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CONTRACT N°

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HTR-M1 Report on results of heavily carburised U720 Turbine Disk material

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Dissemination level: CO
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Project	**HTR-M1**
Project number	
Contract number	
Customer	
Subject	**heavily carburized U720 disk material**
Test type	**strain-controlled LCF**
Unit	**HFR-SFM**
Operator	**S. Ripplinger**
Start Date	**November 2005**
Authors	**S. Ripplinger, H. Rantala & P. Hähner**

HTR-M1:
Low-Cycle Fatigue Tests

The present report summarizes the results of the Low-Cycle Fatigue (LCF) tests performed on the turbine disk material Udimet 720 which has been pretreated to achieve a heavily carburized state, in order to assess the effect of a specific HTR environment. The results are compared to the LCF performance in the as-received state.

Material:

The material Udimet 720 stems from a forged pancake (certificate no. HY540203), which CEA had received from Aubert&Duval. One half of the pancake disk (diameter 320mm, height 80mm) was sent to JRC-IE in the as received state (cast& wrought, forged and fully heat treated for service), henceforth referred to as State I, for specimen machining and further carburization treatment. This treatment was carried out at JRC-IE on six fully machined LCF specimens by exposing them for 1000h at 950ºC to a 1.6 bar absolute Argon+2%CH4 atmosphere. This gives rise to a heavily carburized material state, henceforth called State III. Two specimens were left in the as-received State I for reference tests and temperature profile calibration.

The mechanical tests described below belong to a comprehensive test campaign performed at CEA and JRC, where four material states of U720 forged are compared, namely

State I:	fully heat-treated for service
State Imod:	additional ageing heat treatment in air: 1000h at 950°C
State II:	entirely decarburized in Ar + 500µbar H2 + 50µbar H2O
State III:	heavily carburized in 1.6 bar Argon+2%CH4: 1000h at 950ºC

Due to the fact that the carburization treatment had led to pitting corrosion visible at low magnification on the specimen surface, it was decided to re-polish three specimens according to ASTM E606-92, while leaving the other three specimens in the as exposed state.

Experimental:

All LCF tests were conducted on a digitally controlled electro-mechanical test rig (Instron 8862) at a temperature of 650°C. The heating was achieved by induction (Cheltenham). Within the gauge length of 8mm, temperature was maintained within +/- 2°C by controlling the temperature by a Type N thermocouple, which was spot-welded 6mm below the specimen centre (i.e. 2mm outside the gauge length), but still within the parallel length. For the purpose of the present test series, the extensometer had been re-calibrated to Class1, and the load train misalignment had been verified to be less than 3% bending percentage by the use of a strain-gauged alignment specimen.

The actual specimen diameters and actual gauge lengths of the Sandner clip-on extensometers were determined individually to 10µm accuracy (3 repeat measurements). Room temperature Young's moduli were measured on two opposite specimen sides to check the appropriate specimen mounting and the extensometry. Young's modulus and yield stress ($R_{p0.2\%}$) at 650°C were determined from the first cycle of the LCF test.

All LCF tests were performed in total strain control, using triangular strain waveforms, a strain ratio of R_ε = 0.05 (always tension), and different maximum strain values of 0.6%, 0.7%, 0.8%, and 1.0%. The cycle period varied as to maintain a constant strain rate of +/- 0.1%/s for all tests. The tests were conducted to 15% drop of maximum load or failure or N ~ 45,000 (termination), whatever occurred first.

Test matrix

Specimen id.	state	T (°C)	de/dt (10^{-3}/s)	t_{cycle} (s)	e_{max} (%)	e_{min} (%)
U1	**III**	**650**	**1**	**19.0**	**1.0**	**0.05**
U2	**III**	**650**	**1**	**13.3**	**0.7**	**0.035**
U3 (polished)	**III**	**650**	**1**	**15.2**	**0.8**	**0.04**
U4 (dummy)	**I**	**Temperature profile calibration**				
U5	**III**	**650**	**1**	**11.4**	**0.6**	**0.03**
U6 (polished)	**III**	**650**	**1**	**19.0**	**1.0**	**0.05**
U7 (polished)	**III**	**650**	**1**	**13.3**	**0.7**	**0.035**
U8	**I**	**650**	**1**	**19.0**	**1.0**	**0.05**

Table 1: Test parameters

Results

Table 2 summarizes the main results. One specimen was lost due to a power trip leading to specimen failure by thermal contraction. The other tests are considered valid with fatigue cracking occurring within the parallel length, noting, however, that one specimen (U8) failed close to, but not immediately at, the thermocouple spot-weld, where the temperature was about 4°C lower. All other specimens failed within the gauge length, where the temperature deviation was less than 3°C.

It is obvious from Table 2 and Figures 1 and 2 that the carburization treatment has detrimental effects on the yield strength (σ_y = 910 MPa for State I, whereas $\sigma_y \cong$ 650 MPa for State III), as well as on the LCF performance, in particular, as regards the regime of high strain ranges and low numbers of cycles to failure. For a given strain range of 0.95% (i.e. max. strain 1%), the State I material bears significantly larger stress ranges while LCF lives are still longer. This observation holds irrespective of the surface quality (corrosion pitted, Fig. 2, or re-polished, Fig. 1).

	LCF condition		1st cycle		Test end		Nf/2				
Spec. id	e_{max} **(%)**	e_{min} **(%)**	**E (650°C) (Gpa)**	**Rp0.2% (650°C) (Mpa)**	N_f	**Terminated by**	s_{max} **(Mpa)**	s_{min} **(Mpa)**	De_{tot} **(%)**	De_{pl} **(%)**	De_{el} **(%)**
U1	1.0	0.05	174.5	648	647	brittle fracture inside GL	726.4	-675.7	0.950	0.157	0.804
U2	0.7	0.035	169.3	652	3353	brittle fracture inside GL	696.3	-399.1	0.665	0.024	0.647
U3	0.8	0.04	Specimen went out of control due to general power failure in North Holland								
U5	0.6	0.03	169.5	640	44694	Stopped by operator	638.9	-289.8	0.570	0.024	0.549
U6	1.0	0.05	170.1	650	618	15% load drop crack inside GL	731.6	-651.9	0.953	0.147	0.813
U7	0.7	0.035	168.1	628	45549	Stopped by operator	673.1	-410.9	0.664	0.029	0.64
U8	1.0	0.05	169.1	910	3392	15% load drop crack outside GL	936.3	568.3	0.953	0.068	0.890

Table 2: Overview of test results

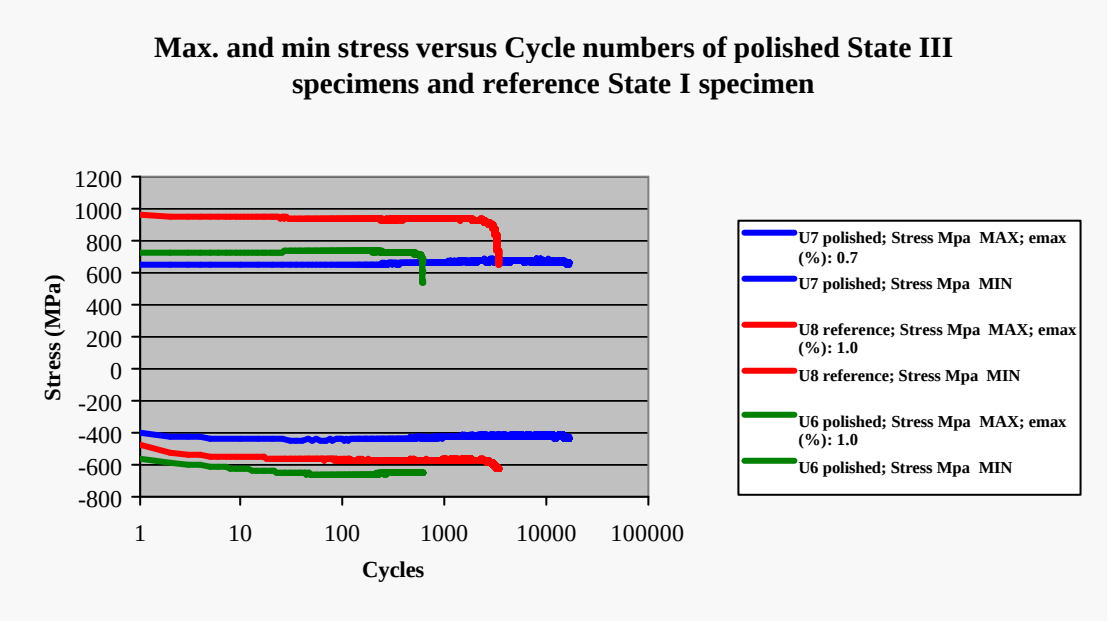


Fig. 1: Cyclic stress maxima and minima of polished State III (ε_{max} = 0.7% and 1.0%) as compared to reference State I (ε_{max} = 1.0%)

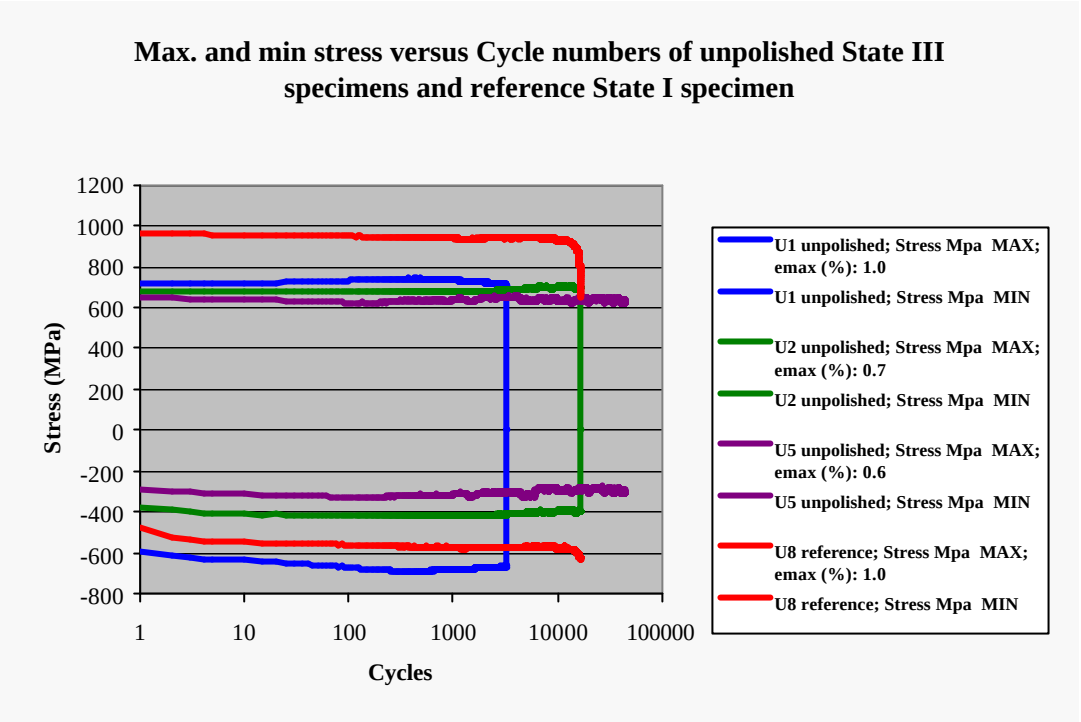


Fig. 2: Cyclic stress maxima and minima of unpolished State III (ε_{max} = 0.7% and 1.0%) as compared to reference State I (ε_{max} = 1.0%)

For a more comprehensive picture, previous LCF results obtained for State I at CEA (ref: HTR-M Deliverable 2.10, Rapport Technique DTEN/DL/2005/013 by R. Couturier et al.) can be taken into account, cf Figures 3 and 4. To justify the comparability of results, one State I specimen was LCF tested using ε_{max} = 1%. In terms of fatigue life and cyclic response, the result fits convincingly into the CEA series of results.

Using the CEA reference, it is concluded that the numbers of cycles to failure are less by a factor of about 5 for State III as compared to State I, if maximum strains ε_{max} > 0.7% are considered. For these conditions re-polishing of the carburized testpieces has little effect, as fatigue lives tend to be bulk controlled. However, surface finish does matter for the lowest max. strain values, since fatigue crack initiation starts from surface defects, such as corrosion pits.

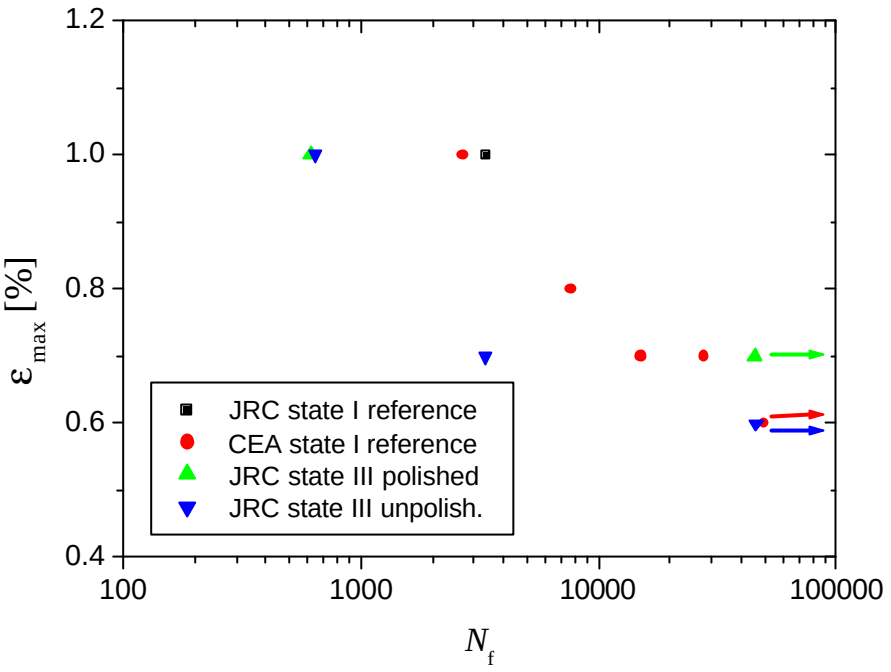


Fig. 3: Maximum total strain versus number of cycles to failure, incl. CEA results for reference State I
(HTR-M Deliverable 2.10, Rapport Technique DTEN/DL/2005/013 by R. Couturier et al.)

If the plastic strain ranges at midlife ($N_f/2$) are plotted vs. N_f, one notes that the State III material can accommodate much larger plastic strains and still survive for more than 45000 cycles, as compared to State I. This holds for the lowest max. strain values and, in particular, the polished State III.

Conclusions

- Carburization results in 30% drop of yield strength.
- Carburization results in up to five times shorter LCF lives albeit stress ranges are lower.

Further microstructural analysis is needed to

- assess the fracture mode (optical microscopy),
- determine the penetration depth of carburization treatment (SEM),
- clarify the role of persistent slip bands in fatigue crack initiation and failure (TEM).

Morover, additional LCF tests on the decarburized condition are desirable to arrive at a comprehensive understanding.

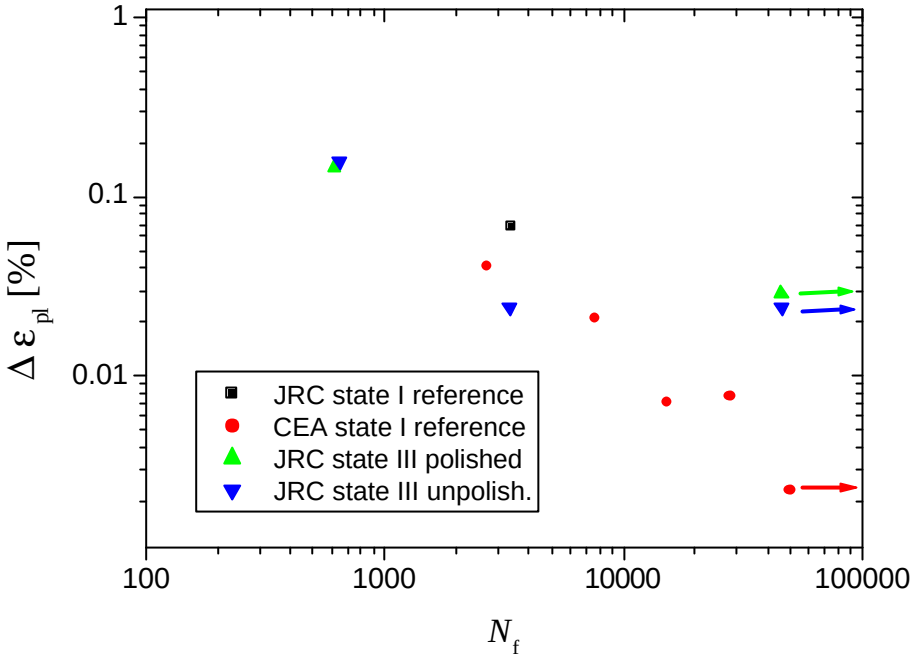
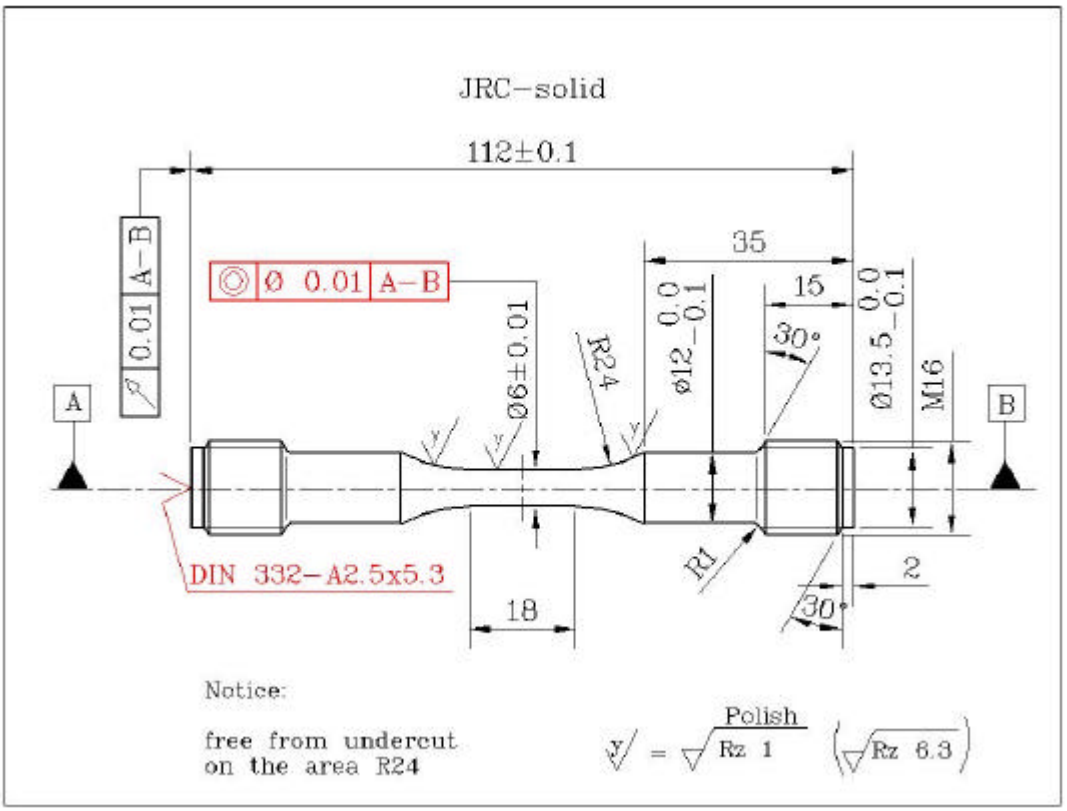


Fig. 4: Plastic strain range versus number of cycles to failure, incl. CEA results for reference State I
(HTR-M Deliverable 2.10, Rapport Technique DTEN/DL/2005/013 by R. Couturier et al.)

Specimen Information

GL diameter	**=**	**~6**	**mm**
area A	**=**	**~28.27**	**mm^2**
position TC	**=**	**- 6**	**mm**
parallel length	**=**	**18**	**mm**
material	**=**	**Udimet 720**	



Common Test data

Test Type	**LCF in total strain control mode**

Project	**HTR-M1**
Contract number	
Project number	
Project year	**2005**
Description	
Unit	**HFR-SFM**
Action Type	**Competitive**
Specimens produced by	**Material rec'd from CEA, specimens machined at IE**
Project leader	**N. Taylor / P Hähner (task leader)**
Operator	**S. Ripplinger**
Tel:	**+31-224-565432**
Fax:	
E-mail	**stefan.ripplinger@jrc.nl**
Test Rig	**Instron III**
Used heating system	**Cheltenham induction 6kW, 120 kHz**
Cooling (water)	**Extra water cooling plates top and bottom specimen**
Cooling (Air)	**no**
Mounting of specimen	**With M16 standard grip plates**

Used TMF control and data-logging program

Data control Instron II	**MAX**
Data logging Instron II	**MAX**

Calibration Results

Cal. Extensometer	**50 m/V calibrated 21/10/2005; class 1**
Alignment of load train	b_{maxs} **= < 3%; 03/06/2005**

Test matrix

Specimen id.	state	T (°C)	de/dt (10^{-3}/s)	t_{cycle} (s)	e_{max} (%)	e_{min} (%)
U1	**III**	**650**	**1**	**19.0**	**1.0**	**0.05**
U2	**III**	**650**	**1**	**13.3**	**0.7**	**0.035**
U3 (polished)	**III**	**650**	**1**	**15.2**	**0.8**	**0.04**
U4 (dummy)	**I**	**Temperature profile calibration**				
U5	**III**	**650**	**1**	**11.4**	**0.6**	**0.03**
U6 (polished)	**III**	**650**	**1**	**19.0**	**1.0**	**0.05**
U7 (polished)	**III**	**650**	**1**	**13.3**	**0.7**	**0.035**
U8	**I**	**650**	**1**	**19.0**	**1.0**	**0.05**

Test-end criteria:

- After 15% drop of maximum load or N = 50.000

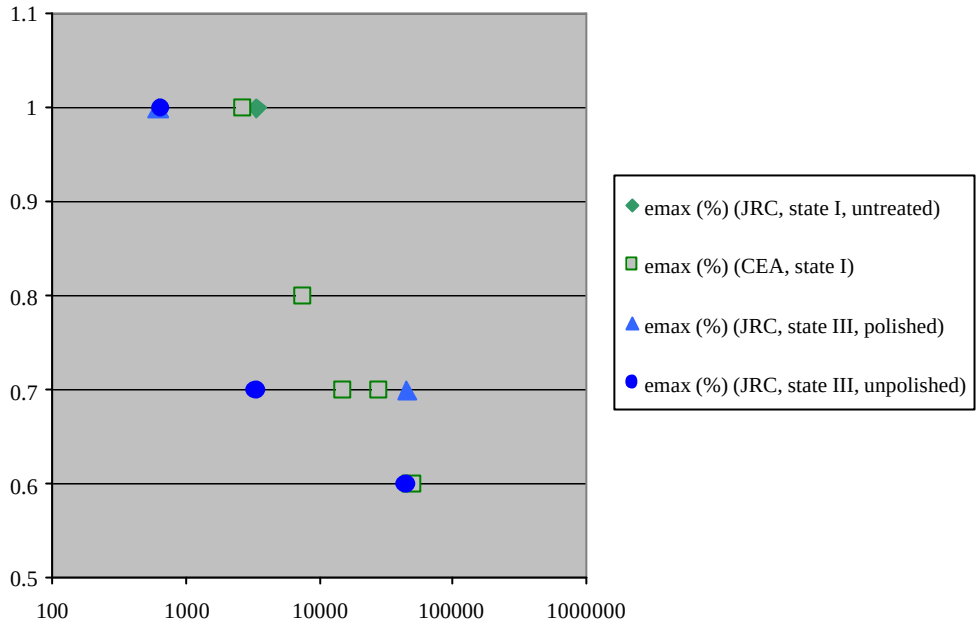
Calibration of temperature profile (Specimen U4):

Control TC middle of gauge length	TC +4 mm	TC –4 mm	TC –6 mm
651 °C	647°C	647°C	648°C

Control TC TC –6 mm	TC + 4 mm	TC middle of gauge length	TC –4 mm
648°C		651°C	
647°C		649-650°C	

Summary of LCF-test results

	LCF condition		1st cycle		Test end		Nf/2				
Spec. id	e_{max} (%)	e_{min} (%)	E (650°C) (Gpa)	R0.2 % (Mpa)	N_f	Terminated by	s_{max} (Mpa)	s_{min} (Mpa)	De_{tot} (%)	De_{pl} (%)	De_{el} (%)
U1	1.0	0.05	174.5	648	647	brittle fracture	726.4	-675.7	0.950	0.157	0.804
U2	0.7	0.035	169.3	652	3353	brittle fracture	696.3	-399.1	0.665	0.024	0.647
U3	0.8	0.04	Specimen failed due to general power failure in North Holland								
U5	0.6	0.03	169.5	640	44694	by operator	638.9	-289.8	0.570	0.024	0.549
U6	1.0	0.05	170.1	650	618	15% load drop	731.6	-651.9	0.953	0.147	0.813
U7	0.7	0.035	168.1	628	45549	by operator	673.1	-410.9	0.664	0.029	0.64
U8	1.0	0.05	169.1	910	3392	15% load drop	936.3	568.3	0.953	0.068	0.890

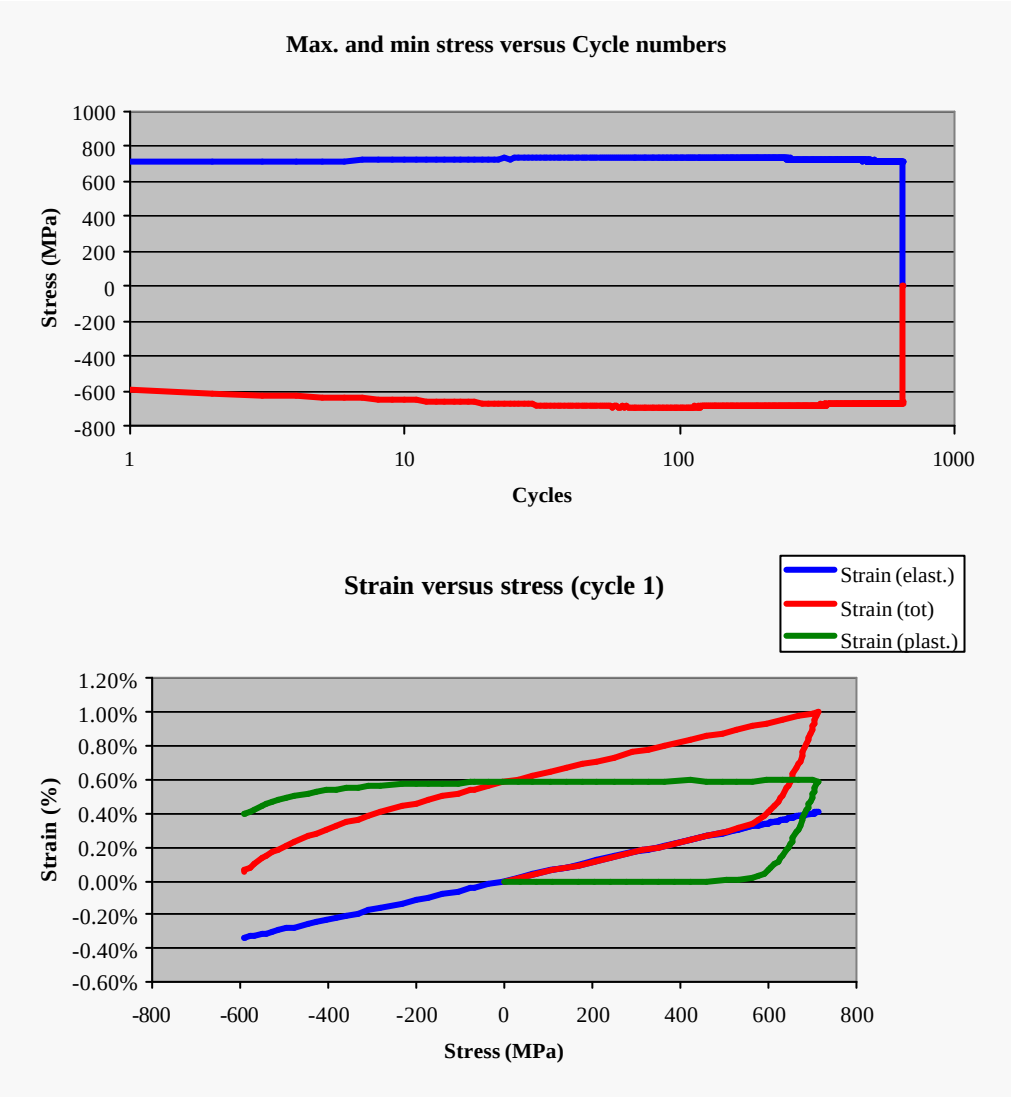

1.1
1
0.9
0.8
0.7
0.6
0.5
100
1000
10000
100000
1000000
emax (%) (JRC, state I, untreated)
emax (%) (CEA, state I)
emax (%) (JRC, state III, polished)
emax (%) (JRC, state III, unpolished)

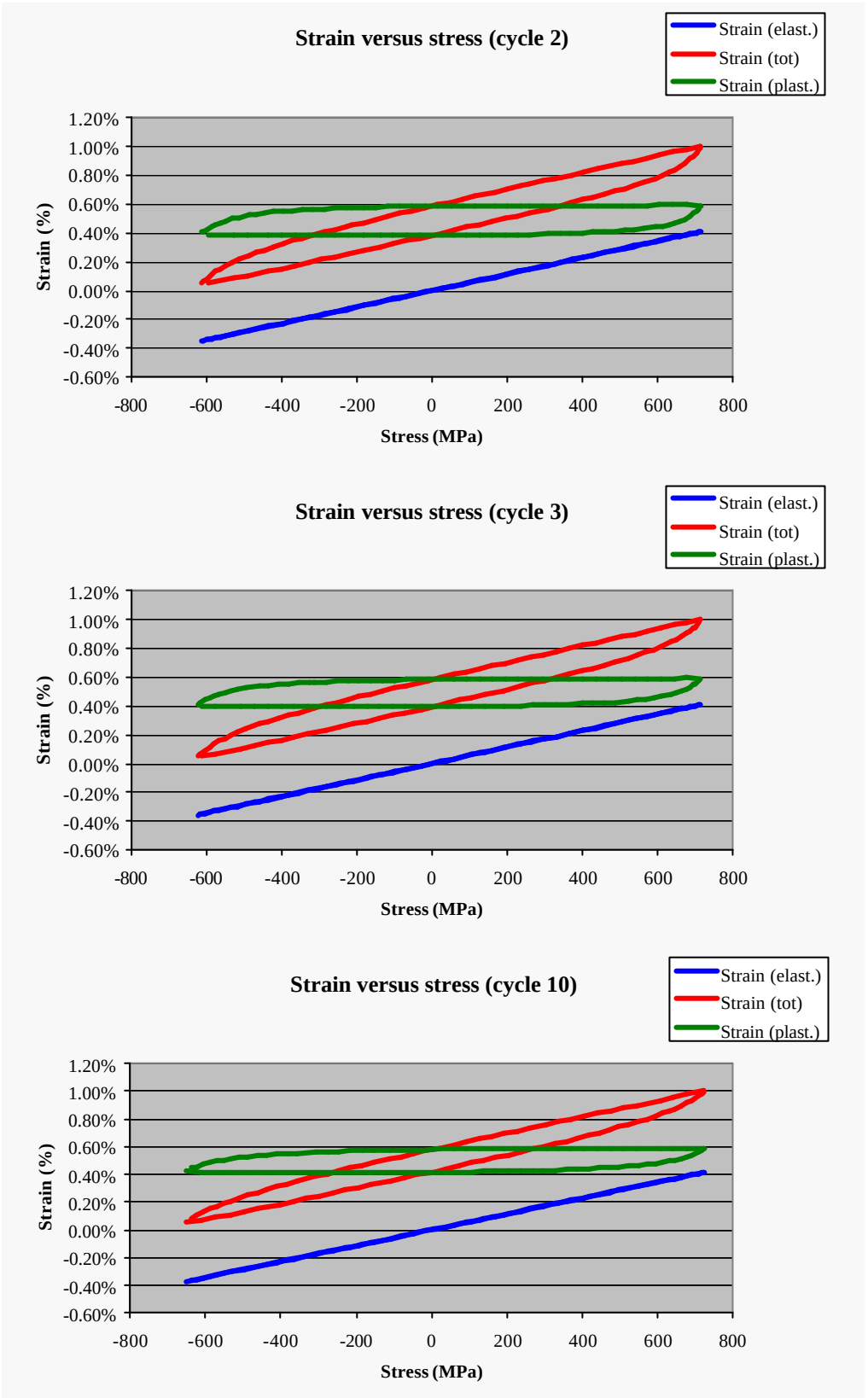
LCF-test “U1” :

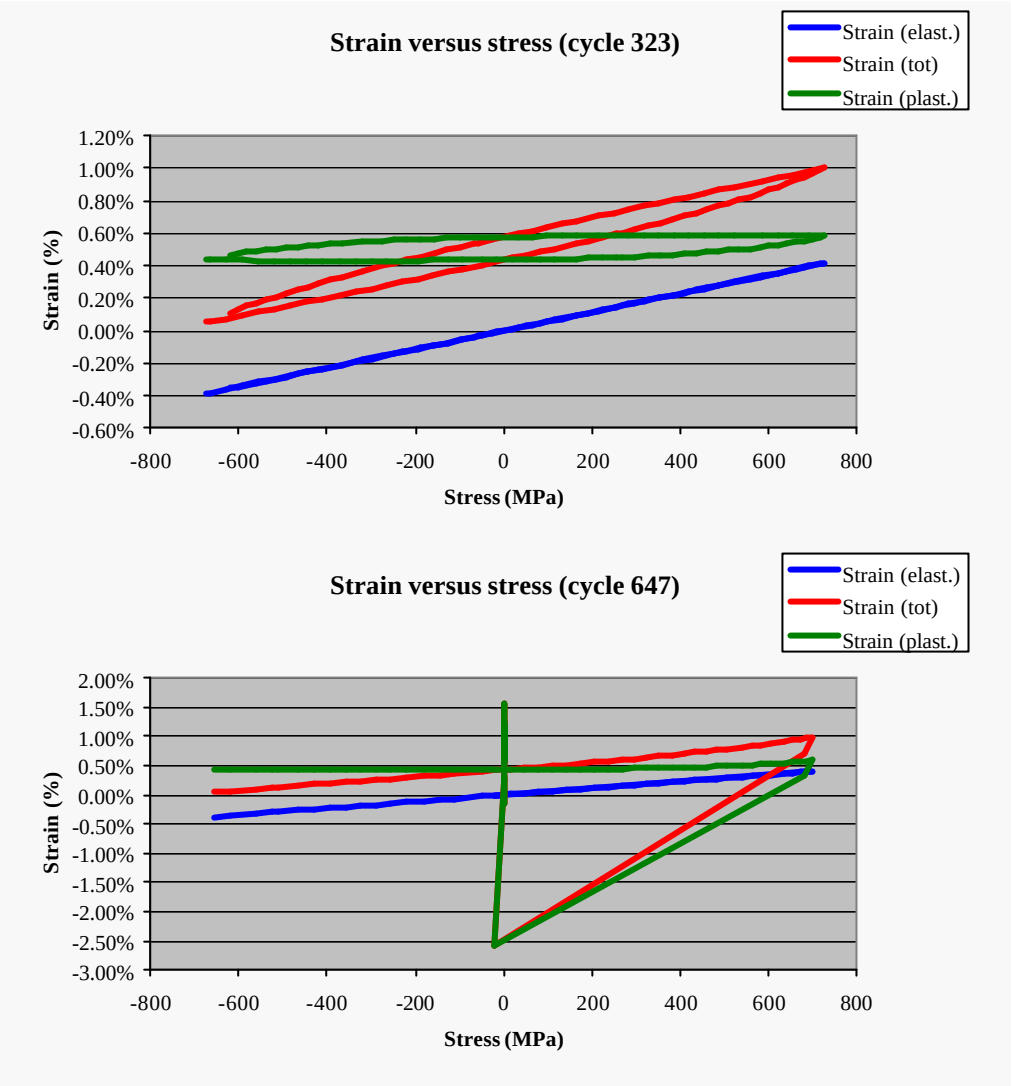
Test conditions:

Material:	**U 720, state III, unpolished**
Temperature:	**650°C**
R_e:	**0.05**
t_{cycle}:	**19.0 s**
e_{max} (%):	**1.0**
e_{min} (%):	**0.05**

Gauge length (measured):	**7481 µm**
E-modulus at 650°C measured at first cycle	**174.5 GPa**
Diameter of CSA:	**6.008 mm**
CSA:	**28.350 mm^2**
Comments:	**none**




Strain versus stress (cycle 2)
Strain (elast.)
Strain (tot)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
Strain (%)
-800
-600
-400
-200
0
200
400
600
800
Stress (MPa)
Strain versus stress (cycle 3)
Strain (elast.)
Strain (tot)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
Strain (%)
-800
-600
-400
-200
0
200
400
600
800
Stress (MPa)
Strain versus stress (cycle 10)
Strain (elast.)
Strain (tot)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
Strain (%)
-800
-600
-400
-200
0
200
400
600
800
Stress (MPa)

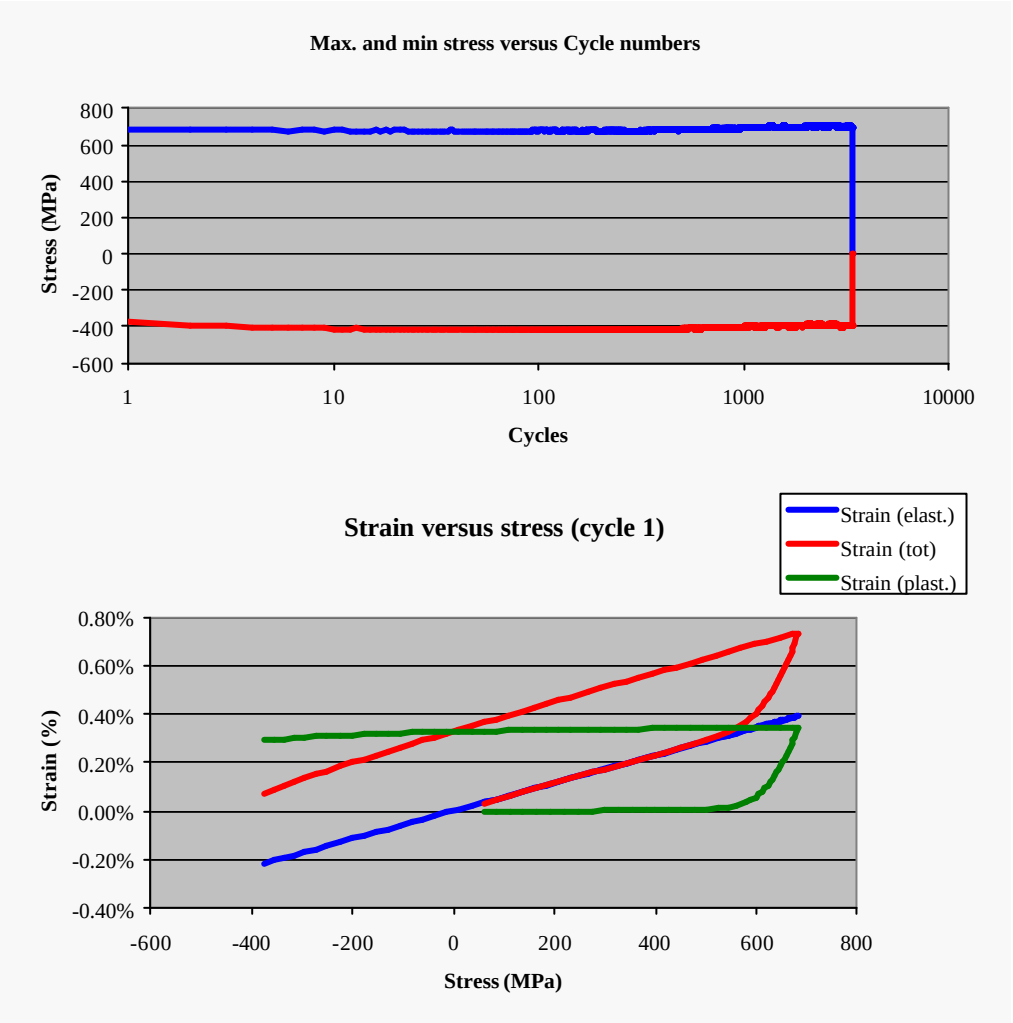

Strain versus stress (cycle 323)
Strain (elast.)
Strain (tot)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
Strain (%)
-800
-600
-400
-200
0
200
400
600
800
Stress (MPa)
Strain versus stress (cycle 647)
Strain (elast.)
Strain (tot)
Strain (plast.)
2.00%
1.50%
1.00%
0.50%
0.00%
-0.50%
-1.00%
-1.50%
-2.00%
-2.50%
-3.00%
Strain (%)
-800
-600
-400
-200
0
200
400
600
800
Stress (MPa)

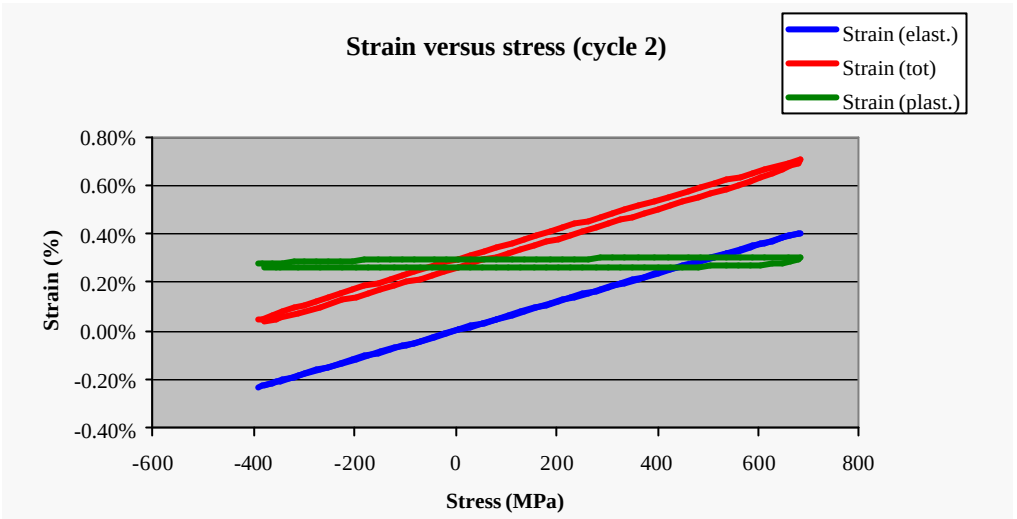
LCF-test “U2” :

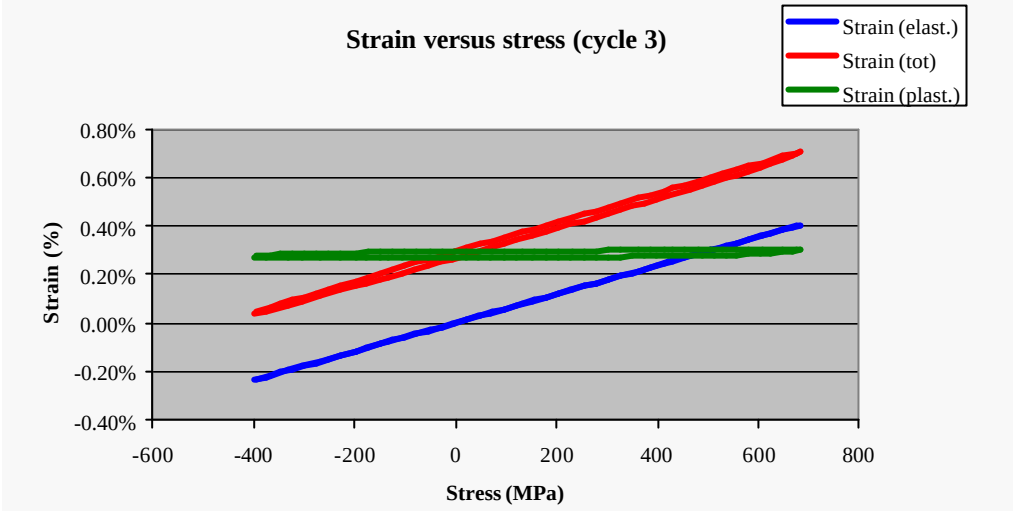
Test conditions:

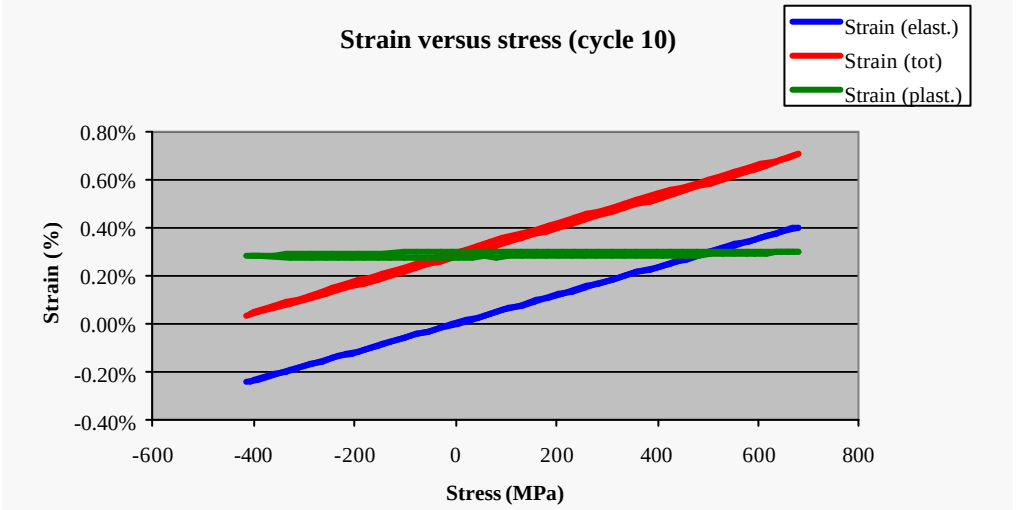
Material:	**U 720, state III, unpolished**
Temperature:	**650°C**
R_e:	**0.05**
t_{cycle}:	**13.3 s**
e_{max} (%):	**0.7**
e_{min} (%):	**0.035**

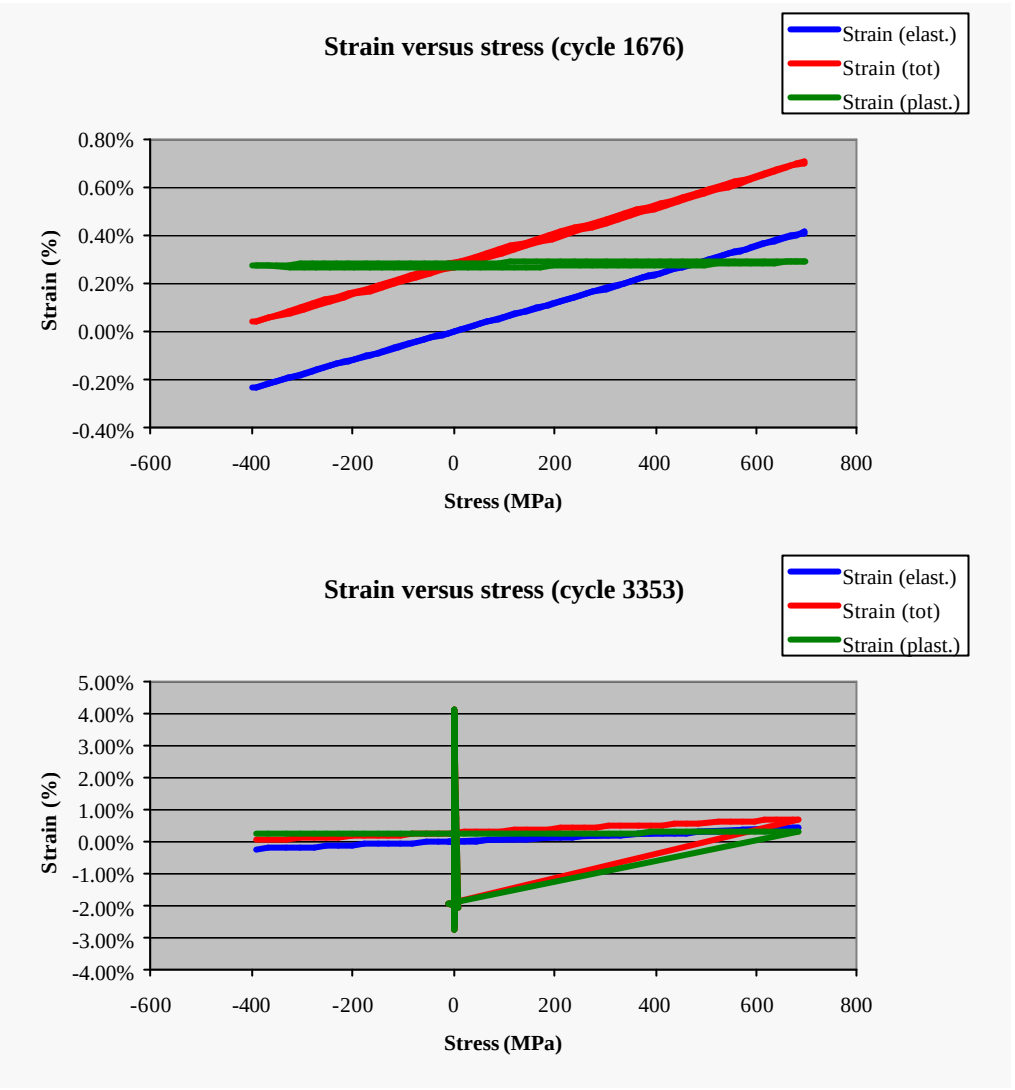
Gauge length (measured):	**7425 µm**
E-modulus at 650°C measured at first cycle	**169.3 GPa**
Diameter of CSA:	**6.017 mm**
CSA:	**28. 435 mm^2**
Comments:	**none**




Strain versus stress (cycle 2)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Strain (%)
-600
-400
-200
0
200
400
600
800
Stress (MPa)


Strain versus stress (cycle 3)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Strain (%)
-600
-400
-200
0
200
400
600
800
Stress (MPa)


Strain versus stress (cycle 10)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Strain (%)
-600
-400
-200
0
200
400
600
800
Stress (MPa)

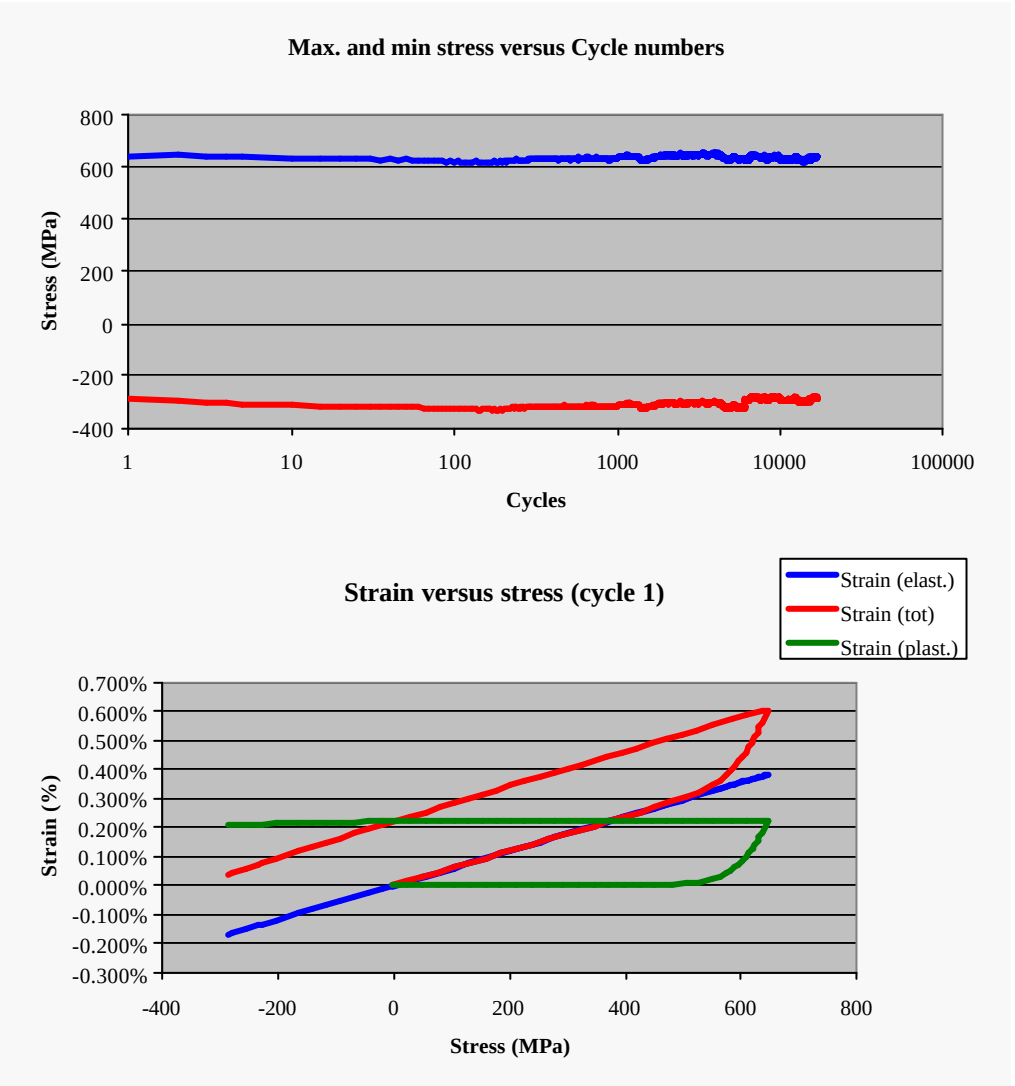

Strain versus stress (cycle 1676)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Strain (%)
-600
-400
-200
0
200
400
600
800
Stress (MPa)
Strain versus stress (cycle 3353)
Strain (elast.)
Strain (tot)
Strain (plast.)
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
-1.00%
-2.00%
-3.00%
-4.00%
Strain (%)
-600
-400
-200
0
200
400
600
800
Stress (MPa)

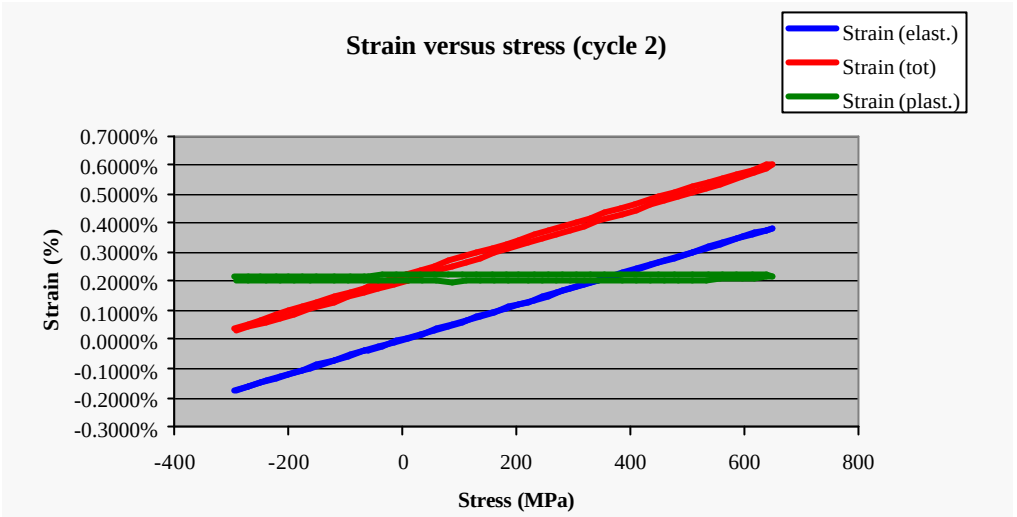
LCF-test “U5” :

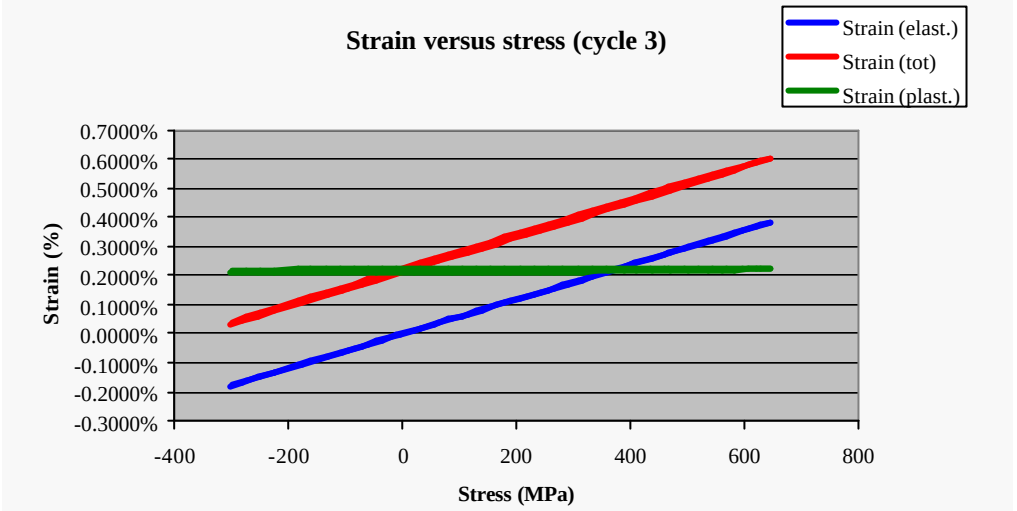
Test conditions:

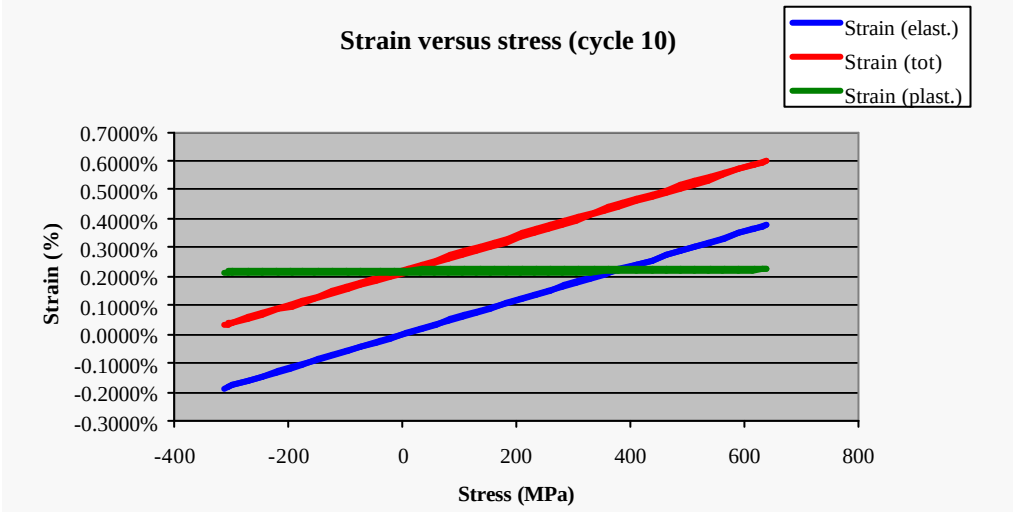
Material:	**U 720, state III, unpolished**
Temperature:	**650°C**
R_e:	**0.05**
t_{cycle}:	**13.3 s**
e_{max} (%):	**0.7**
e_{min} (%):	**0.035**

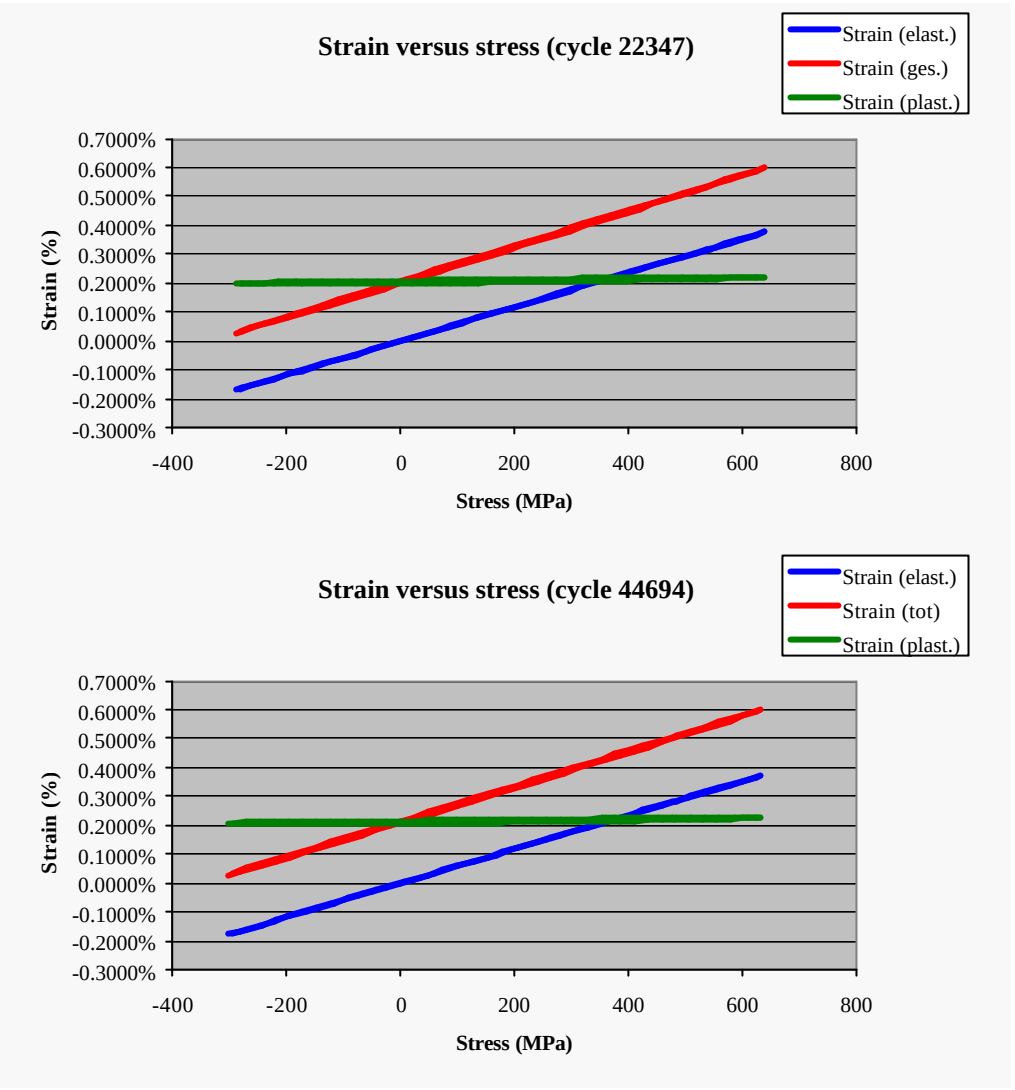
Gauge length (measured):	**7503 µm**
E-modulus at 650°C measured at first cycle	**169.5 GPa**
Diameter of CSA:	**6.026 mm**
CSA:	**28. 52 mm^2**
Comments:	**none**




Strain versus stress (cycle 2)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.7000%
0.6000%
0.5000%
0.4000%
0.3000%
0.2000%
0.1000%
0.0000%
-0.1000%
-0.2000%
-0.3000%
Strain (%)
-400
-200
0
200
400
600
800
Stress (MPa)


Strain versus stress (cycle 3)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.7000%
0.6000%
0.5000%
0.4000%
0.3000%
0.2000%
0.1000%
0.0000%
-0.1000%
-0.2000%
-0.3000%
Strain (%)
-400
-200
0
200
400
600
800
Stress (MPa)


Strain versus stress (cycle 10)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.7000%
0.6000%
0.5000%
0.4000%
0.3000%
0.2000%
0.1000%
0.0000%
-0.1000%
-0.2000%
-0.3000%
Strain (%)
-400
-200
0
200
400
600
800
Stress (MPa)

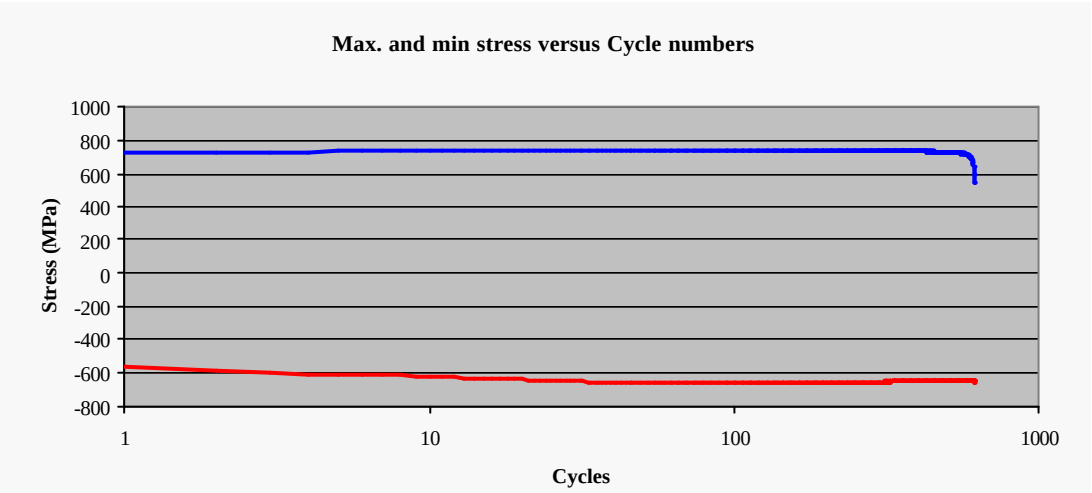

Strain versus stress (cycle 22347)
Strain (elast.)
Strain (ges.)
Strain (plast.)
0.7000%
0.6000%
0.5000%
0.4000%
0.3000%
0.2000%
0.1000%
0.0000%
-0.1000%
-0.2000%
-0.3000%
Strain (%)
-400
-200
0
200
400
600
800
Stress (MPa)
Strain versus stress (cycle 44694)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.7000%
0.6000%
0.5000%
0.4000%
0.3000%
0.2000%
0.1000%
0.0000%
-0.1000%
-0.2000%
-0.3000%
Strain (%)
-400
-200
0
200
400
600
800
Stress (MPa)

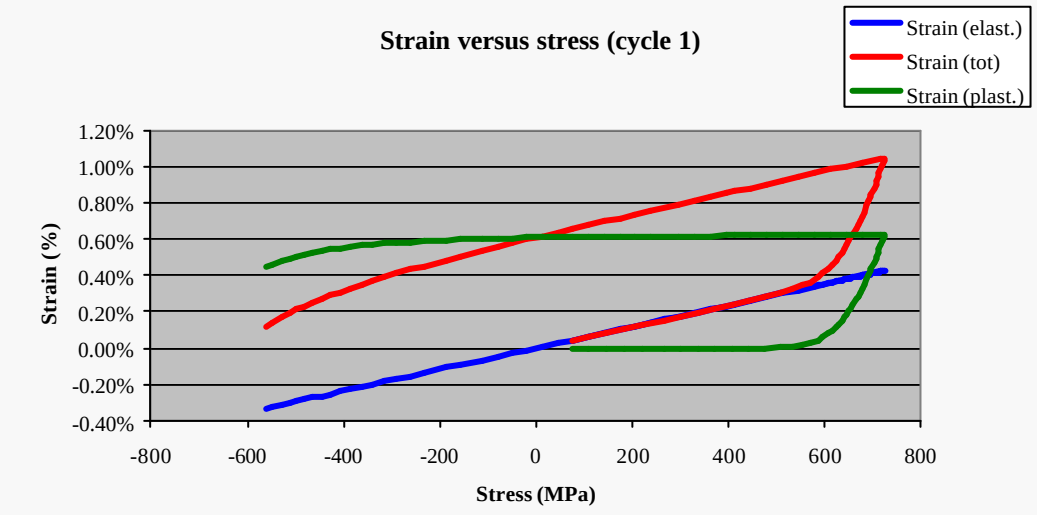
LCF-test “U6” :

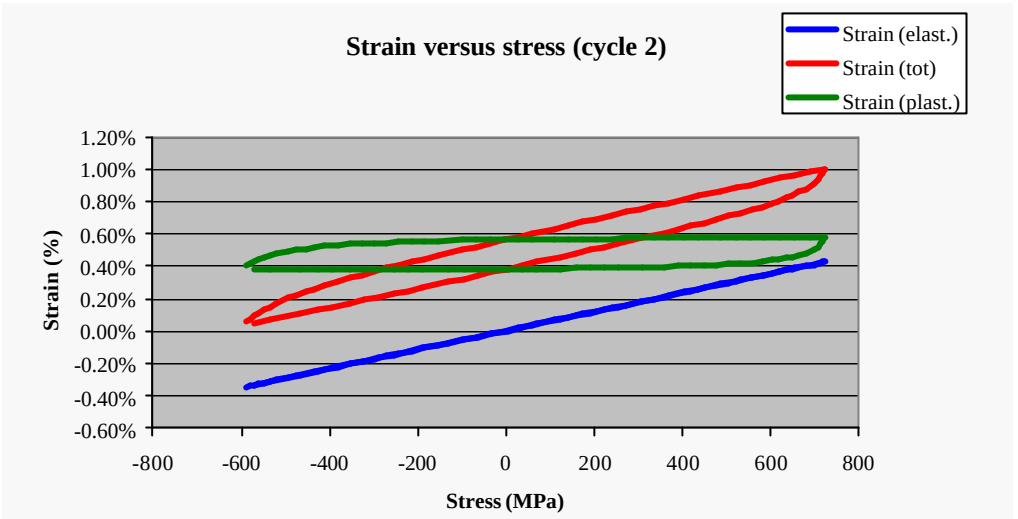
Test conditions:

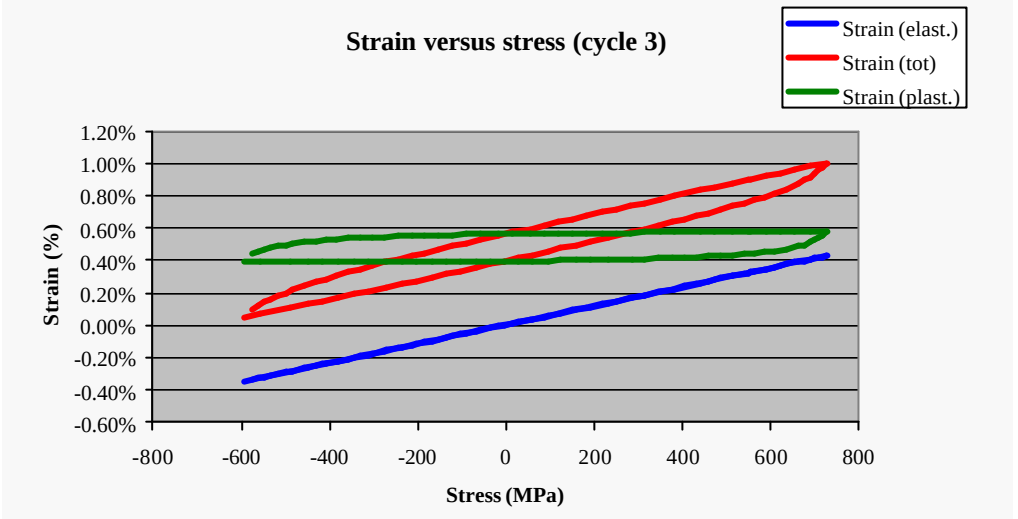
Material:	**U 720, state III, polished**
Temperature:	**650°C**
R_e:	**0.05**
t_{cycle}:	**19.0 s**
e_{max} (%):	**1.0**
e_{min} (%):	**0.05**

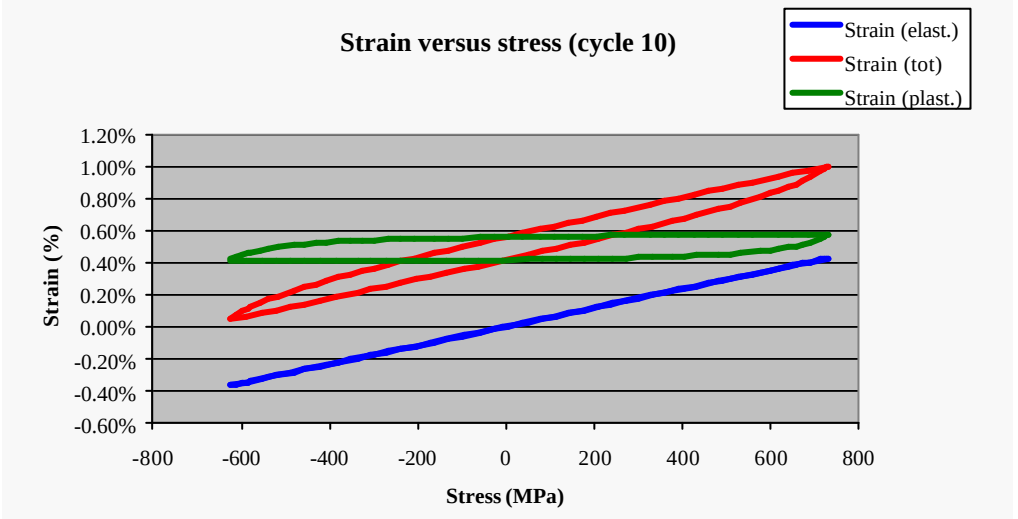
Gauge length (measured):	**7450 µm**
E-modulus at 650°C measured at first cycle	**170.125 GPa**
Diameter of CSA:	**5.976 mm**
CSA:	**28.049 mm²**
Comments:	**none**

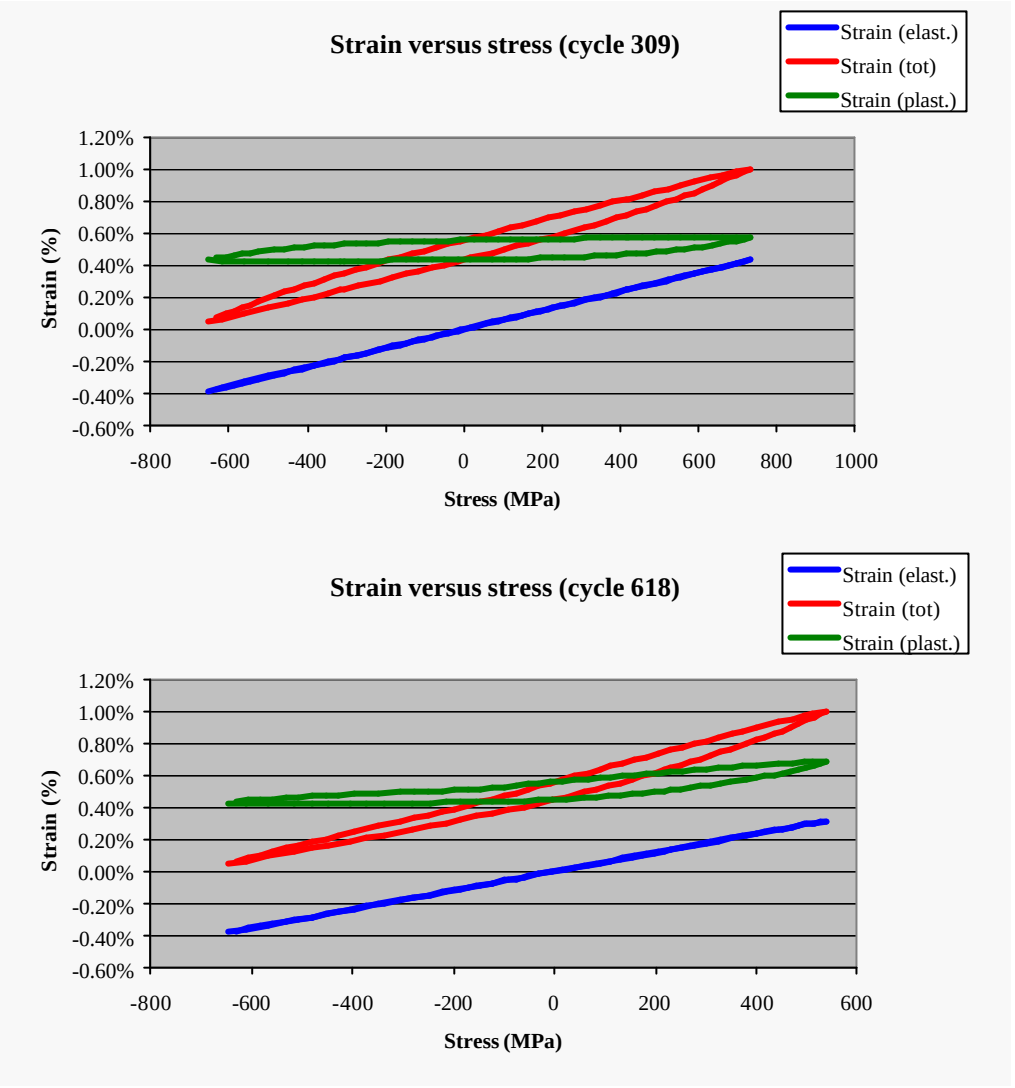





Strain versus stress (cycle 2)
Strain (elast.)
Strain (tot)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
Strain (%)
-800
-600
-400
-200
0
200
400
600
800
Stress (MPa)


Strain versus stress (cycle 3)
Strain (elast.)
Strain (tot)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
Strain (%)
-800
-600
-400
-200
0
200
400
600
800
Stress (MPa)


Strain versus stress (cycle 10)
Strain (elast.)
Strain (tot)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
Strain (%)
-800
-600
-400
-200
0
200
400
600
800
Stress (MPa)

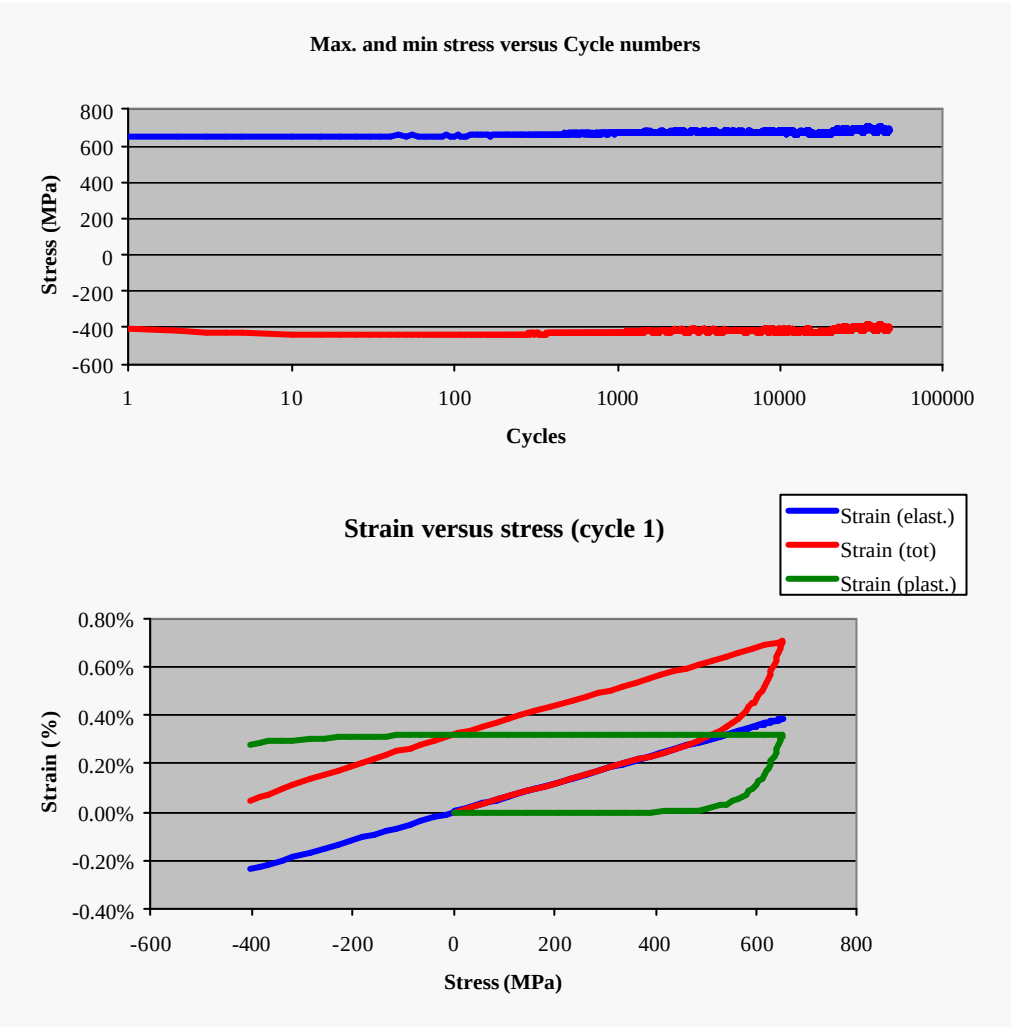

Strain versus stress (cycle 309)
Strain (elast.)
Strain (tot)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
Strain (%)
-800
-600
-400
-200
0
200
400
600
800
1000
Stress (MPa)
Strain versus stress (cycle 618)
Strain (elast.)
Strain (tot)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
Strain (%)
-800
-600
-400
-200
0
200
400
600
Stress (MPa)

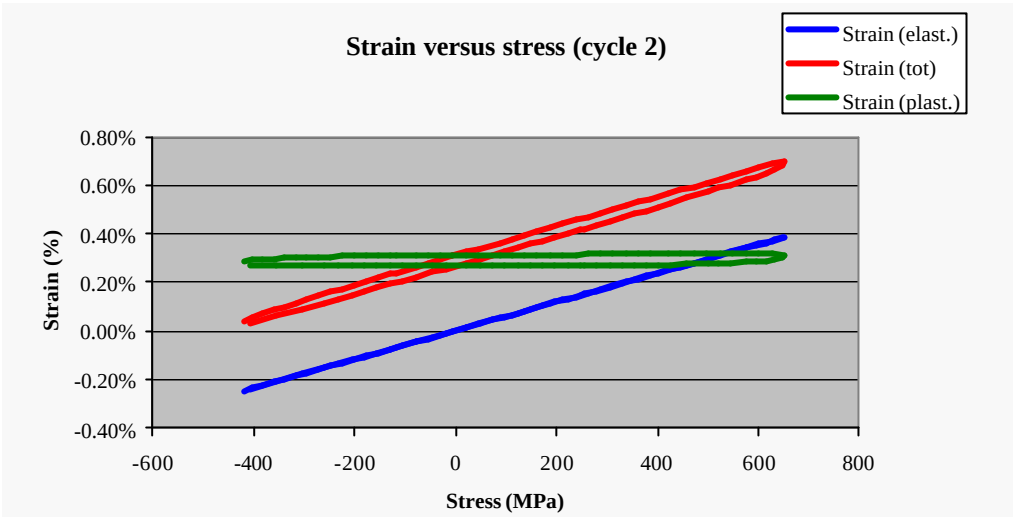
LCF-test “U7” :

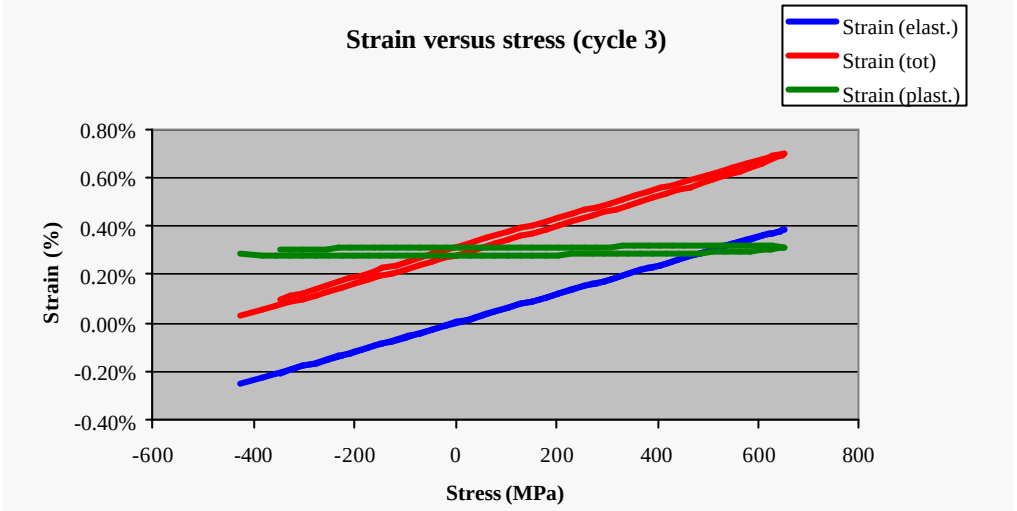
Test conditions:

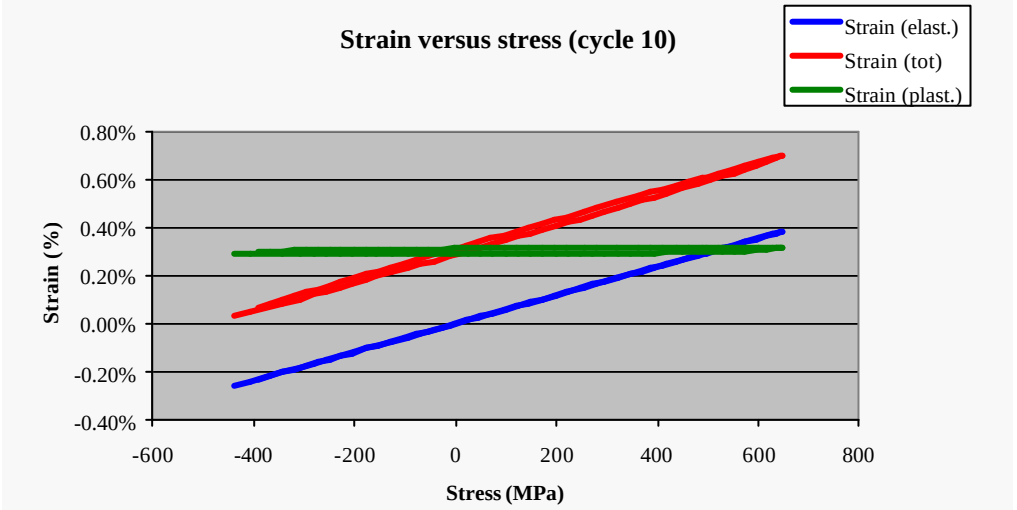
Material:	**U 720, state III, polished**
Temperature:	**650°C**
R_e:	**0.05**
t_{cycle}:	**13.3 s**
e_{max} (%):	**0.7**
e_{min} (%):	**0.035**

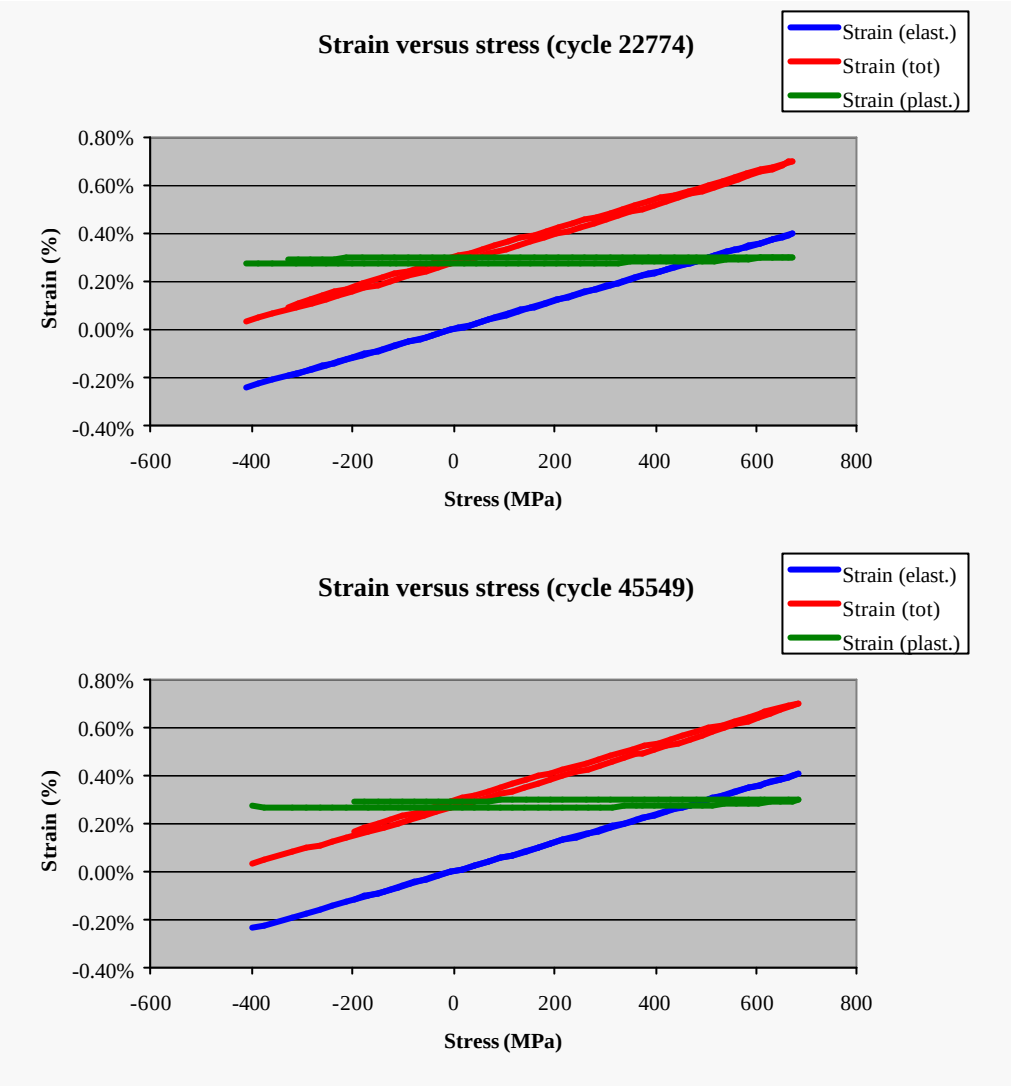
Gauge length (measured):	**7579 µm**
E-modulus at 650°C measured at first cycle	**168.1 GPa**
Diameter of CSA:	**5.948 mm**
CSA:	**27.786 mm^2**
Comments:	**Test stopped after 45549 cycles by operator.**




Strain versus stress (cycle 2)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Strain (%)
-600
-400
-200
0
200
400
600
800
Stress (MPa)


Strain versus stress (cycle 3)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Strain (%)
-600
-400
-200
0
200
400
600
800
Stress (MPa)


Strain versus stress (cycle 10)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Strain (%)
-600
-400
-200
0
200
400
600
800
Stress (MPa)

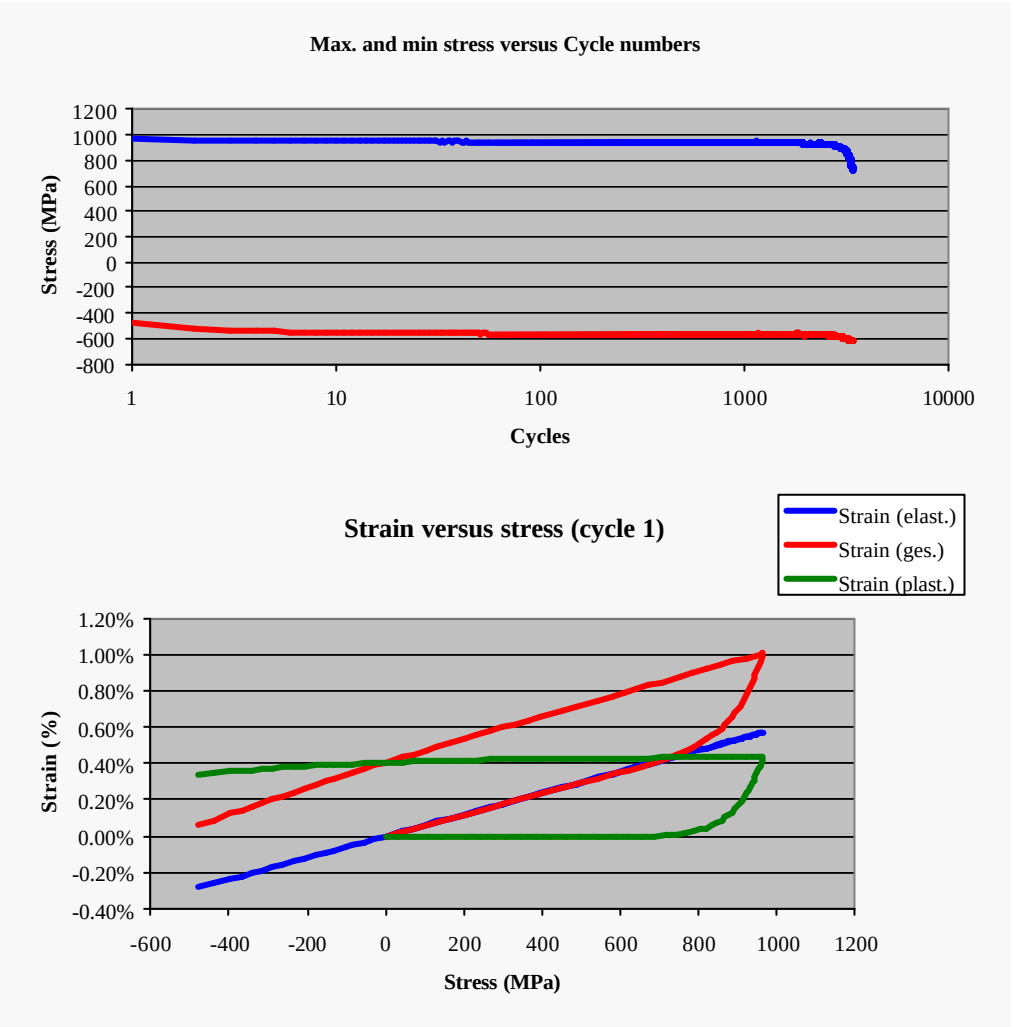

Strain versus stress (cycle 22774)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Strain (%)
-600
-400
-200
0
200
400
600
800
Stress (MPa)
Strain versus stress (cycle 45549)
Strain (elast.)
Strain (tot)
Strain (plast.)
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Strain (%)
-600
-400
-200
0
200
400
600
800
Stress (MPa)

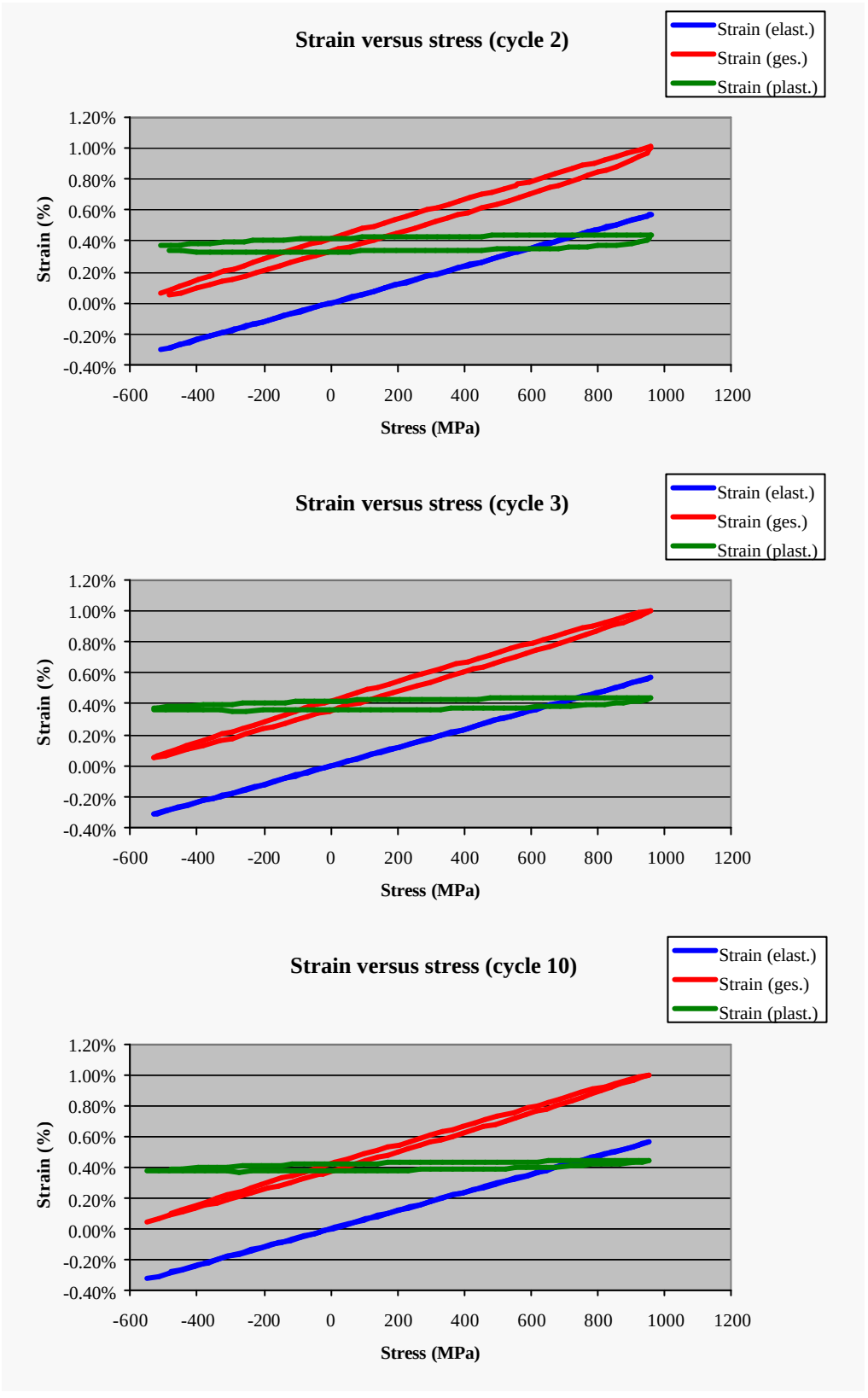
LCF-test “U8” :

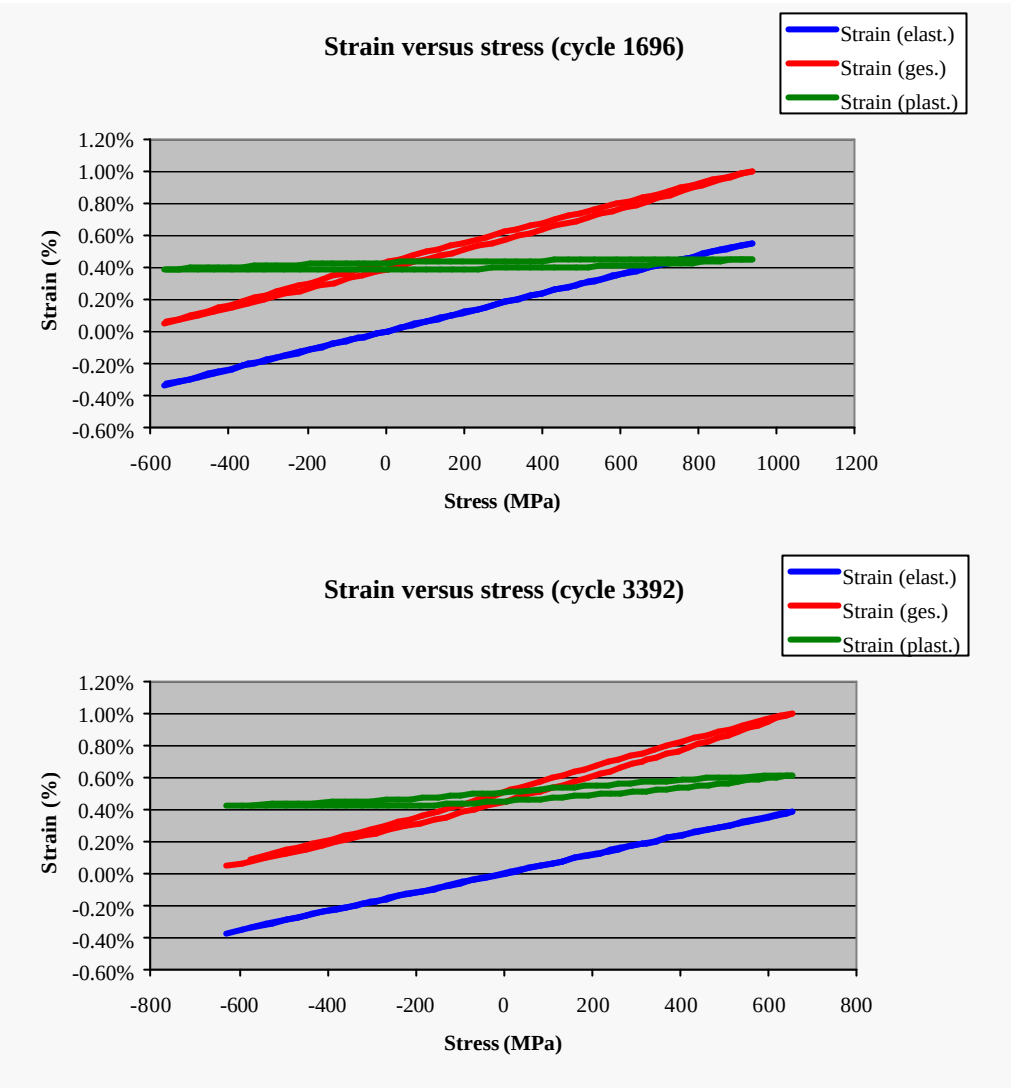
Test conditions:

Material:	**U 720, state I, unpolished**
Temperature:	**650°C**
R_e:	**0.05**
t_{cycle}:	**19.0 s**
e_{max} (%):	**1.0**
e_{min} (%):	**0.05**

Gauge length (measured):	**7475 µm**
E-modulus at 650°C measured at first cycle	**169.1 GPa**
Diameter of CSA:	**6.012 mm**
CSA:	**28. 388 mm^2**
Comments:	**none**




Strain versus stress (cycle 2)
Strain (elast.)
Strain (ges.)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Strain (%)
-600
-400
-200
0
200
400
600
800
1000
1200
Stress (MPa)
Strain versus stress (cycle 3)
Strain (elast.)
Strain (ges.)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Strain (%)
-600
-400
-200
0
200
400
600
800
1000
1200
Stress (MPa)
Strain versus stress (cycle 10)
Strain (elast.)
Strain (ges.)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Strain (%)
-600
-400
-200
0
200
400
600
800
1000
1200
Stress (MPa)


Strain versus stress (cycle 1696)
Strain (elast.)
Strain (ges.)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
Strain (%)
-600
-400
-200
0
200
400
600
800
1000
1200
Stress (MPa)
Strain versus stress (cycle 3392)
Strain (elast.)
Strain (ges.)
Strain (plast.)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
Strain (%)
-800
-600
-400
-200
0
200
400
600
800
Stress (MPa)