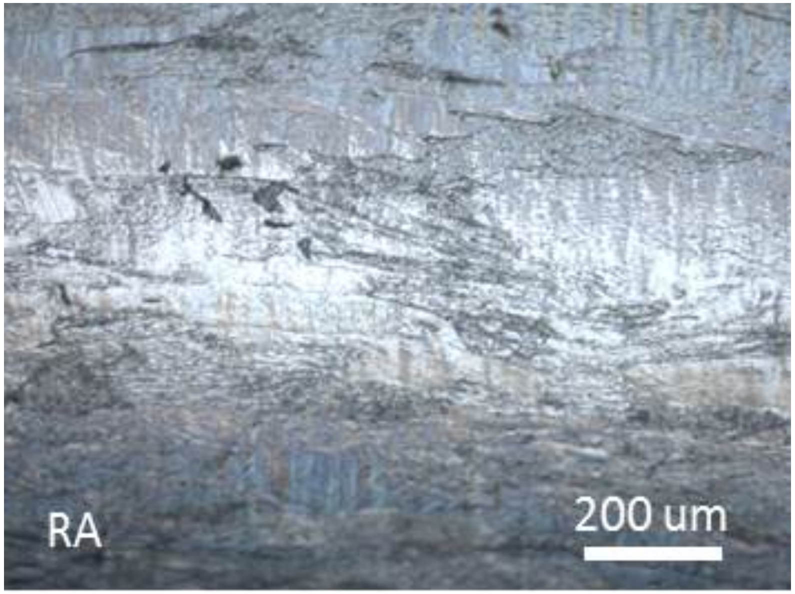
Specimen Grips

Specimen Surfaces

Sintered and Hipped

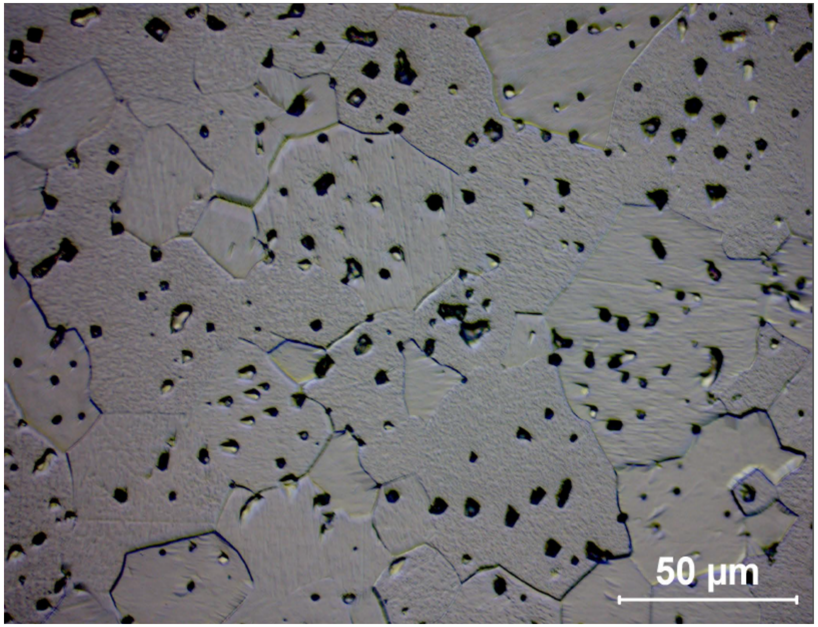


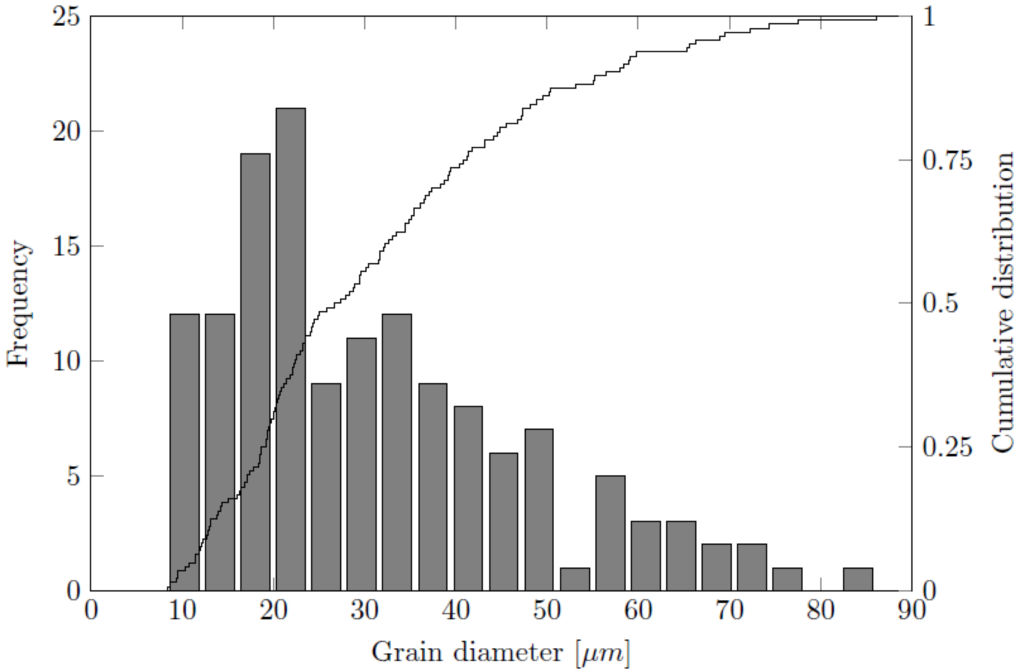
Rolled and Annealed



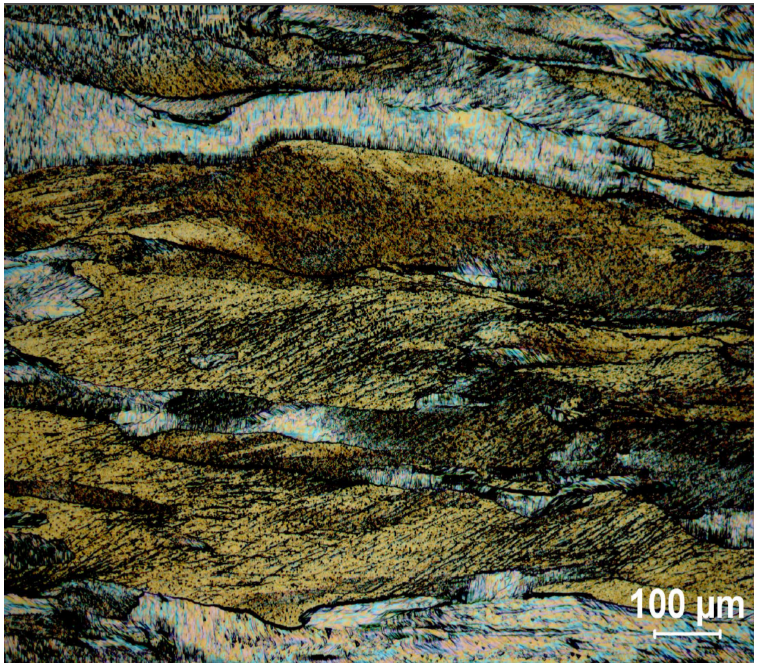
Surface roughness: 1.6μm (max.)

Grain size distribution in the Sintered and HIPed specimen

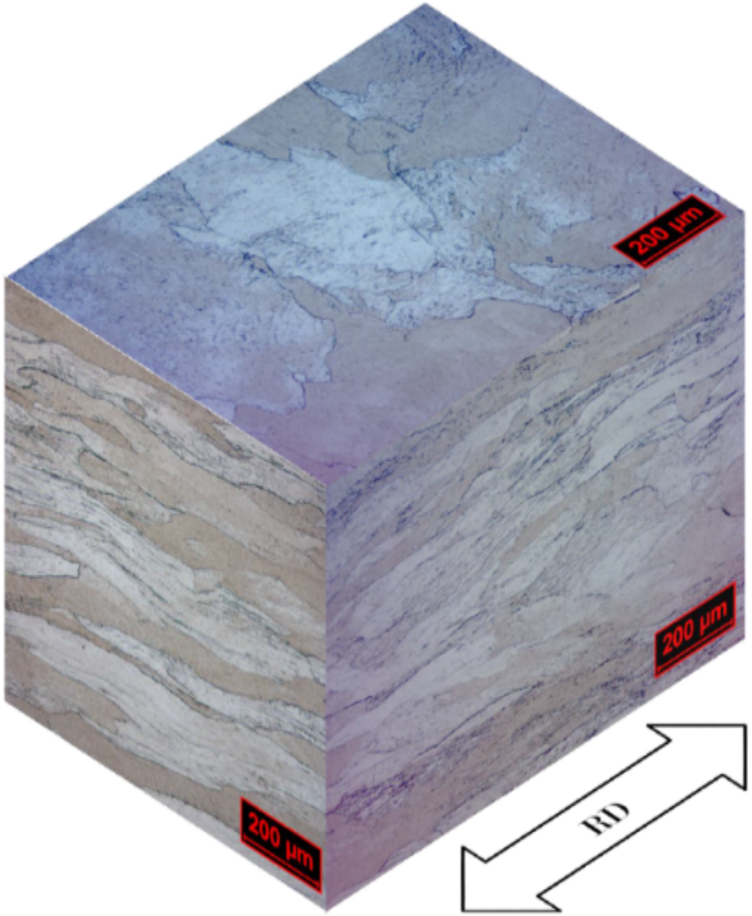




Rolled and annealed specimen



Elongated grains in the RD

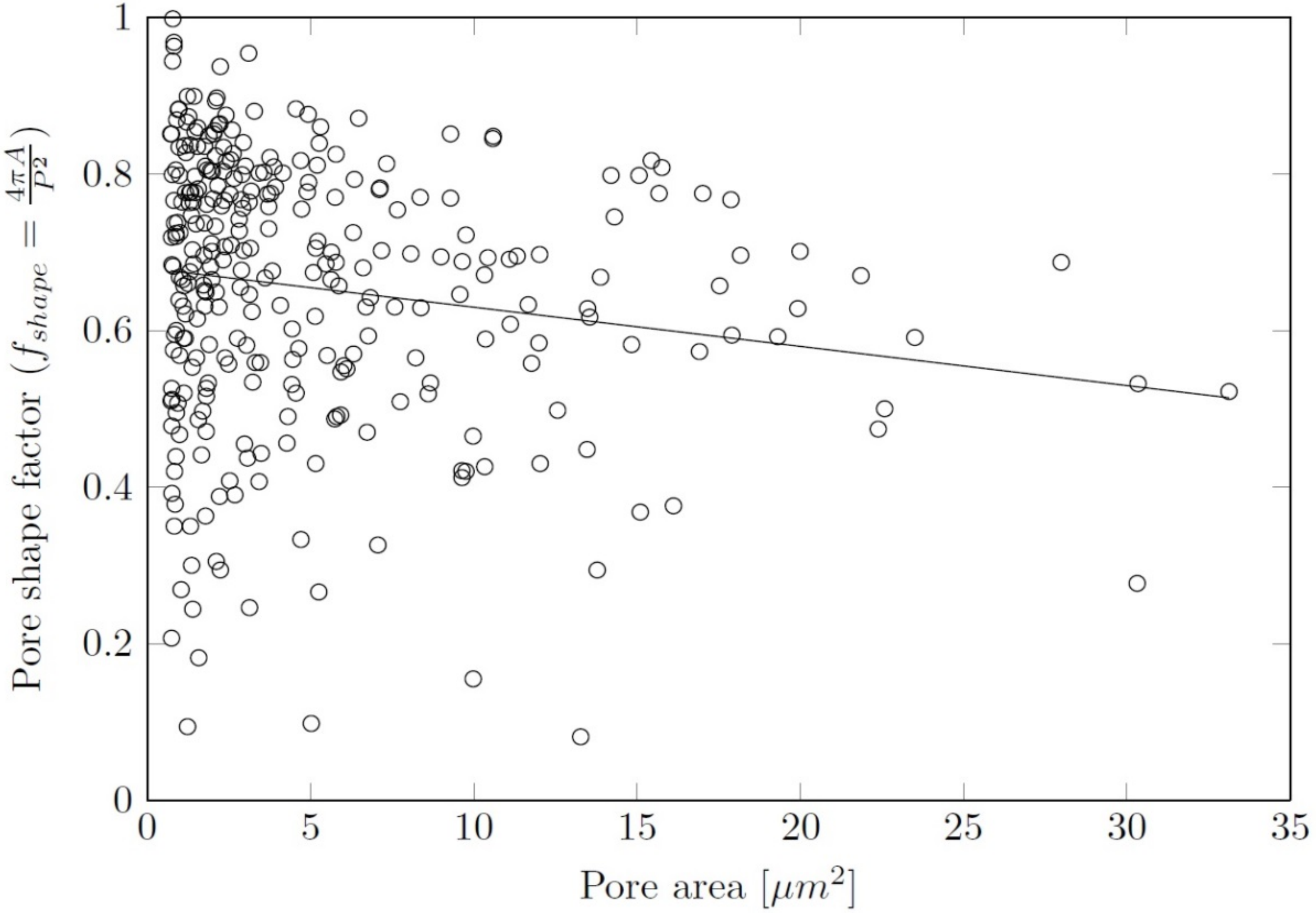


Triplanar micrograph showing the major RD

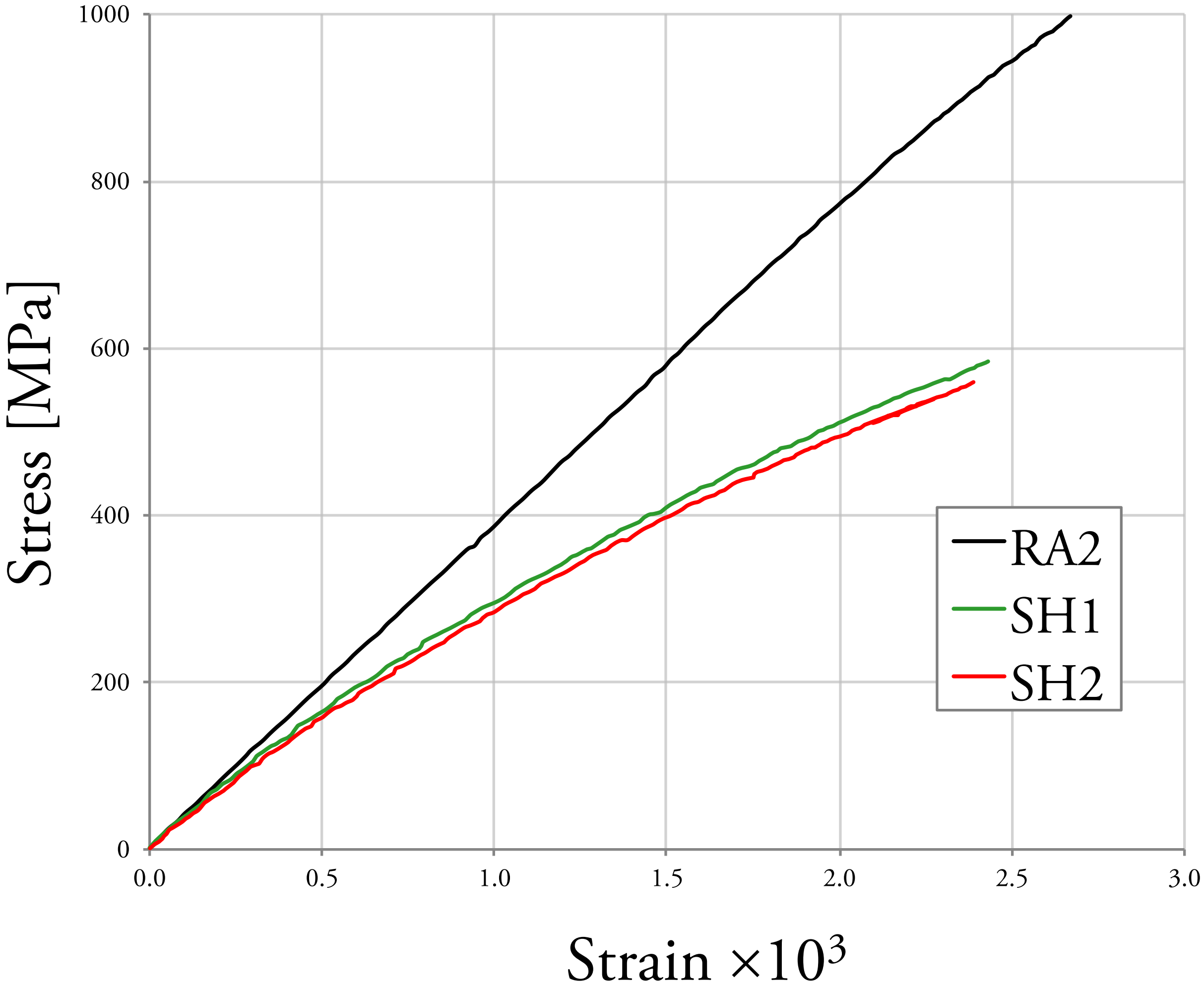
Density measurements at 20°C

Specimen	Density [Mg/m³]	Porosity [%]
SH11	18.465	4.326
RA10	19.271	0.15

Pore shape vs pore size in the sintered and HIPed specimens

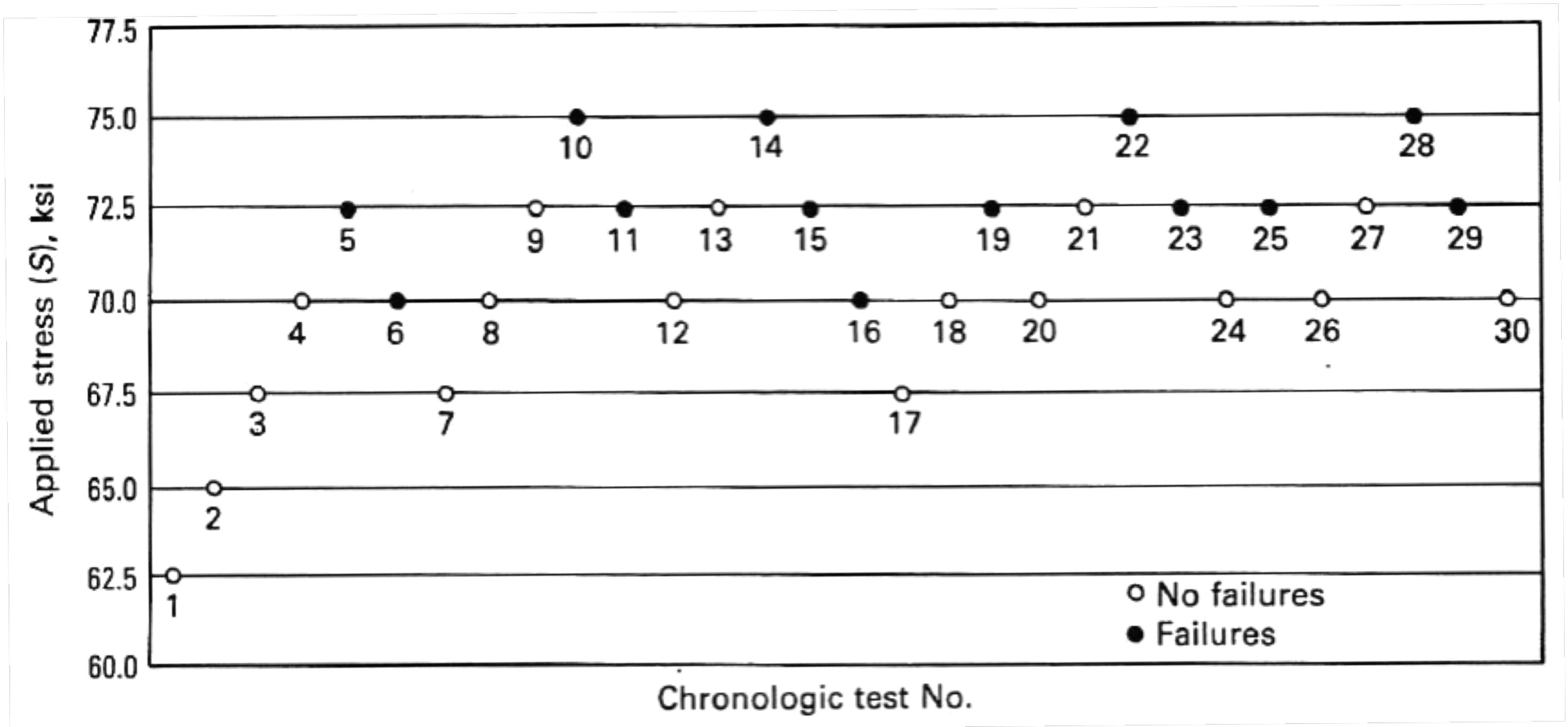


Tensile tests at room temperature

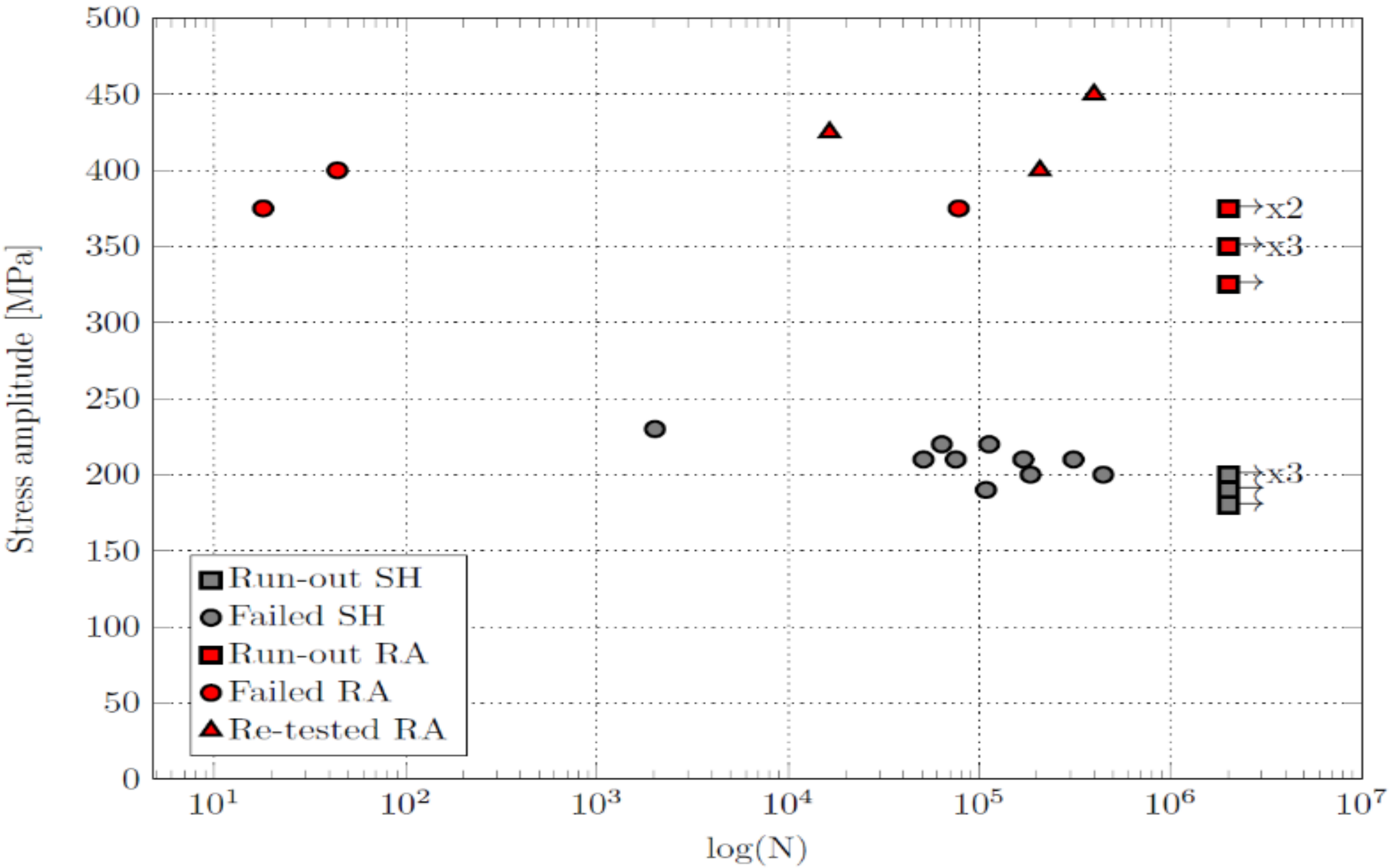


Property	SH1	SH2	RA2
Young's Modulus [GPa]	323	332	393
UTS [MPa]	560	573	998
Elastic Strain (×10⁴)	17	17	26
Plastic Strain (×10⁴)	6.9	6.65	0.877

The Up and Down method



Stress-controlled Fatigue Tests



Summary of Staircase Test Data for SH and RA specimens

Specimen	S_a [MPa]	S_{max} [MPa]	N_f (cycles)	Specimen	S_a [MPa]	S_{max} [MPa]	N_f
SH4	180	365	Runout	RA5	325	655	Runout
SH5	230	465	2013	RA7	350	705	Runout
SH6	220	445	112514	RA9	375	755	18
SH7	210	425	170053	RA10	350	705	Runout
SH8	200	405	85874	RA11	375	755	Runout
SH9	190	385	108398	RA15	400	805	44
SH10	190	385	Runout	RA16	375	755	78020
SH11	200	405	Runout	RA18	350	705	Runout
SH12	210	425	75370	RA20	375	755	Runout
SH13	200	405	Runout				
SH14	210	425	310985				
SH15	200	405	Runout				
SH16	210	425	51097				
SH17	200	405	444943				
SH18	190	385	104094	SH19	220	445	63725

Mean fatigue limit and standard deviation [MPa]

Material	S	σ
SH	185	26.4
RA	371	13.3

For SH specimens in the high cycle, low strain regime,
S_a = Stress amplitude = $376.94 \times (2N_f)^{-0.0501}$ MPa

Crack propagation in RA specimens initiated by grip indentations

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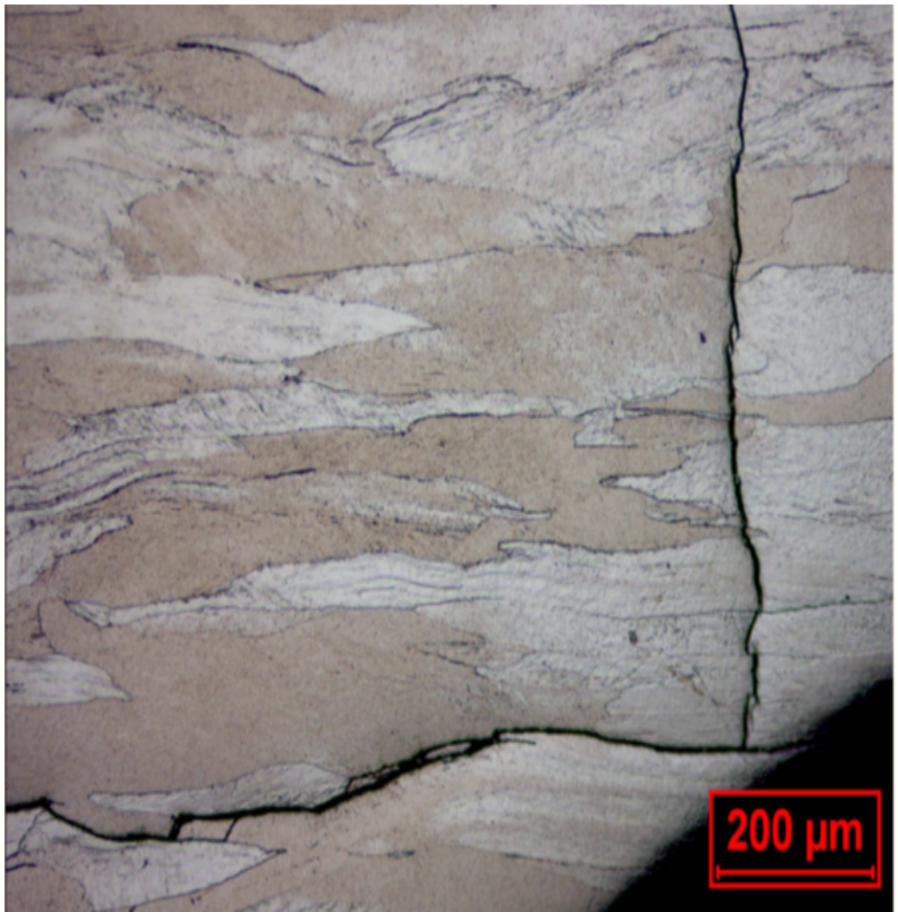
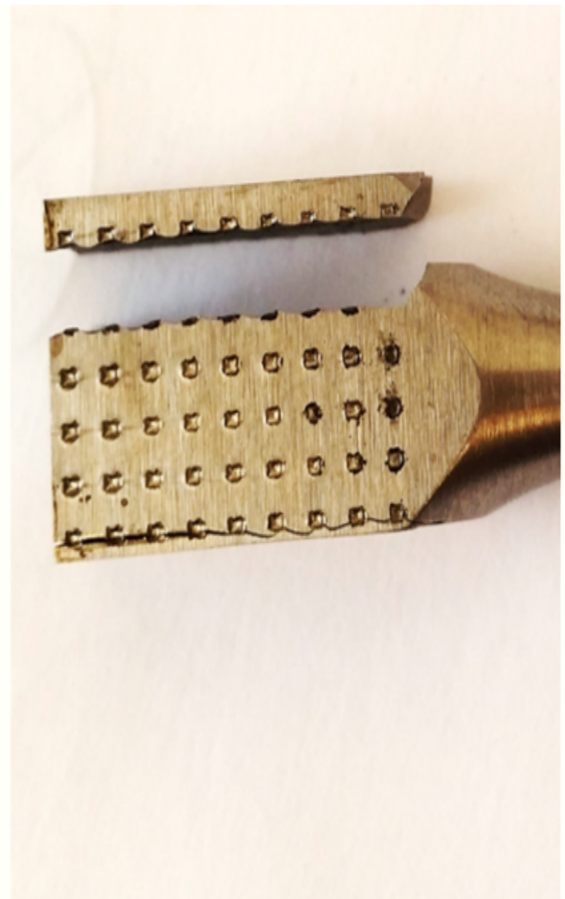
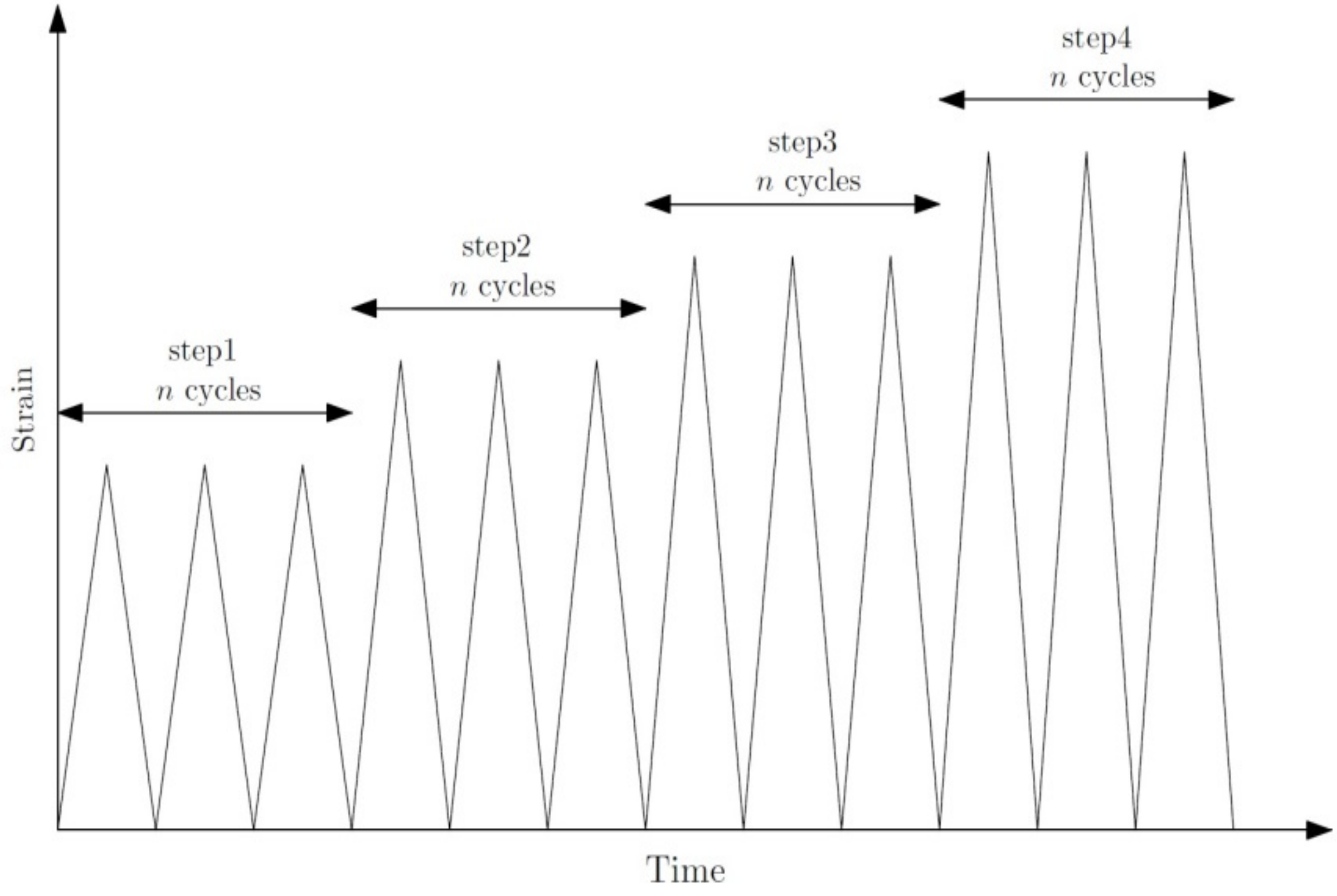
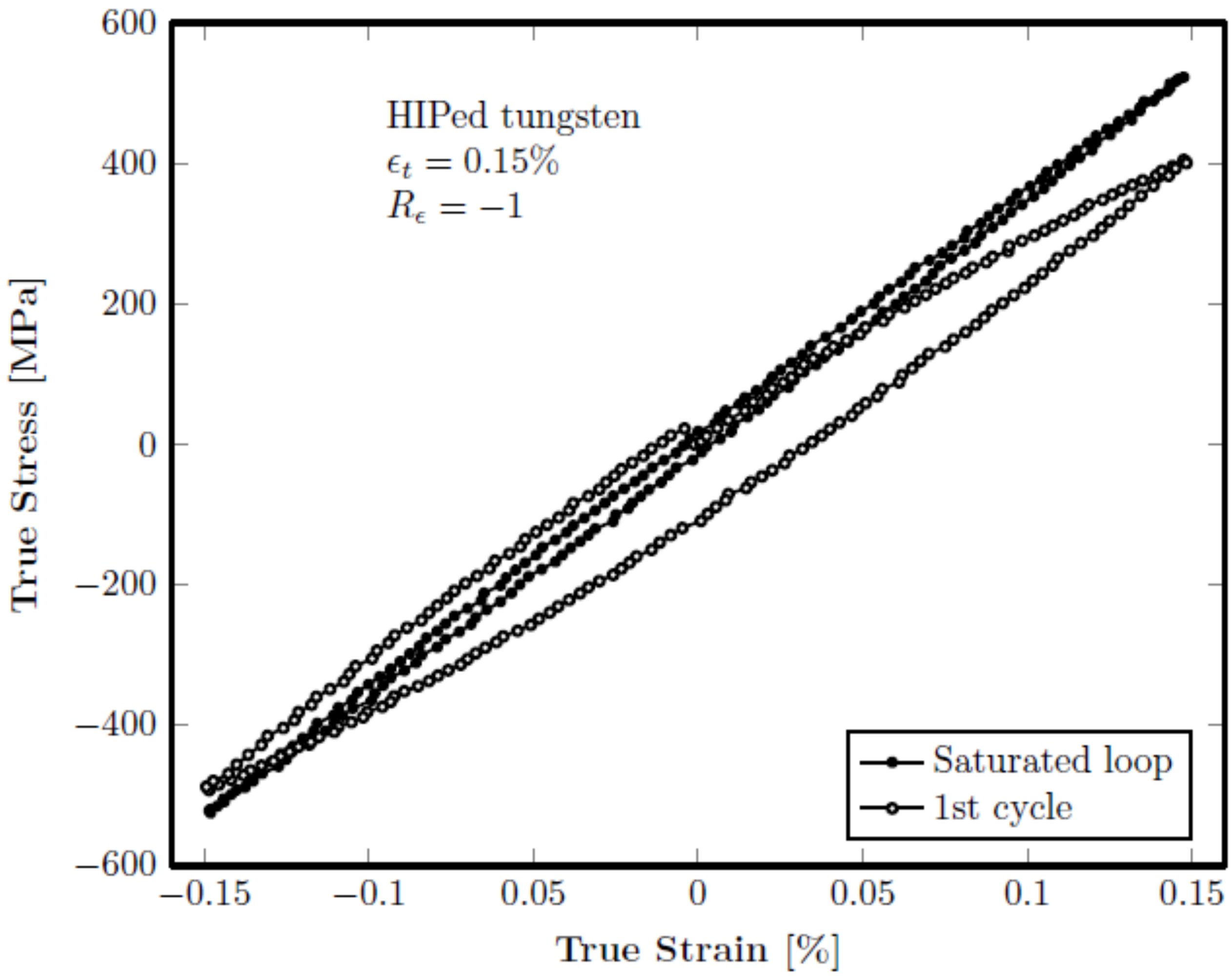




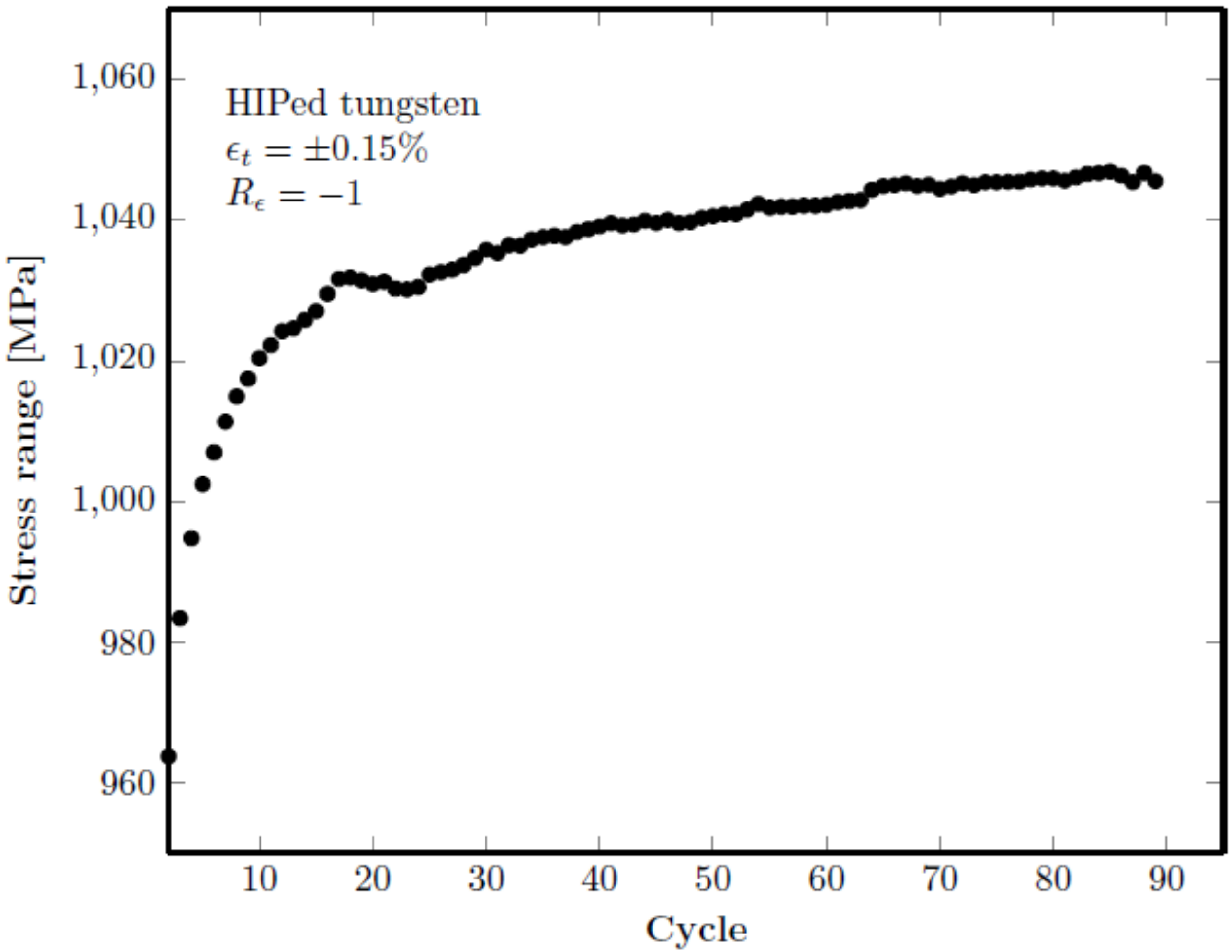
Multiple-step, strain-controlled fatigue testing



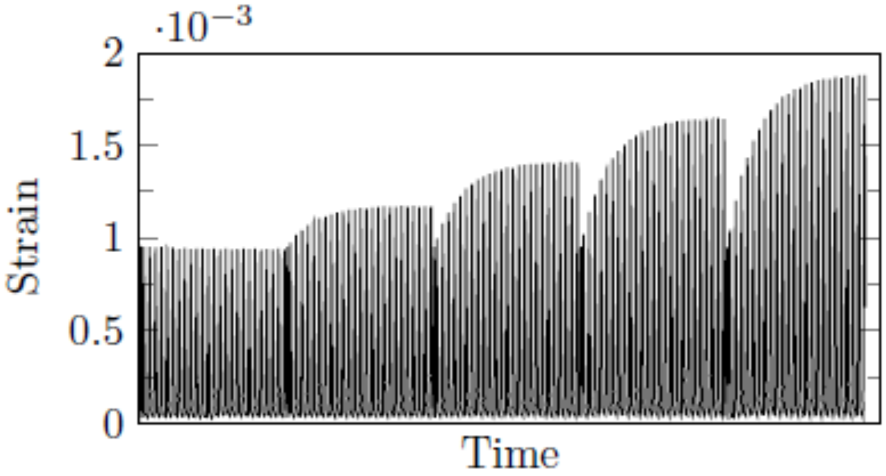
Strain-controlled fatigue testing

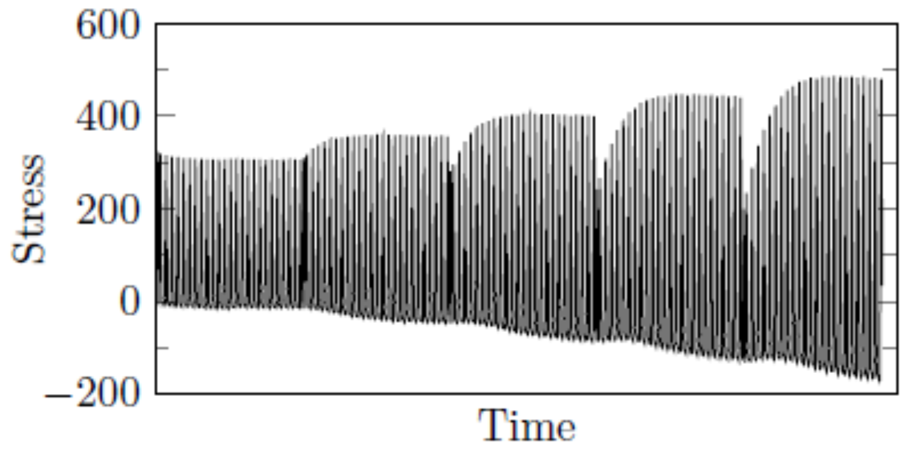


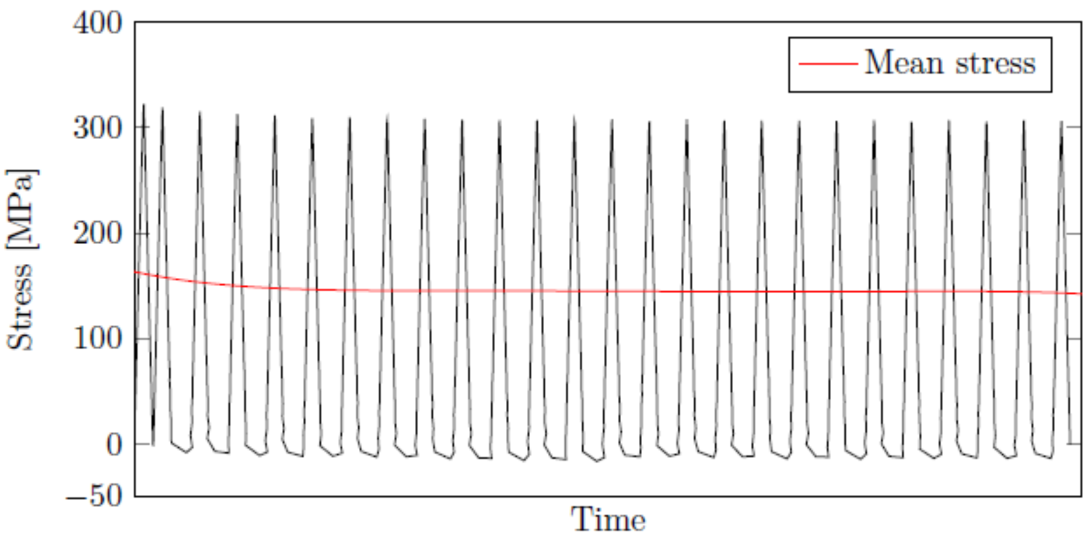
Hardening of SH Tungsten during a strain-controlled fatigue test



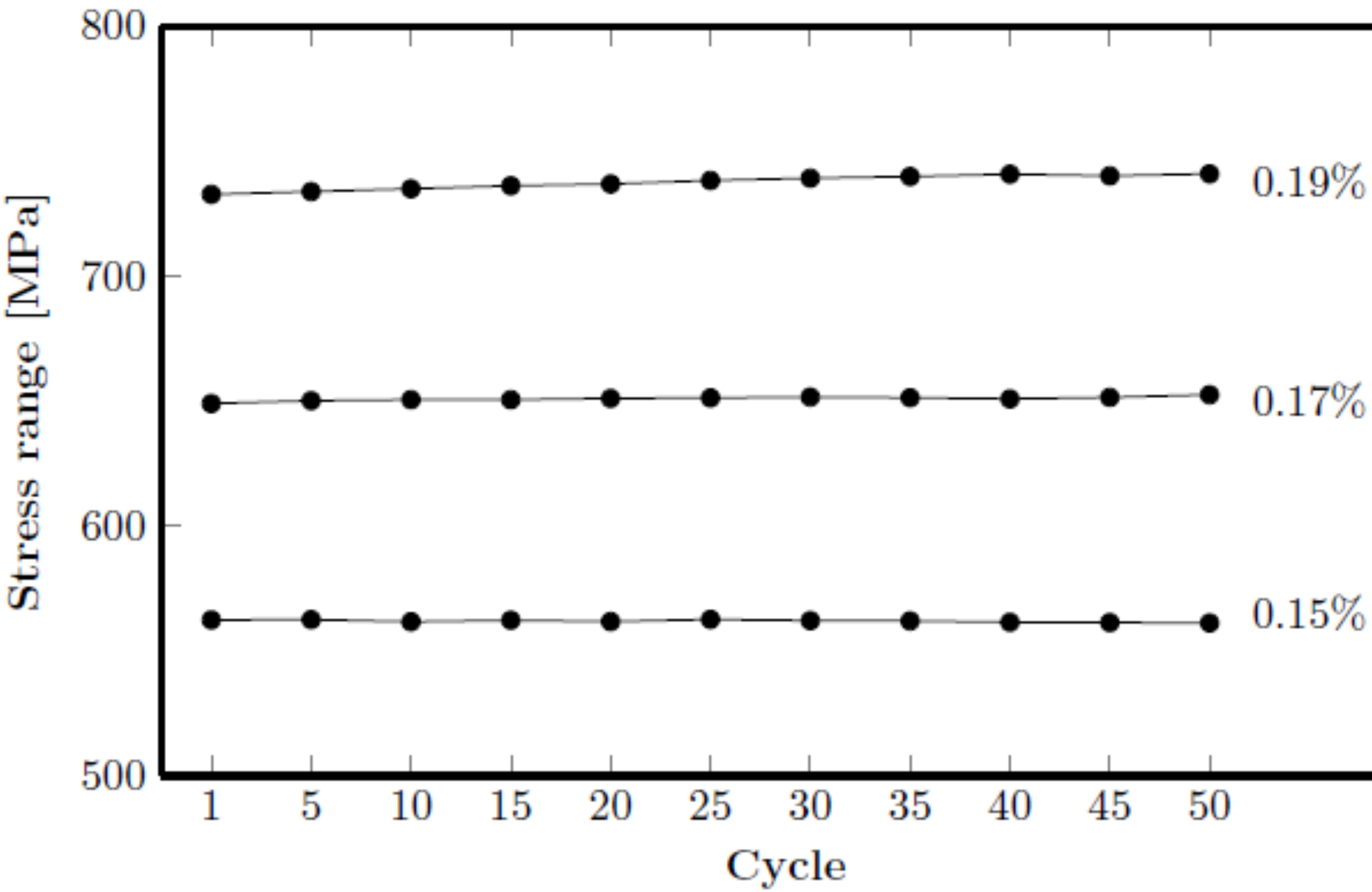
Mechanical response of a SH specimen



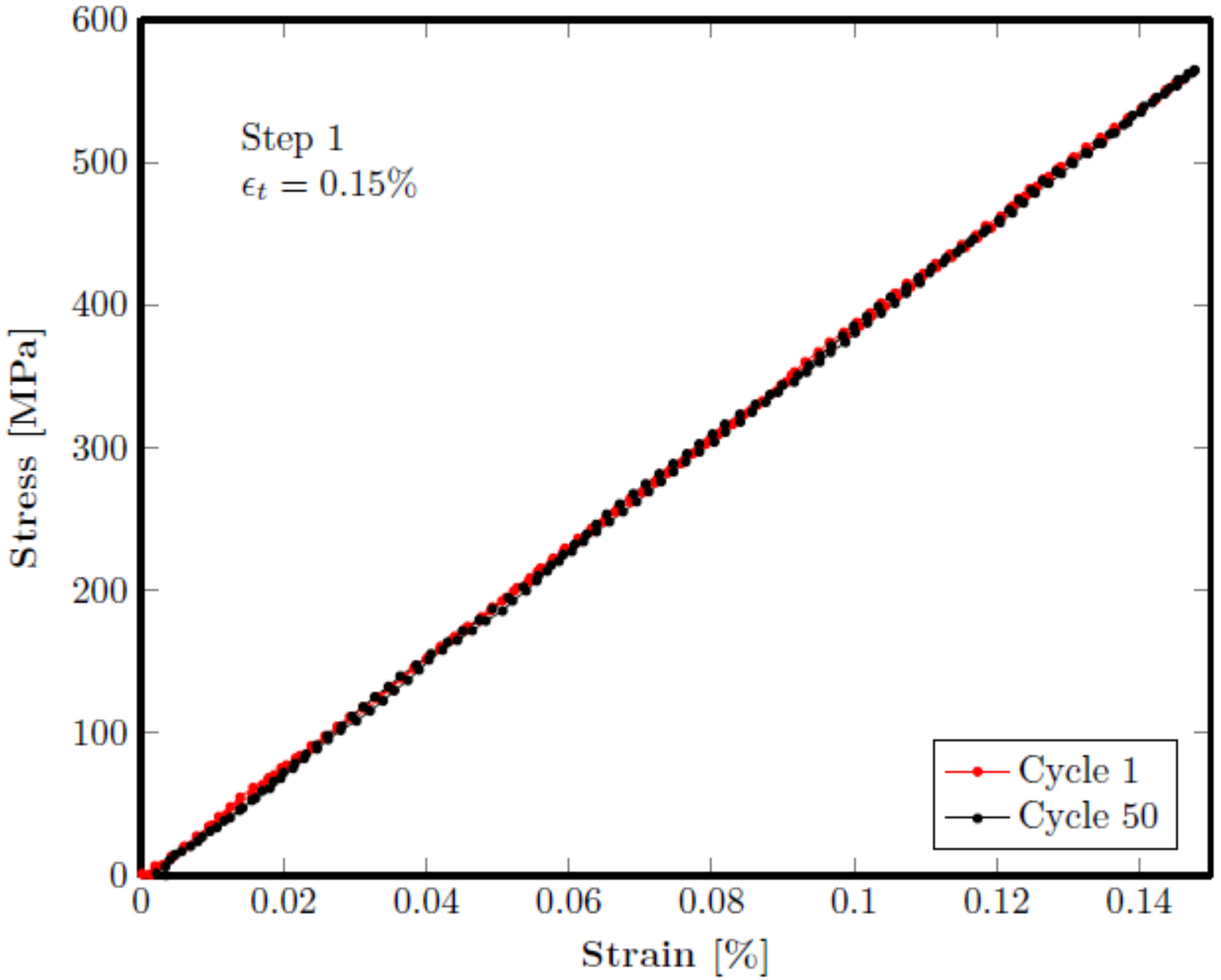




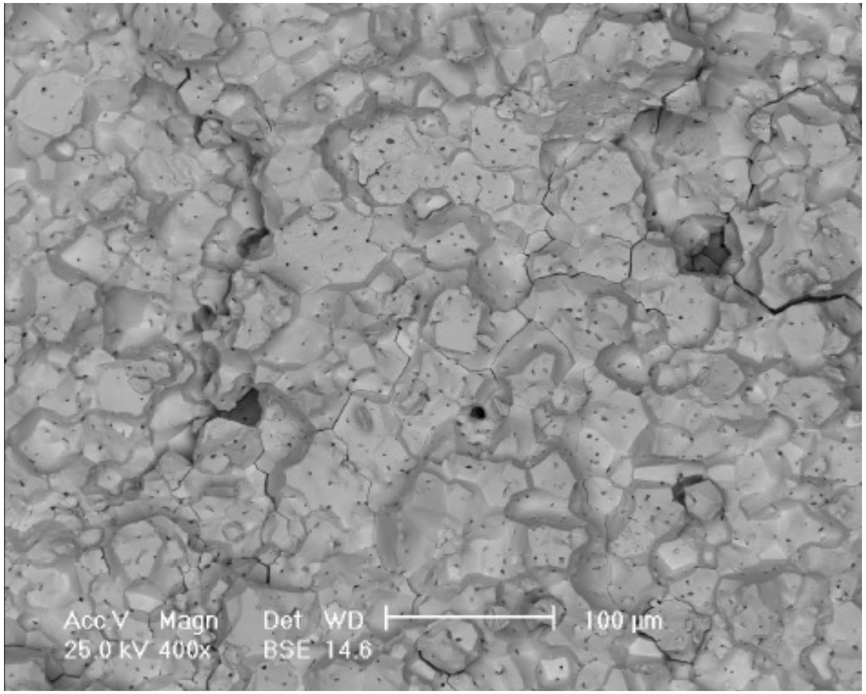
Variation of stress with cyclic strain for a RA specimen



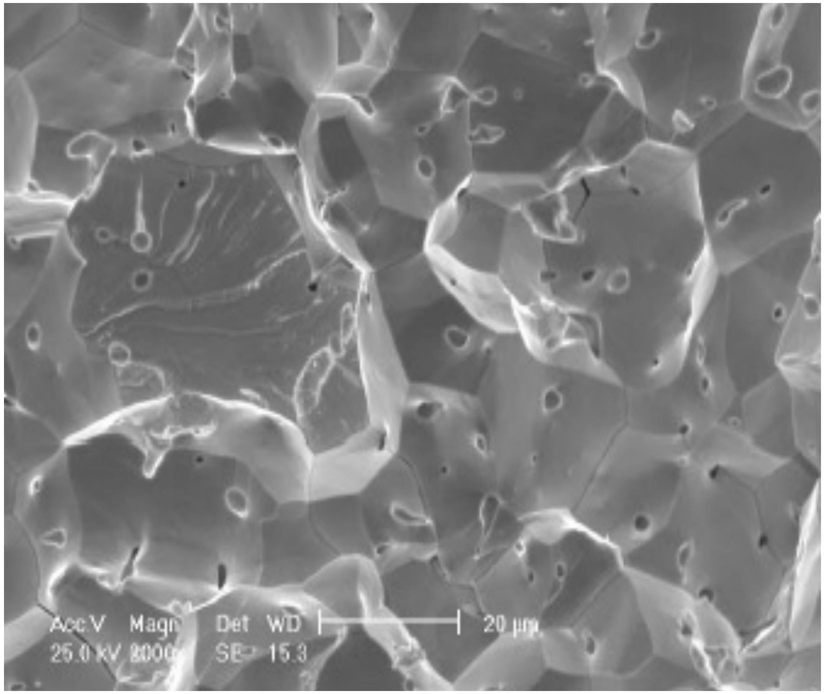
Elastic response of a RA specimen



Fracture Surfaces – SH specimens

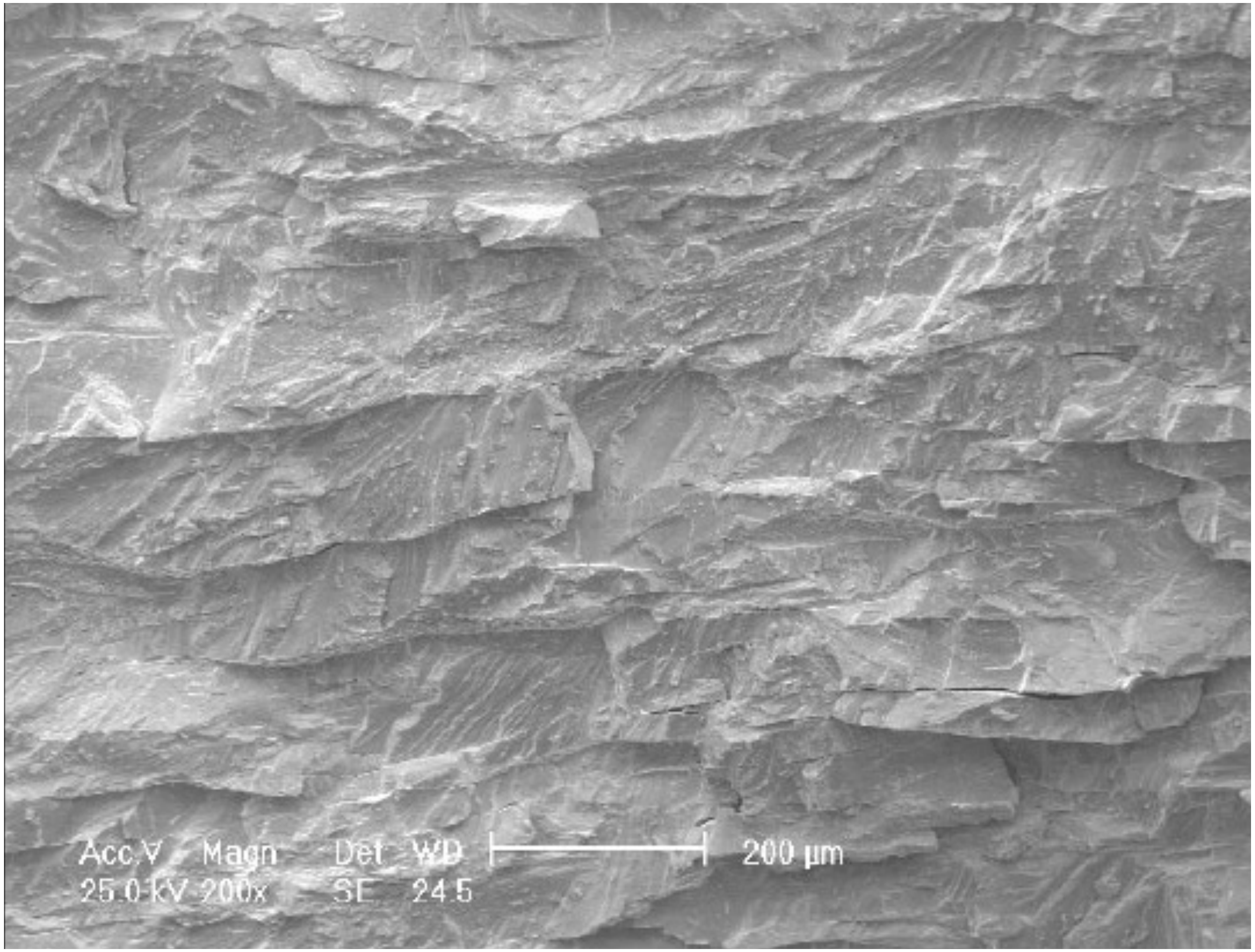


Predominantly intergranular Fracture (SH14)



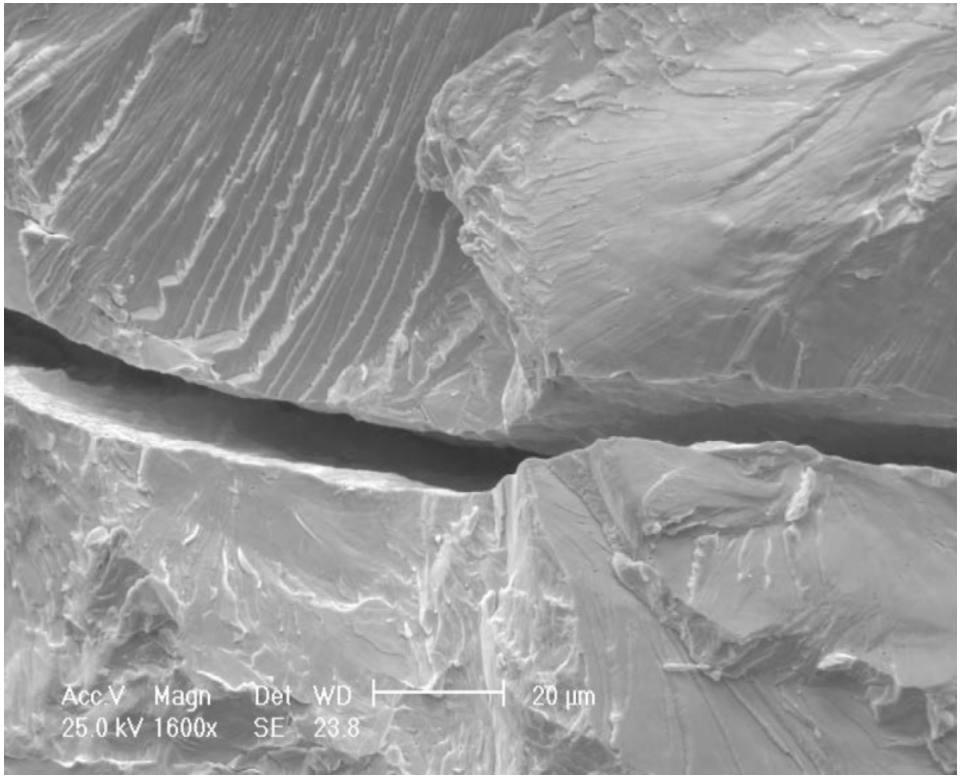
Mixed inter- and transgranular Fracture (SH2)

Brittle Fracture in RA specimens

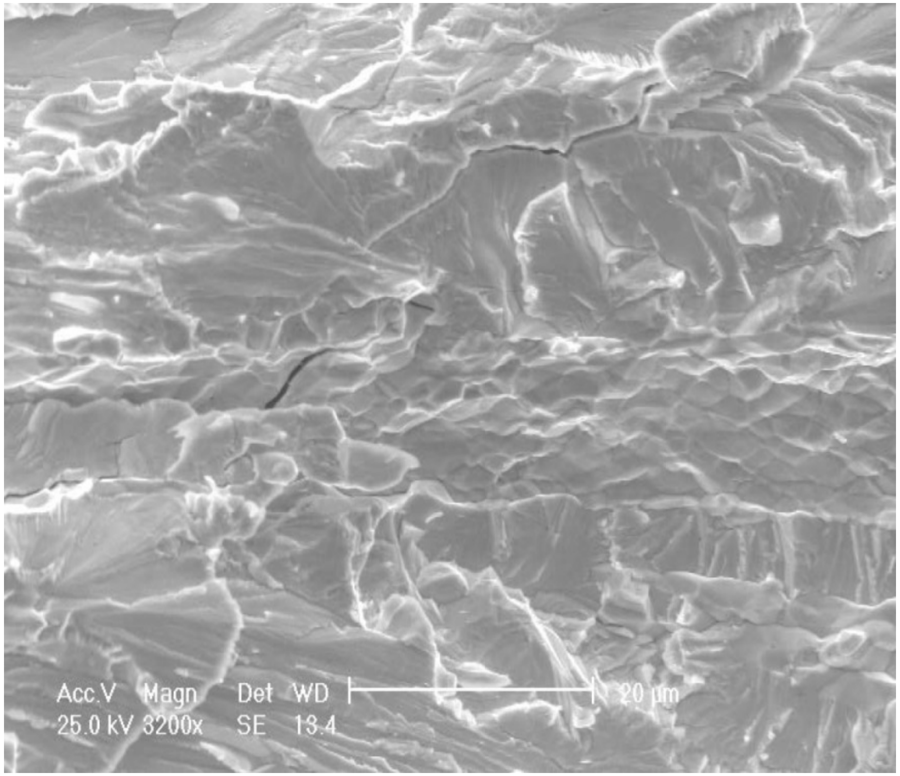


Transgranular cleavage in specimen RA10

Brittle failures in RA specimens



River lines



Intergranular subgrain fracture

Surface Condition

- A smooth specimen surface is usually associated with better fatigue properties.
- However, compressive stresses at the surface are important and suppress crack propagation during cyclic loading.
- ESS-Bilbao’s study (September 2016) confirms that W-specimens with high compressive residual stresses (250-1000 MPa) showed good tensile properties.
- This is supported by the present study in which electropolished tungsten specimens showed lower fatigue limits relative to the unpolished specimens.

Current Work and Target Operating Conditions

- Stress amplitudes in this study are much larger than those induced by the beam pulse
- Correspond better to the beam trips associated with stress amplitudes of about 110 MPa.
- However, it’s worrying that the UTS of irradiated tungsten could be as low as 60 MPa (I. V. Gorynin et al, J. Nucl.Mater., 191-194 (1992) 421-425).
- Tungsten Target with Ta-cladding at ISIS operates at a maximum stress of 202 MPa (P. Loveridge and D. Wilcox, 5th High Power Targetry Workshop, Fermilab, May 2014).

Summary

Sintered & HIPed

- 180 MPa fatigue strength,
- Grain size 10-85 μm, average ~30 μm
- ~4% porosity
- The pores are small, round and uniformly distributed. Larger pores have an irregular shape.
- Mean stress relaxation (zero strain ratio)
- Low scatter
- Predominantly intergranular fracture

Summary

Rolled & Annealed

- Large interlocking ”pancake” shaped grains
- Near full density
- High fatigue limit (350 MPa)
- High tensile strength (998 MPa)
- Very low levels of plasticity
- Vickers microhardness → $508VHN_{0.4}$
- Not suitable for serrated wedge grips due to brittleness
- Pure transgranular cleavage
- Subgrains contribute to intergranular fracture.