

Material characterization

EuCARD-2 WP11 Topical Meeting, April 28-29, 2016, University of Malta

Lorenzo Peroni



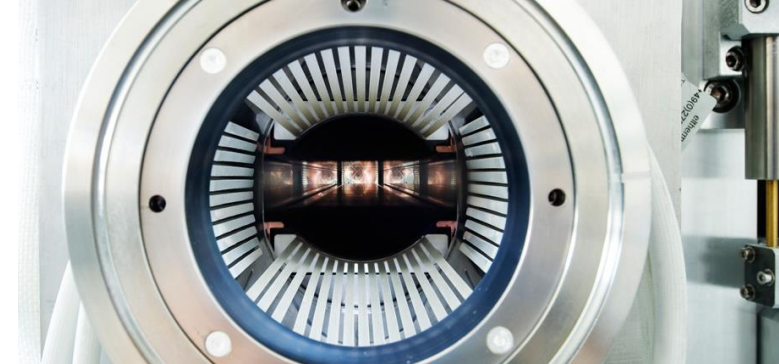
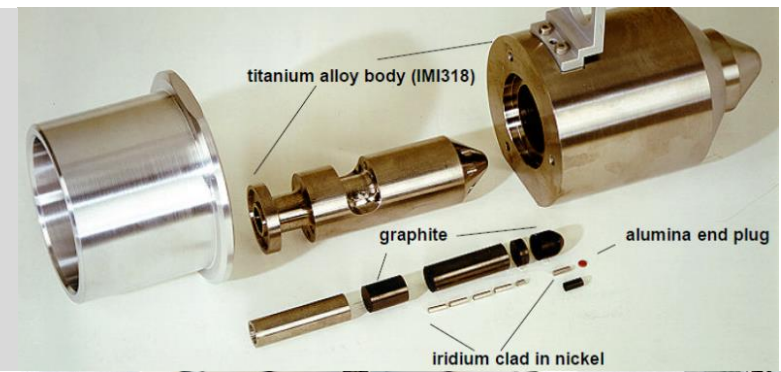
**POLITECNICO
DI TORINO**

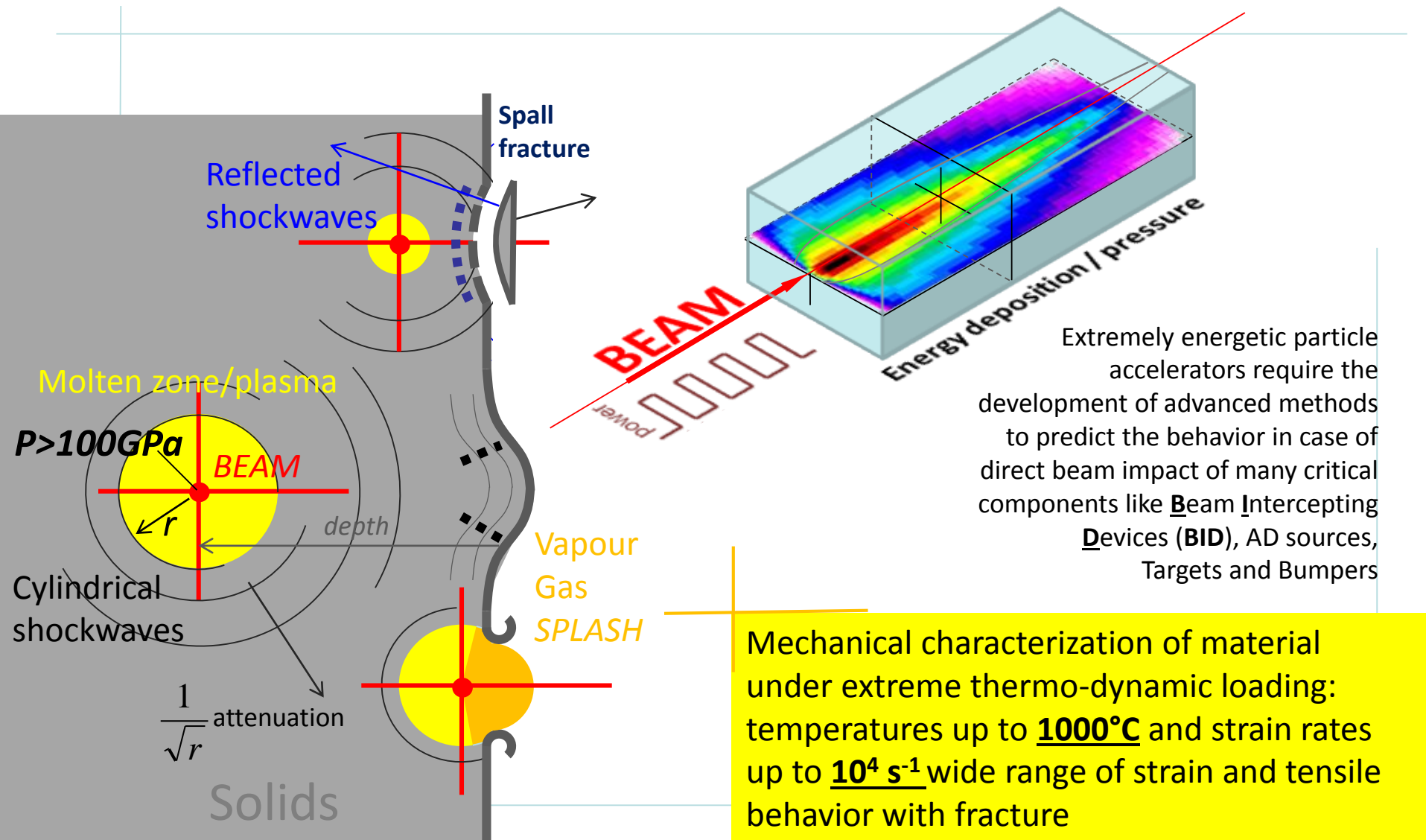
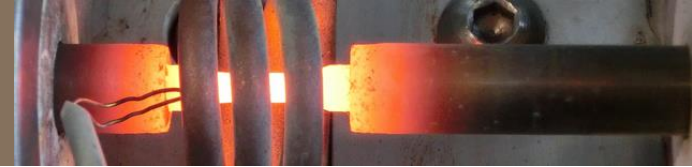
There are a lot of engineering scenarios in which the material can operate in high strain-rate and high temperature conditions such as metalworking, metal forming, aerospace and aeronautics structures, nuclear technologies, blasts, space debris impacts and high energy depositions (lasers and particle beams).

✓ The materials involved in such phenomena have to satisfy a lot of requirements related to the mechanical response under the above mentioned “shock” loading conditions.

✓ **This context gives impulse to the development and testing of ceramic based materials and refractory metals and alloys** molybdenum, tungsten, niobium and iridium

*Courtesy of EN-STI, EN-MME, Mechanical Workshop, CERN
Engineering Department*

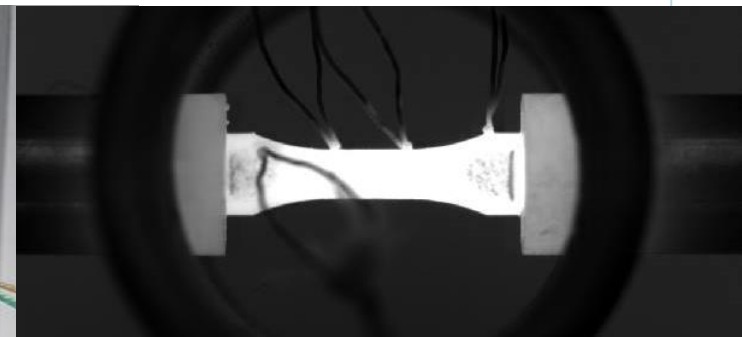
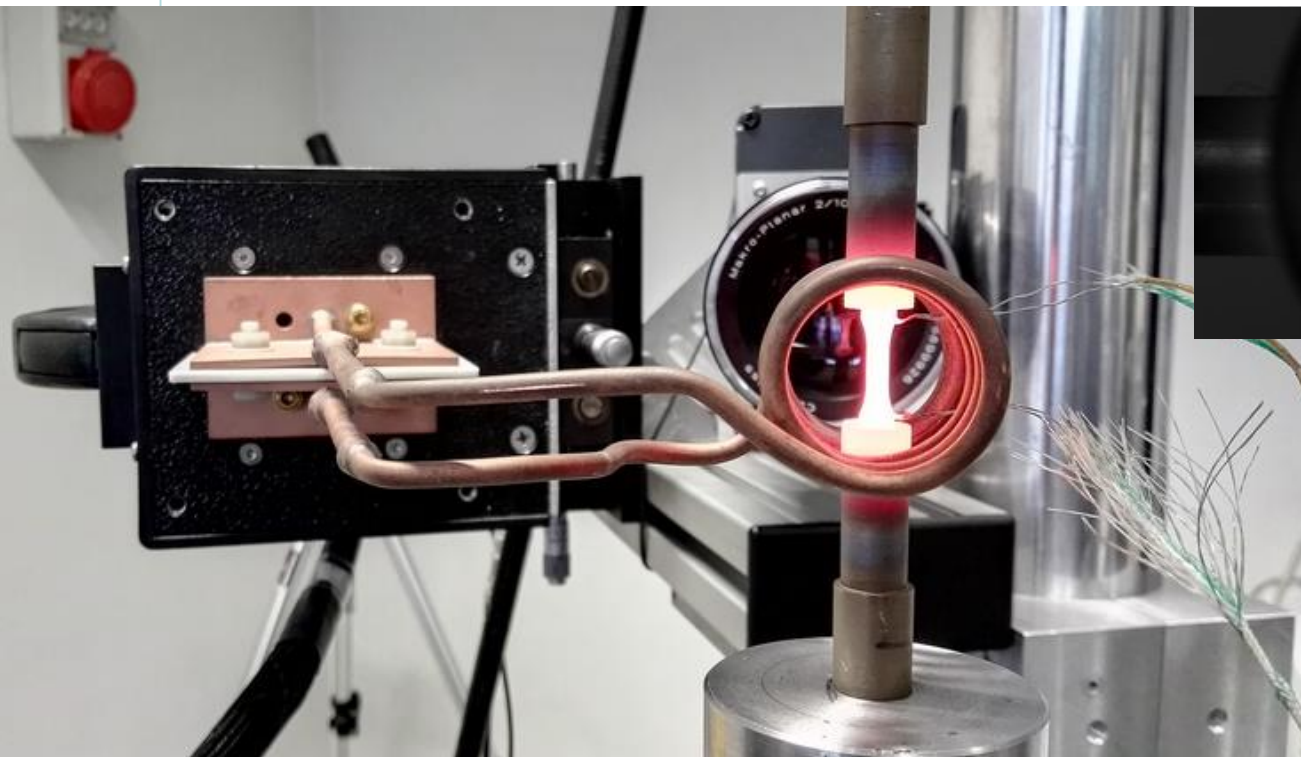
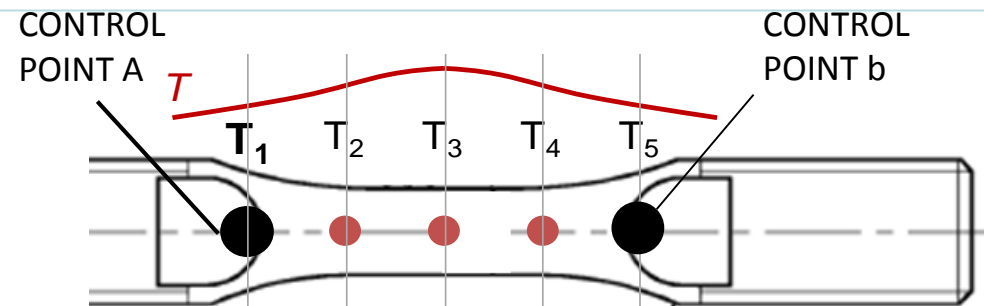




Material behaviour in beam impacts scenarios

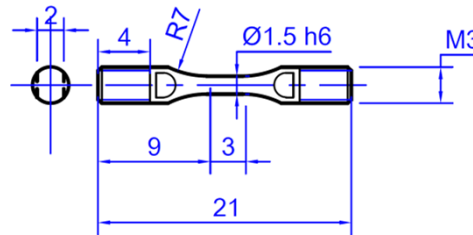
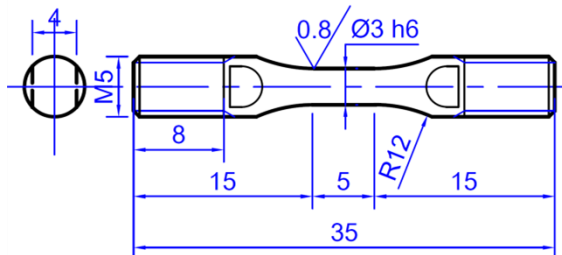
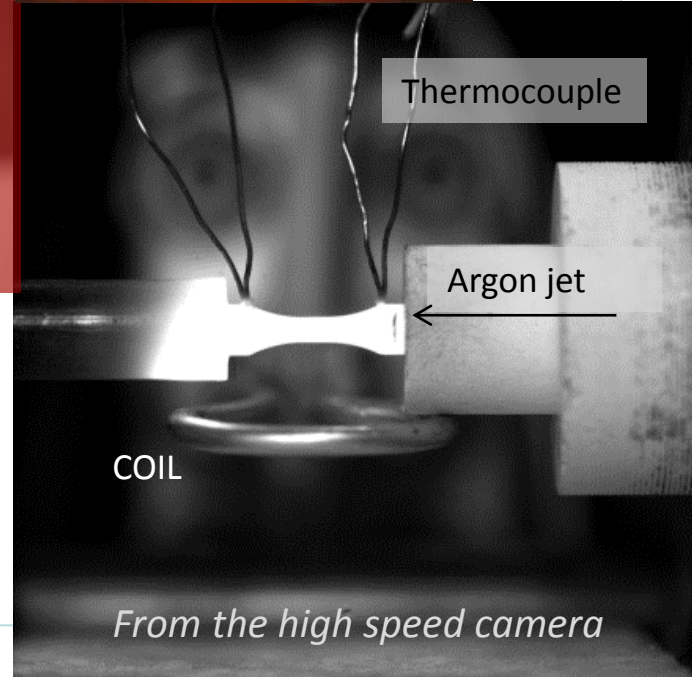
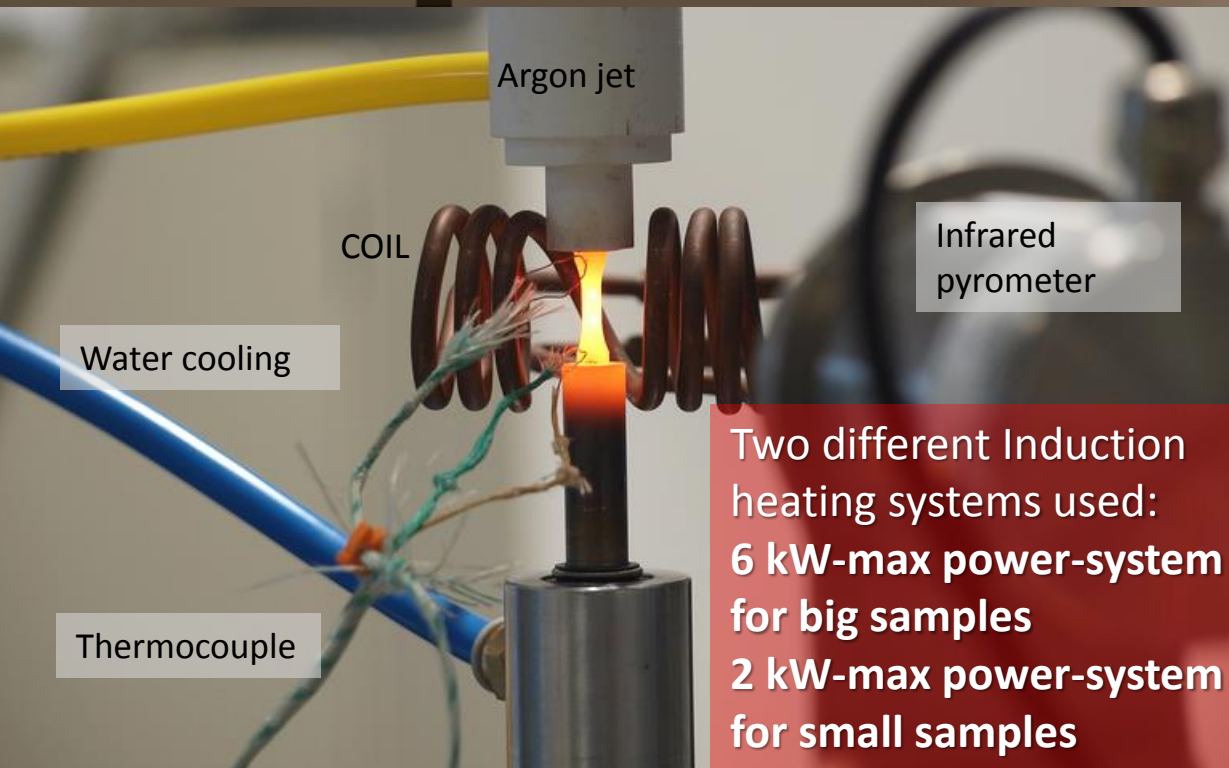


The heating of the specimens was obtained with an induction coil system, designed to concentrate the heat flux in the gage length of the specimen.

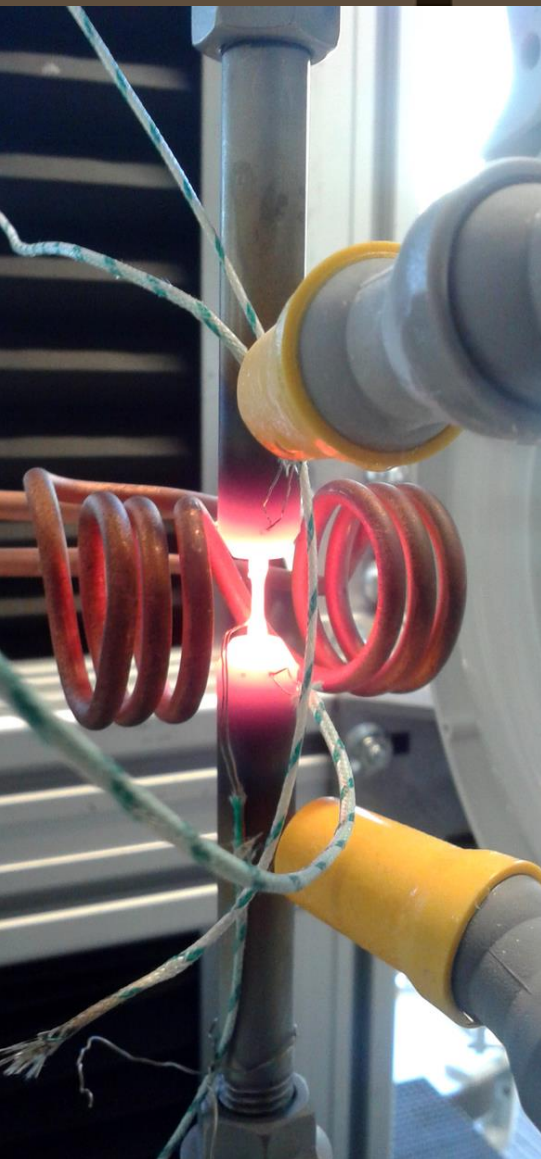


A feedback loop, based on measurements from thermocouples directly welded on the specimen, was used to control the temperature. The temperature range varied between **RT** and **1250 °C**.

Experimental setup - Heating



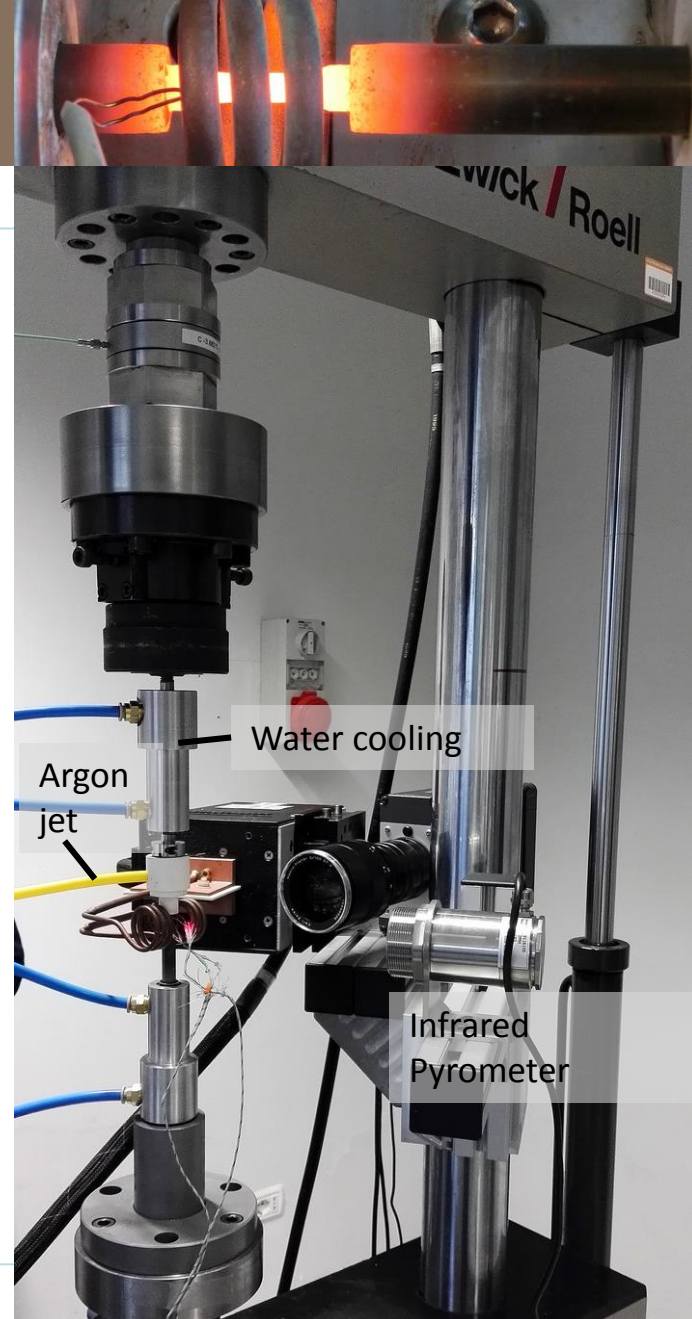
Experimental setup - Heating



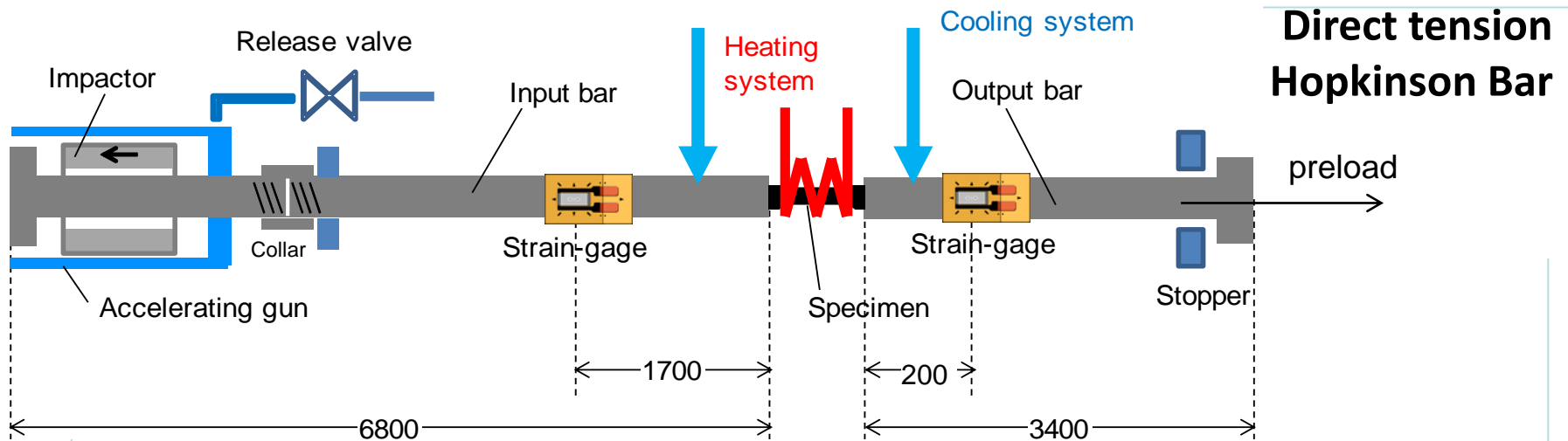
- ✓ Electro-mechanical testing system
- ✓ Nominal strain-rate $10^{-3} - 10^{-1} \text{ s}^{-1}$
- ✓ Video acquisition with high resolution camera (2500x2000 px)

Position controlled

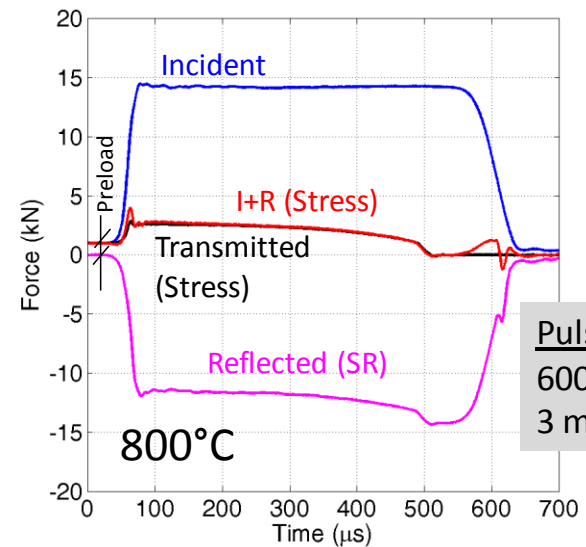
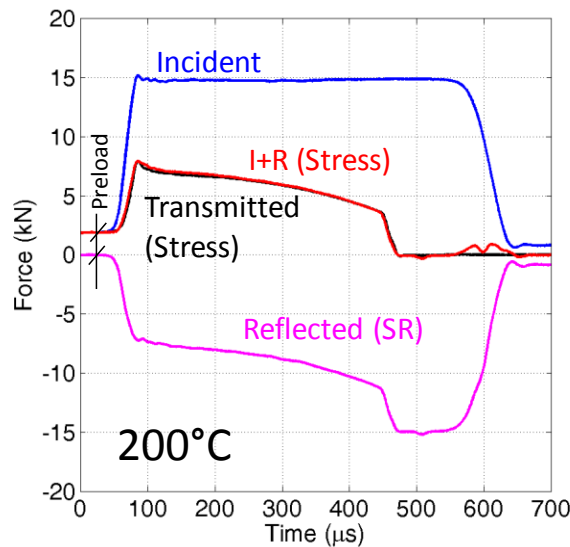
- ✓ Servo-hydraulic testing system
- ✓ Nominal strain-rate $1 - 10 \text{ s}^{-1}$
- ✓ Video acquisition with high speed camera at maximum resolution (1280x1024 px)



Quasi-static and medium strain-rate tests

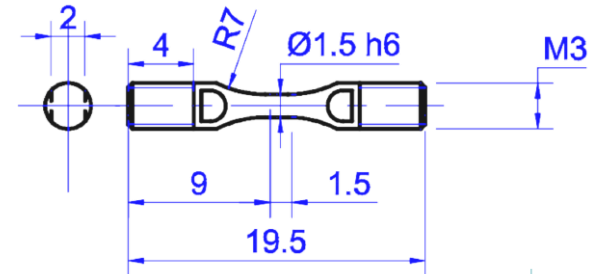
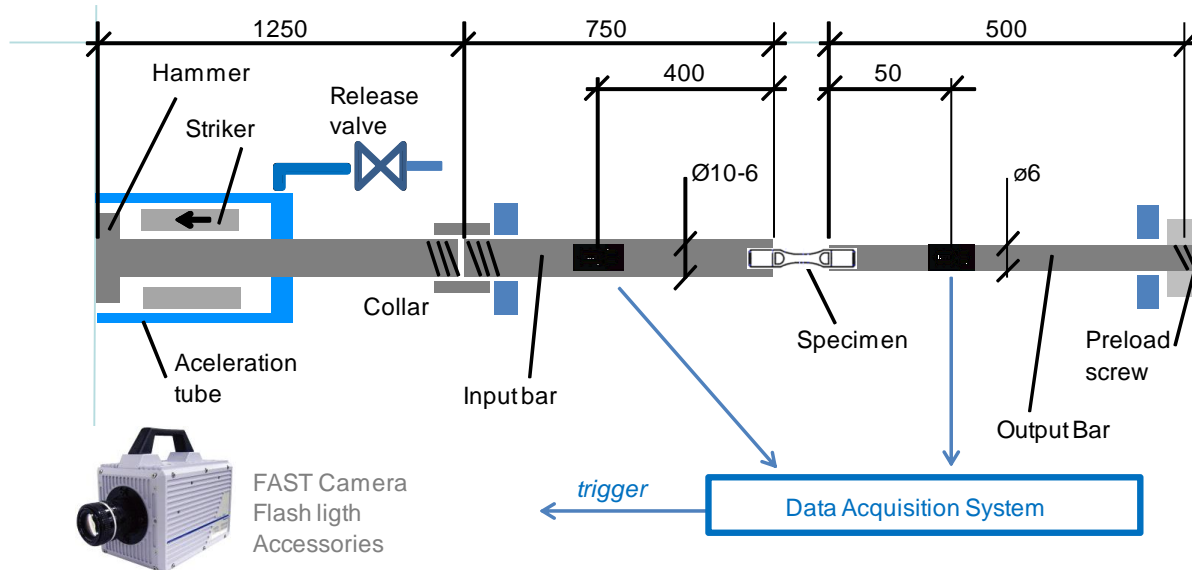


The signal on the input bar is the trigger for the switch-off of the induction system and the switch-on (with a programmable delay) of the high speed camera and lighting system

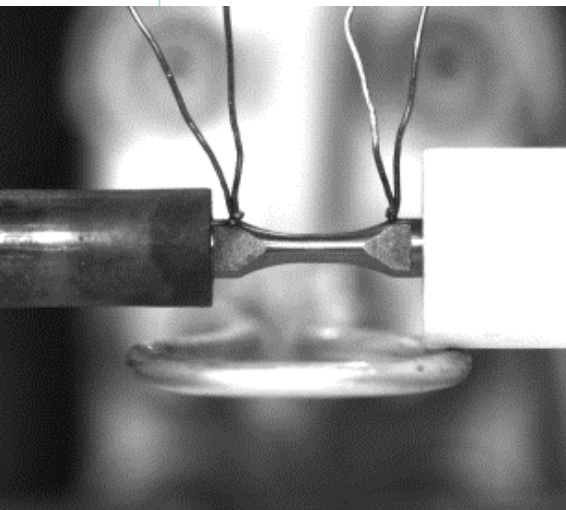


Pulse duration:
600 μs
3 m in steel

High strain-rate tests (10^3 s^{-1})

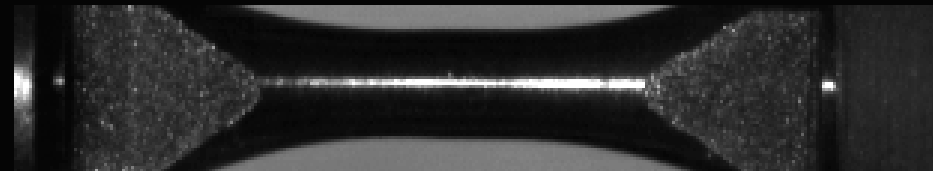


PULSE DURATION: 100 μ s
about 25 m/s in 20 μ s! ($>10^5$ g)



300000 fps
1/2713000 sec
320 x 56
frame : 16
+0.053333 ms

Tungsten @400°C



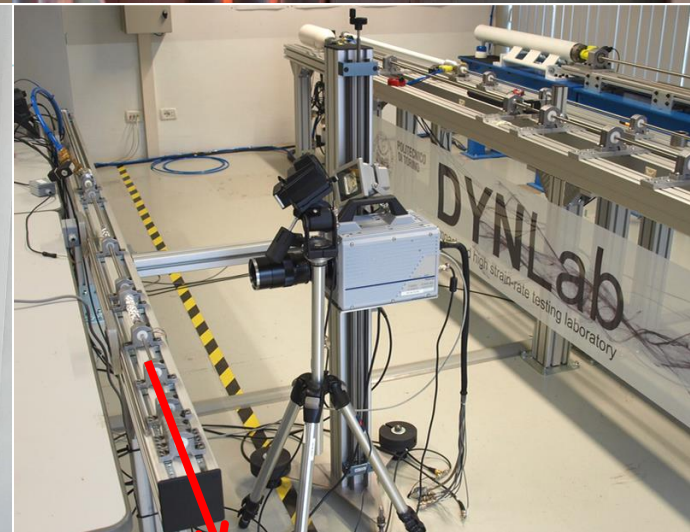
Courtesy of EN-STI CERN Engineering Department

Ultra-High strain-rate tests $>10^4$ s⁻¹

5 Hopkinson bar systems

(3 tension, compression & bending, miniaturized) with semiconductor straingages and fast data acquisition system (up to 100 MHz);

Standard test (tensile, compression), miniaturized tensile test, Brazilian and Spalling test (brittle), triaxiality effects (notched specimens), fracture toughness ...



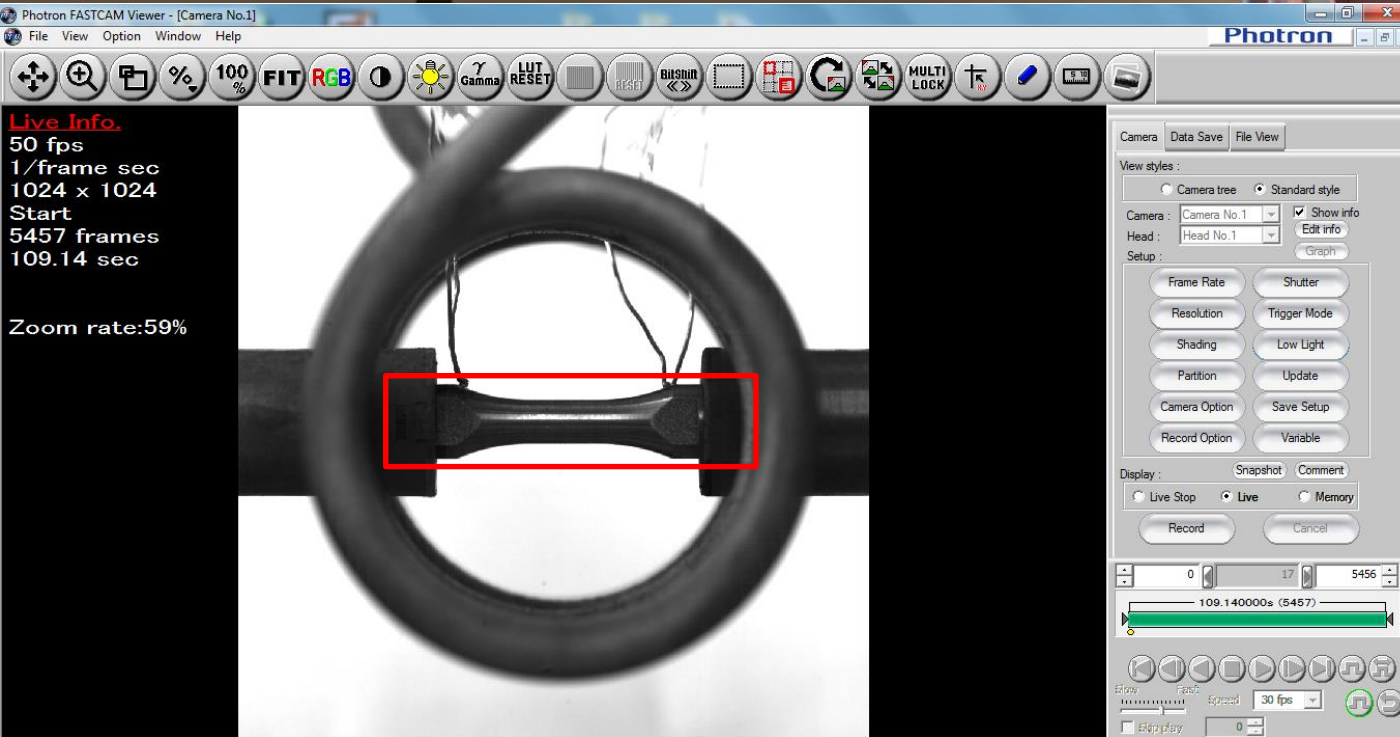
Miniaturized tension
(W, Ir)

Compression/Bending
(Mo, W, Gr)

Low strength mat tension
(Pb, Si, Gr, MoGr)

High strength mat tension
(W, Mo, Ir)

High strain-rate tests ($10^3 - 10^4 \text{ s}^{-1}$)



- ✓ Measurement of specimen gage length history
- ✓ Evaluation of the deformed shape/failure mode of the specimen
- ✓ Velocity/equilibrium check
- ✓ Oxidation control

100000 fps in 10^3 s^{-1} tests

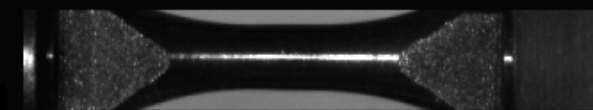
100000 fps
1/2713000 sec
512 x 128
frame : 0
+0.00 ms

Pure tungsten @400°C

300000 fps in 10^4 s^{-1} tests

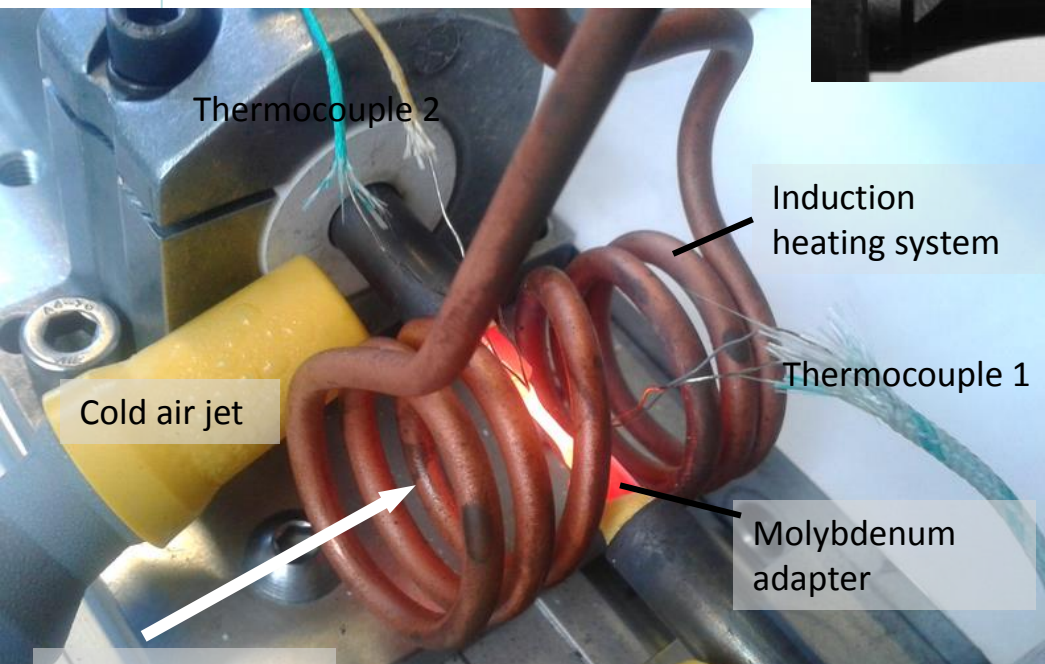
300000 fps
1/2713000 sec
320 x 56
frame : 16
+0.053333 ms

Pure tungsten @400°C

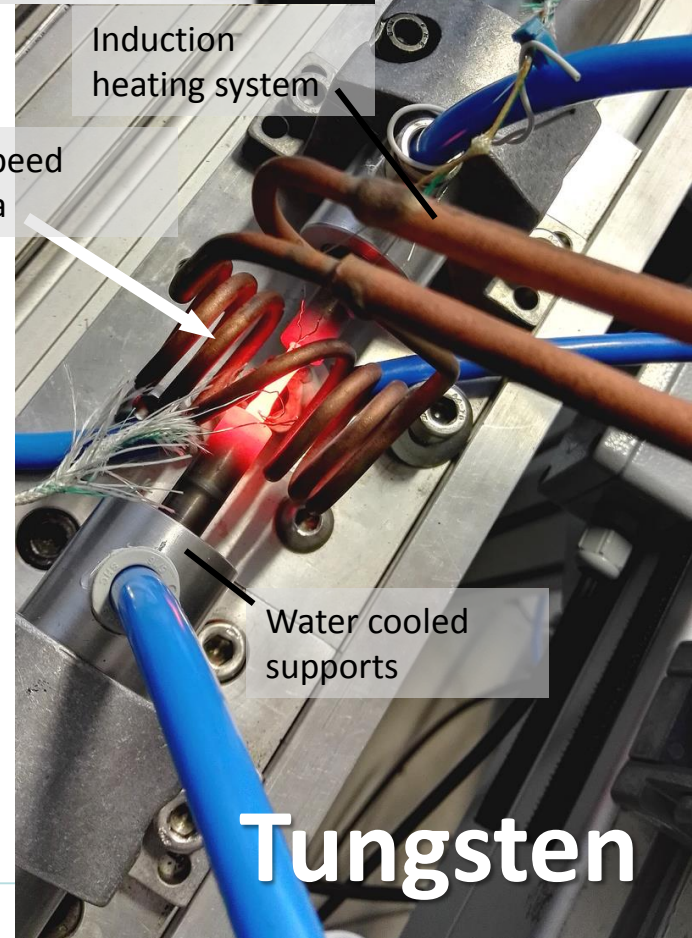
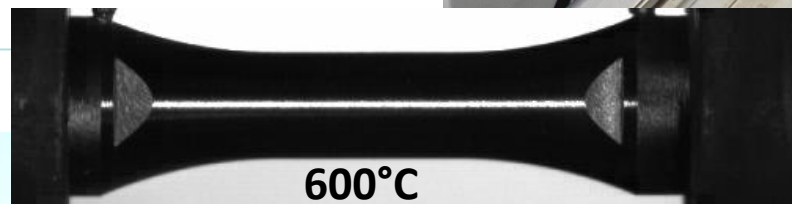
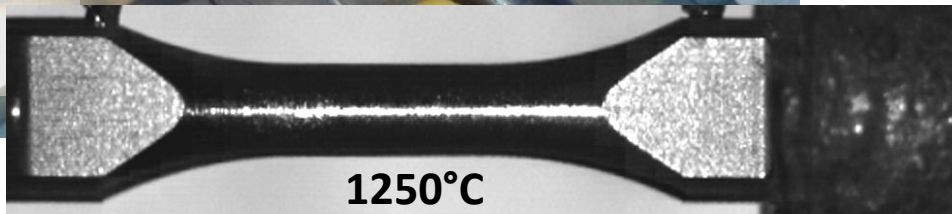


High speed camera for high strain-rate test

Iridium



High speed camera



Tungsten

Courtesy of EN-STI CERN Engineering Department

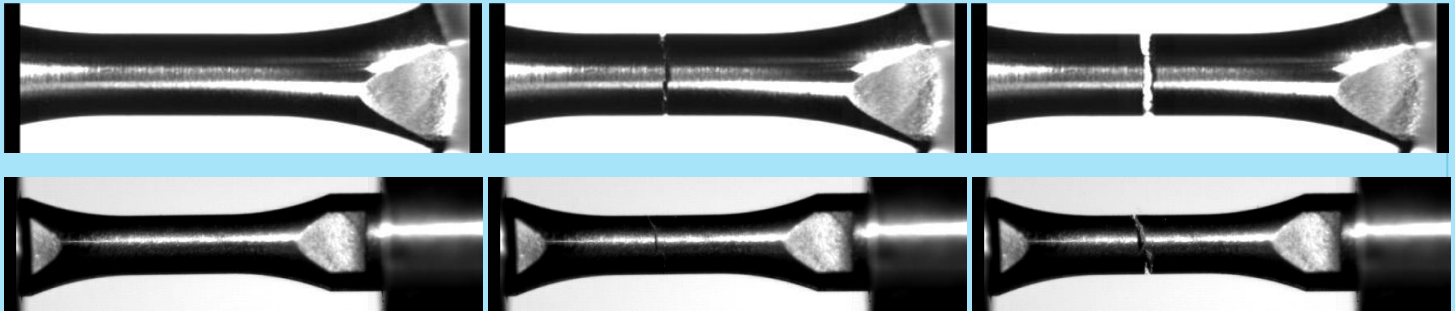
High strain-rate tests (10^3 s^{-1})



Many refractory metals exhibit a brittle behaviour at high strain-rates at room temperature: tests on SHTB in these loading conditions were very difficult to perform (many fractures in the threaded ends of the specimen)

IT180

25°C



Mo

Photron FASTCAM SA5 model 1000...

1/2713000 sec

512 x 120

100000 fps

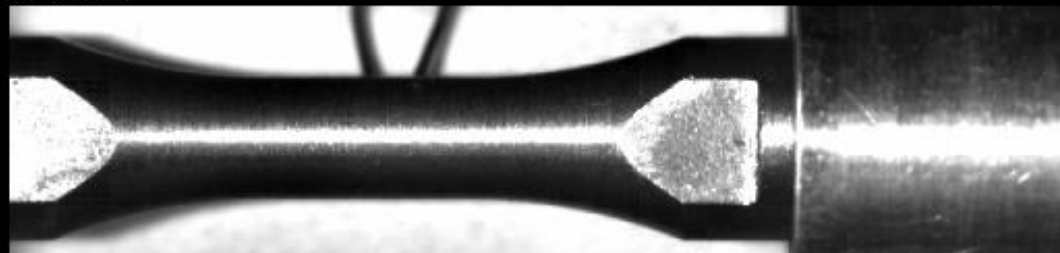
frame : 30

+0.30 ms

Start

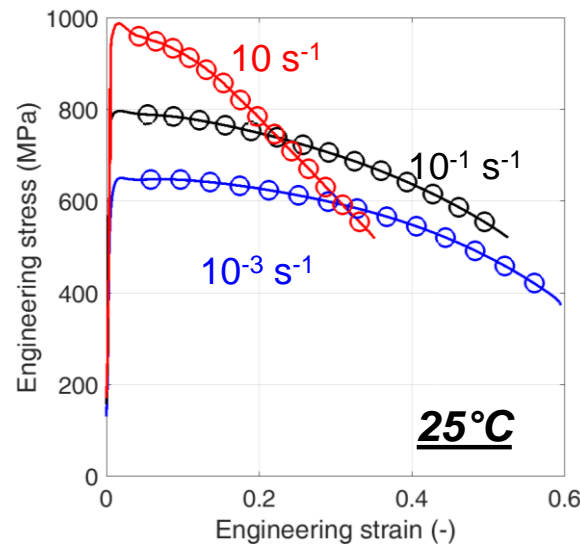
Time : 15:00

Date : 2014/12/23

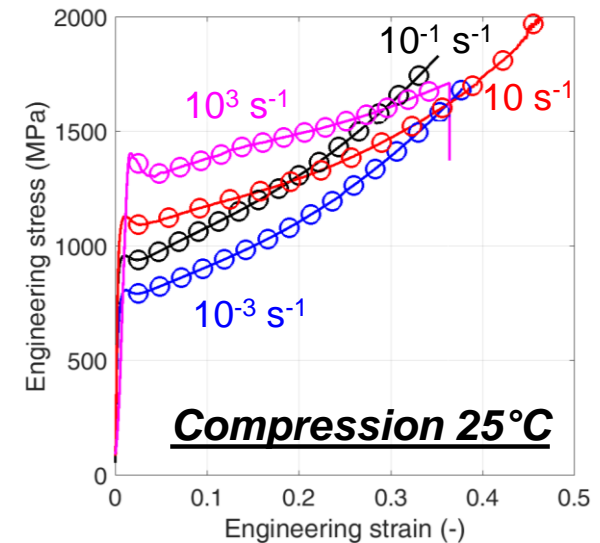
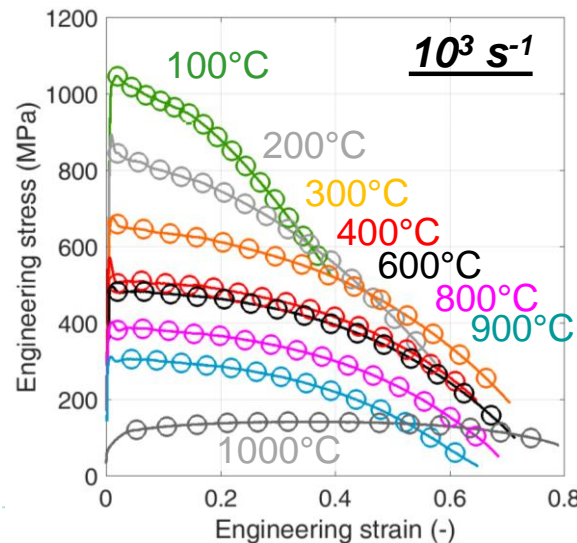
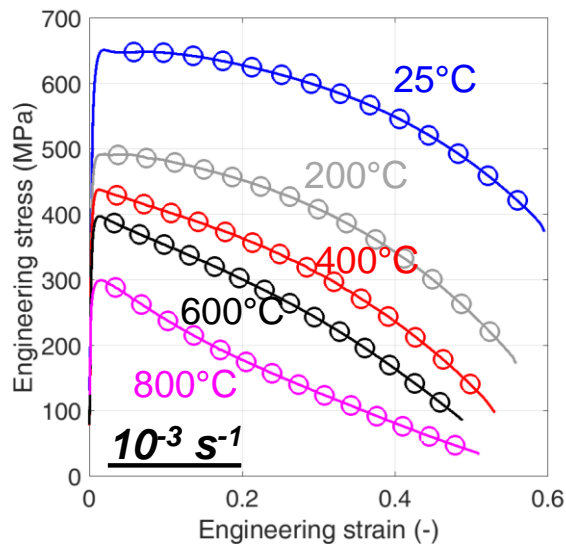
**Mo**
@200°C

DBTT@ 10^3 s^{-1}
IT180 >200°C
Mo >100°C
W >400°C

Ductile/Brittle transition

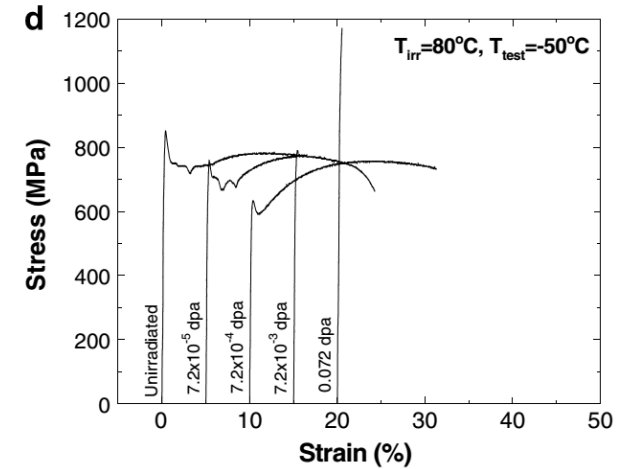
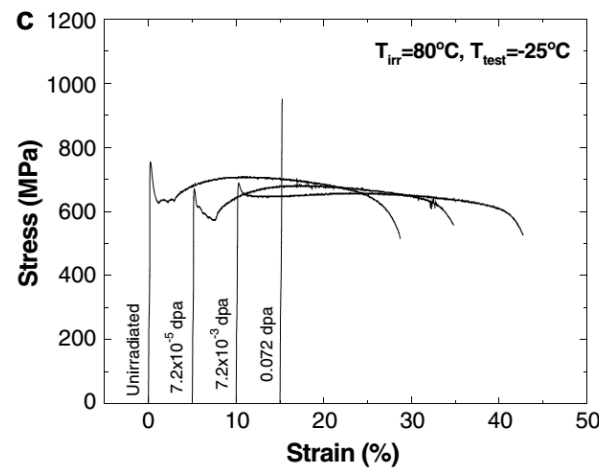
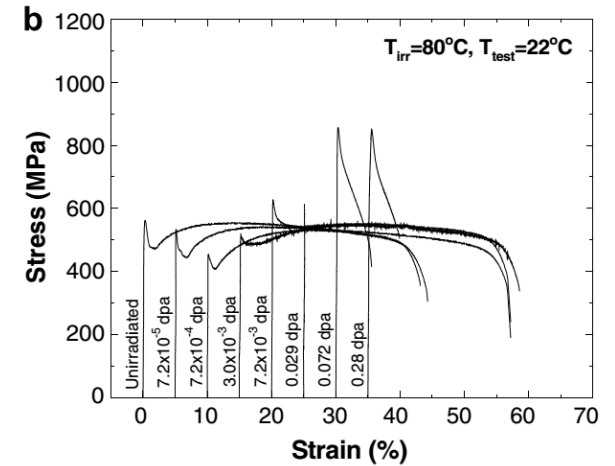
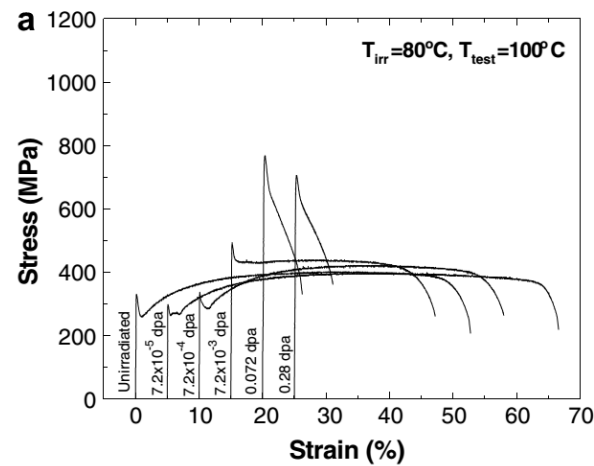
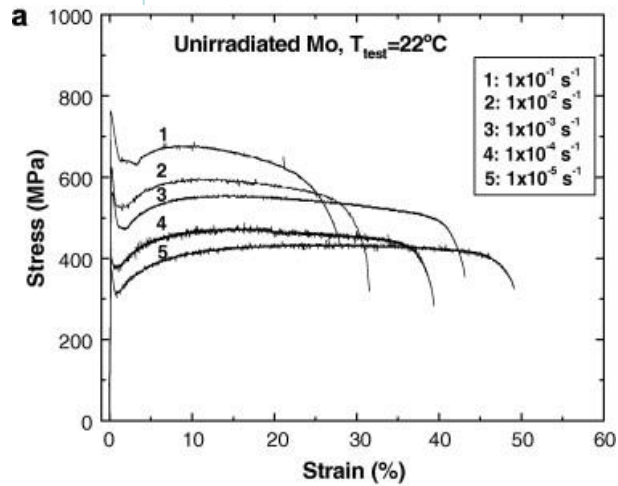


- ✓ Low strain at failure only @high strain-rate @RT
- ✓ Yielding instabilities
- ✓ Localized necking
- ✓ Transition over 900°C (recrystallization)
- ✓ Oxidation during heating



Courtesy of EN-MME Group CERN

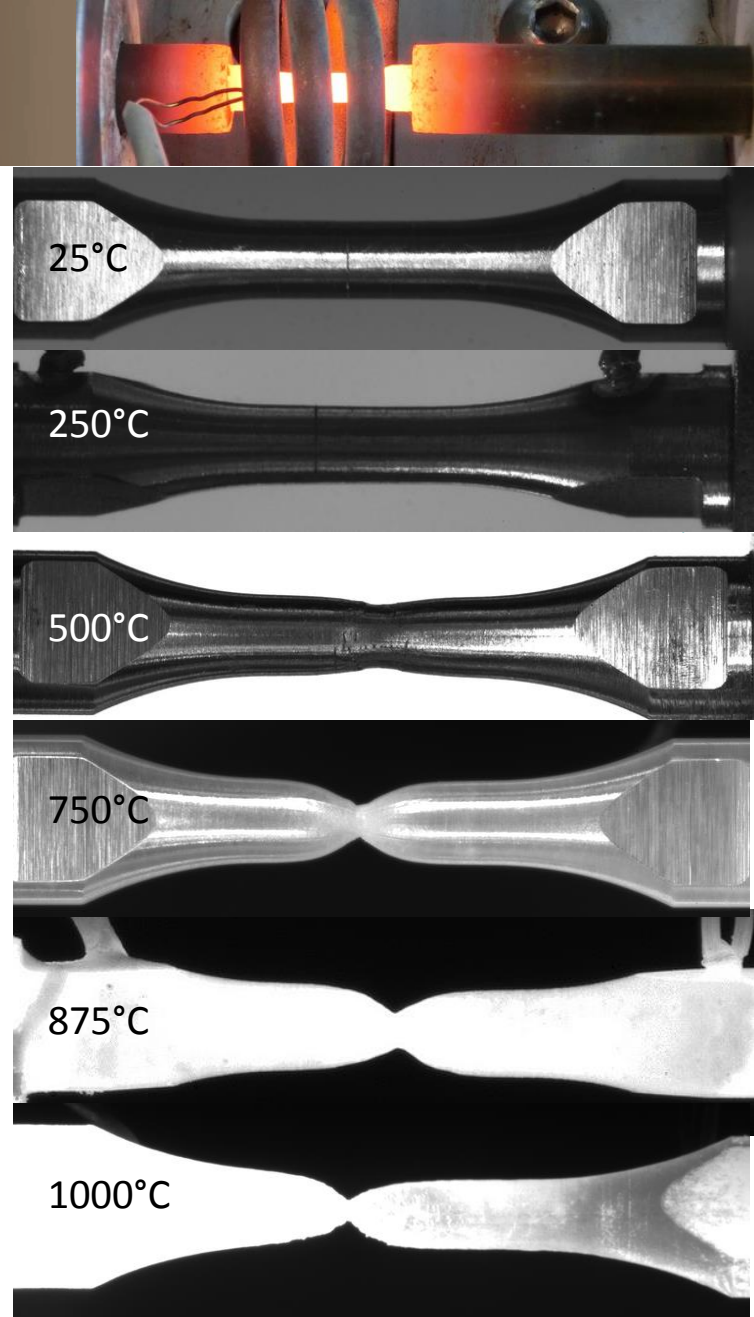
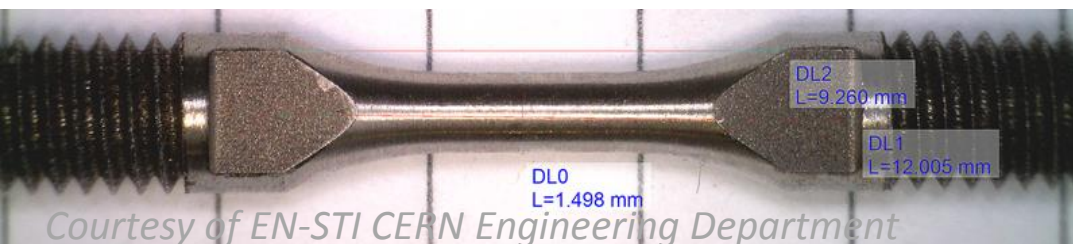
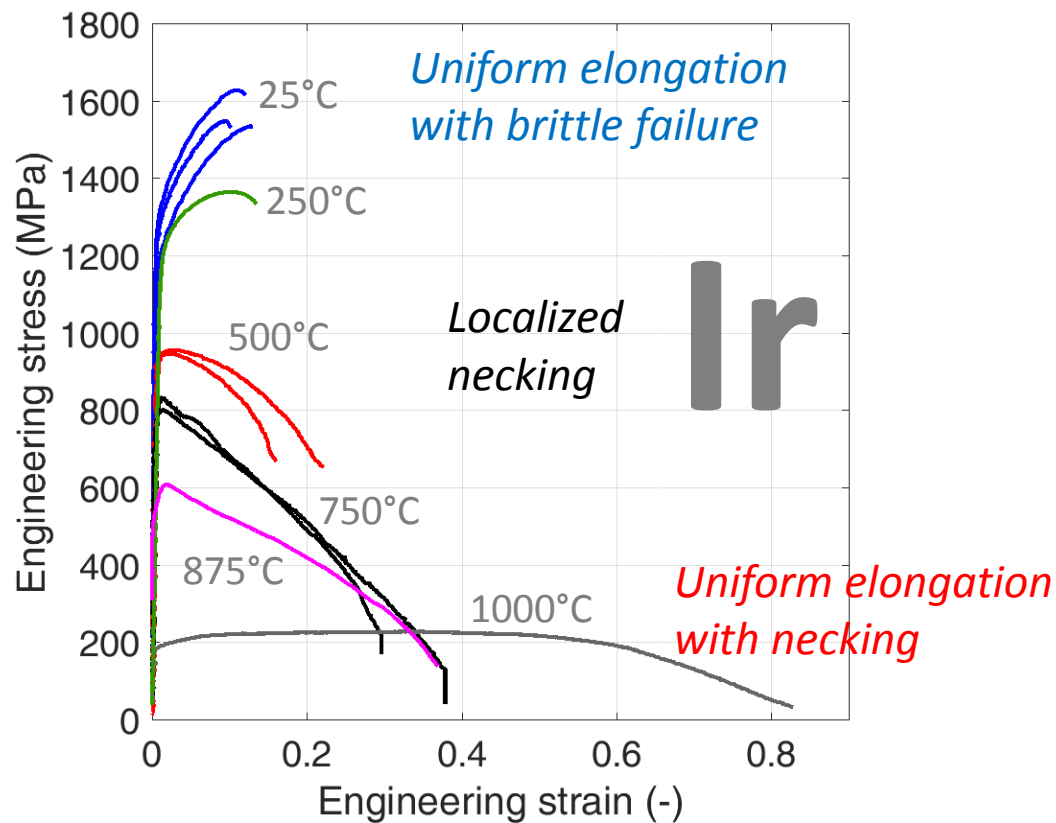
Results – Molybdenum Plansee



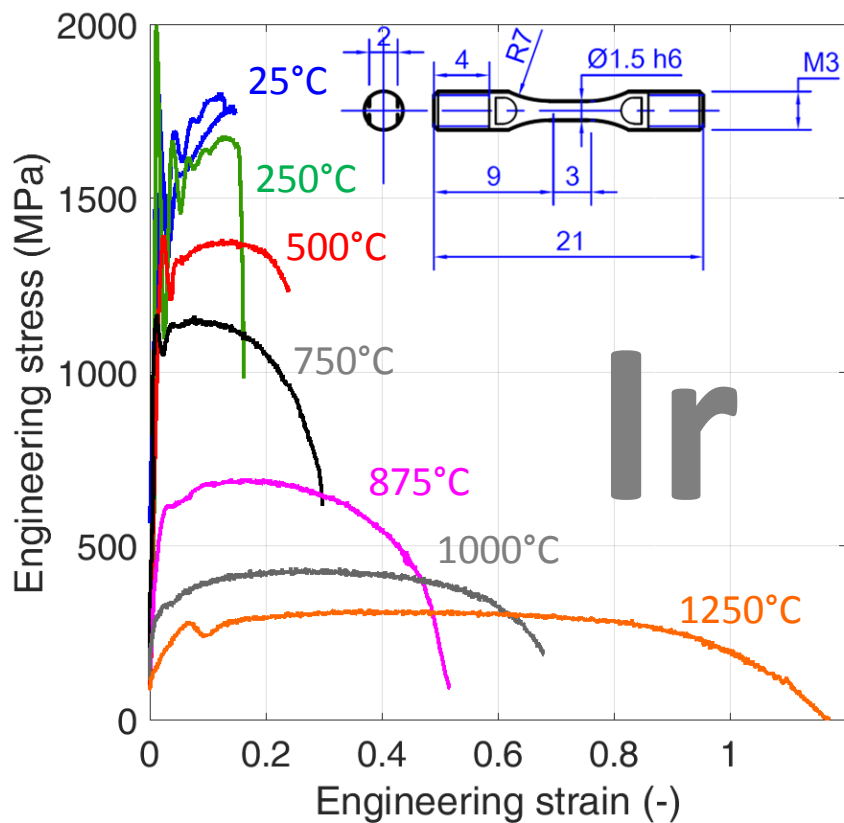
Low temperature neutron irradiation effects on microstructure and tensile properties of molybdenum

Meimei Li, M. Eldrup, T.S. Byun, N. Hashimoto, L.L. Snead, S.J. Zinkle

Irradiation?

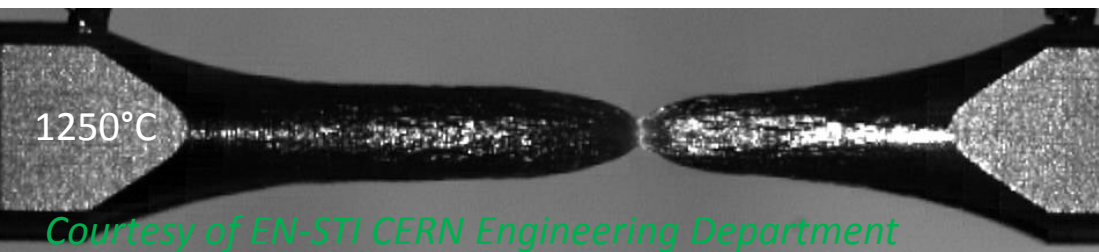
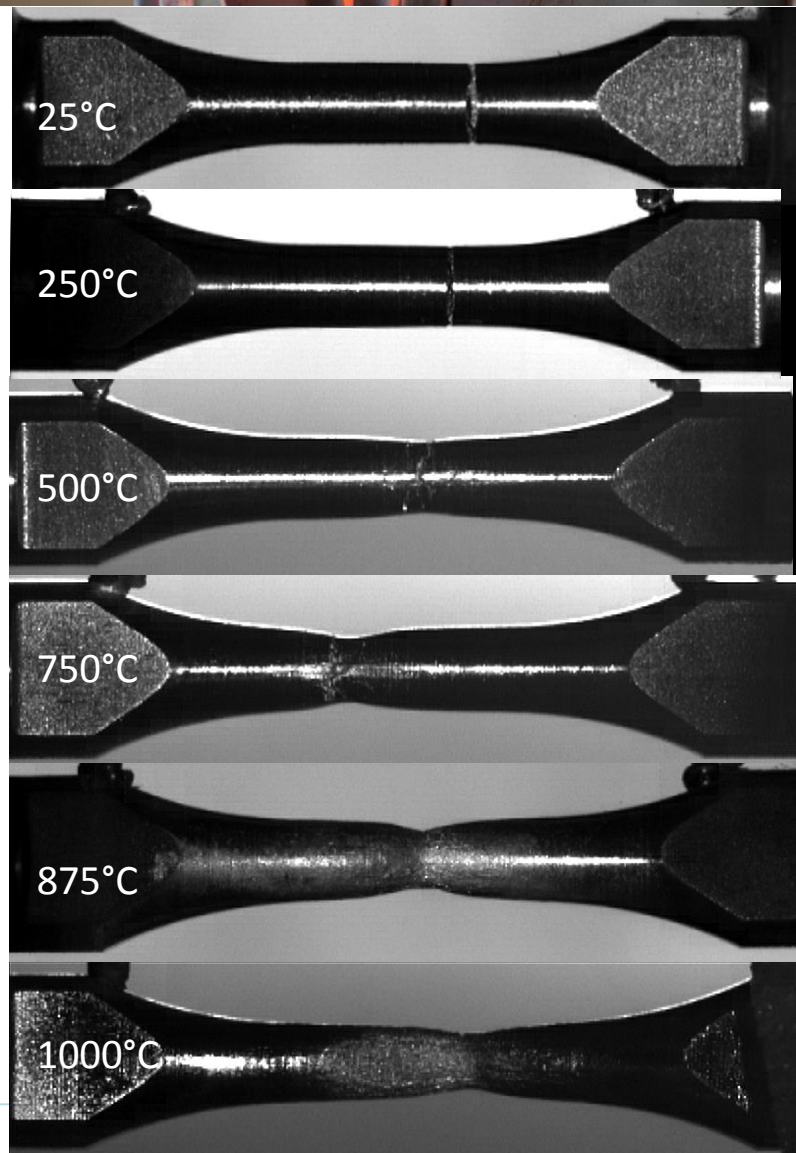


Iridium – Quasi static tests



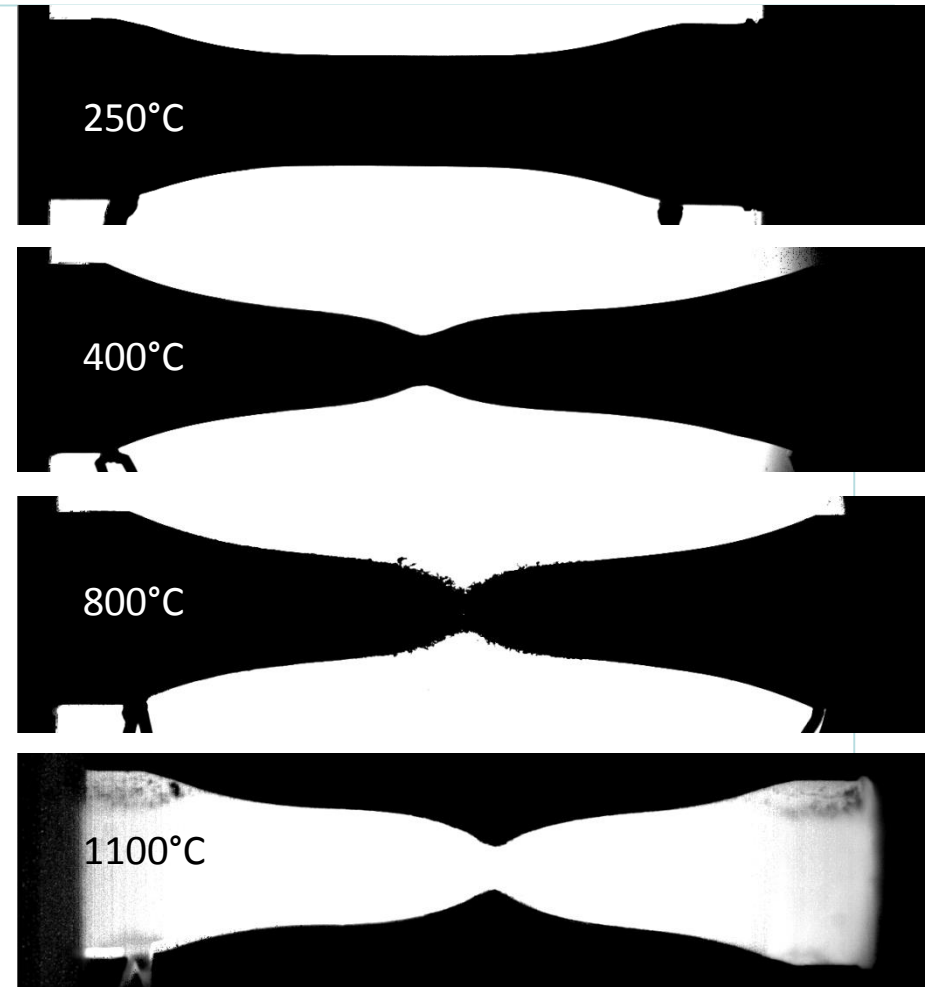
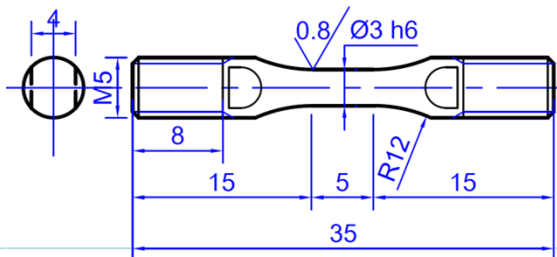
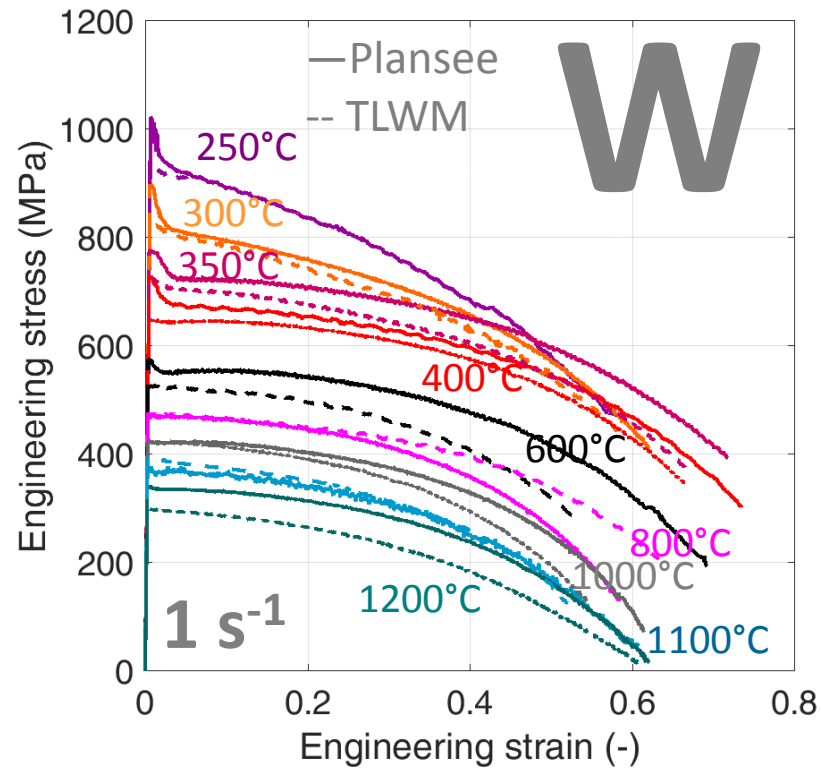
Uniform elongation
with brittle failure

Uniform elongation
with necking



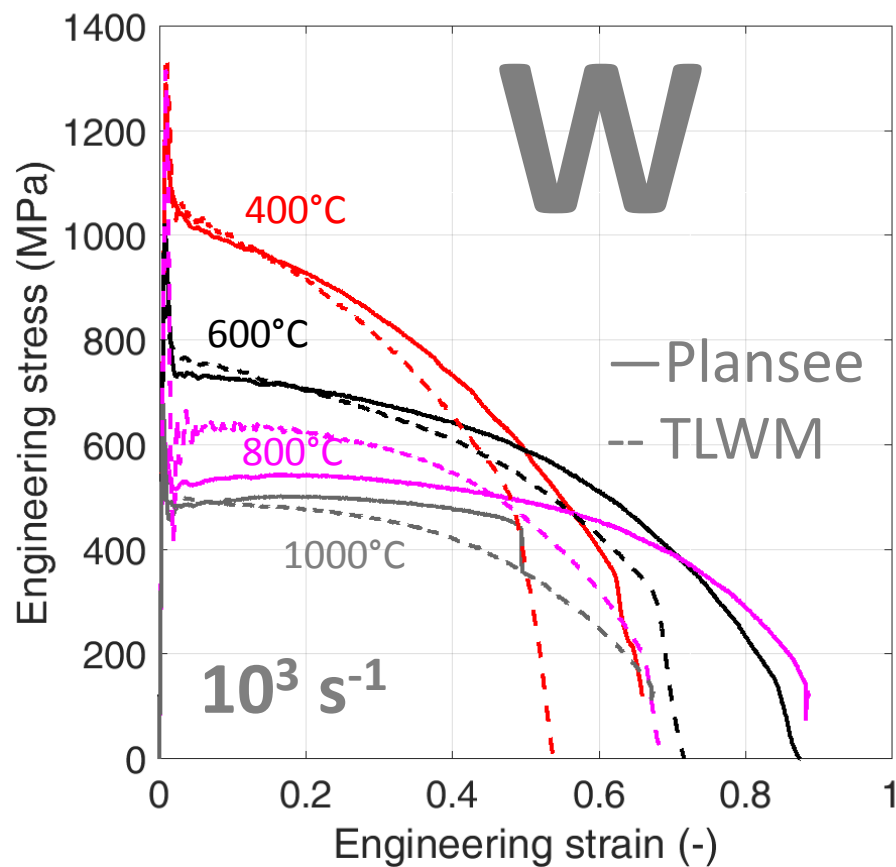
Courtesy of EN-STI CERN Engineering Department

Iridium – Dynamic tests (10^3 s^{-1})



Courtesy of EN-STI CERN Engineering Department

W – Quasi-static tests



100000 fps
1/2713000 sec
512 x 128
frame : 0
+0.00 ms

400°C

100000 fps
1/2713000 sec
512 x 128
frame : 0
+0.00 ms

600°C

100000 fps
1/2713000 sec
512 x 128
frame : 0
+0.00 ms

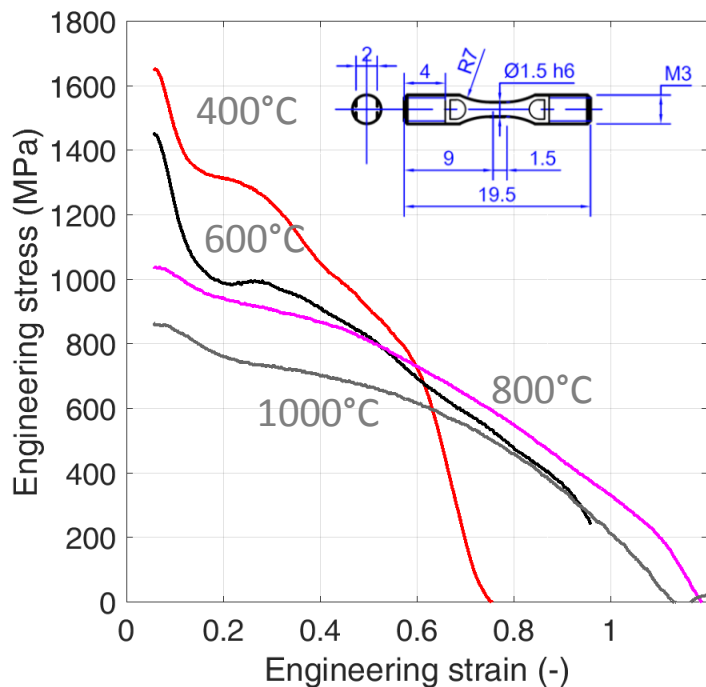
800°C

100000 fps
1/2713000 sec
512 x 128
frame : 0
+0.00 ms

1000°C

Courtesy of EN-STI CERN Engineering Department

W – Dynamic tests



300000 fps
1/2713000 sec
320 x 56
frame : 0
+0.000000 ms
Date : 2016/1/20
Time : 17:17

1000°C

300000 fps
1/2713000 sec
320 x 56
frame : 0
+0.000000 ms
Date : 2016/1/18
Time : 15:23

400°C

300000 fps
1/2713000 sec
320 x 56
frame : 0
+0.000000 ms
Date : 2016/1/18
Time : 17:17

600°C

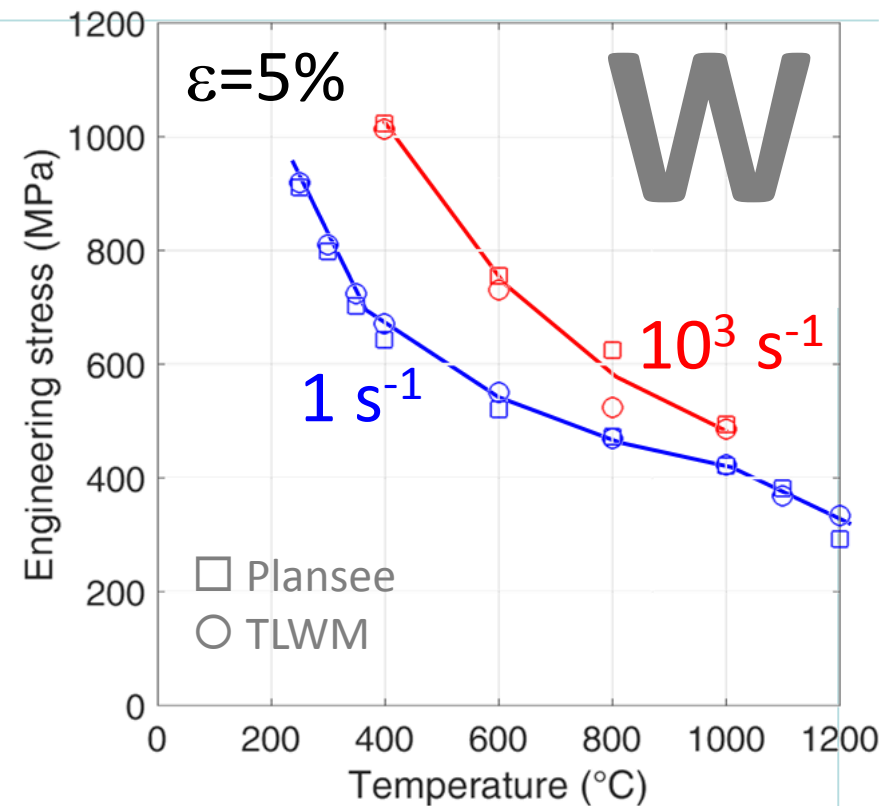
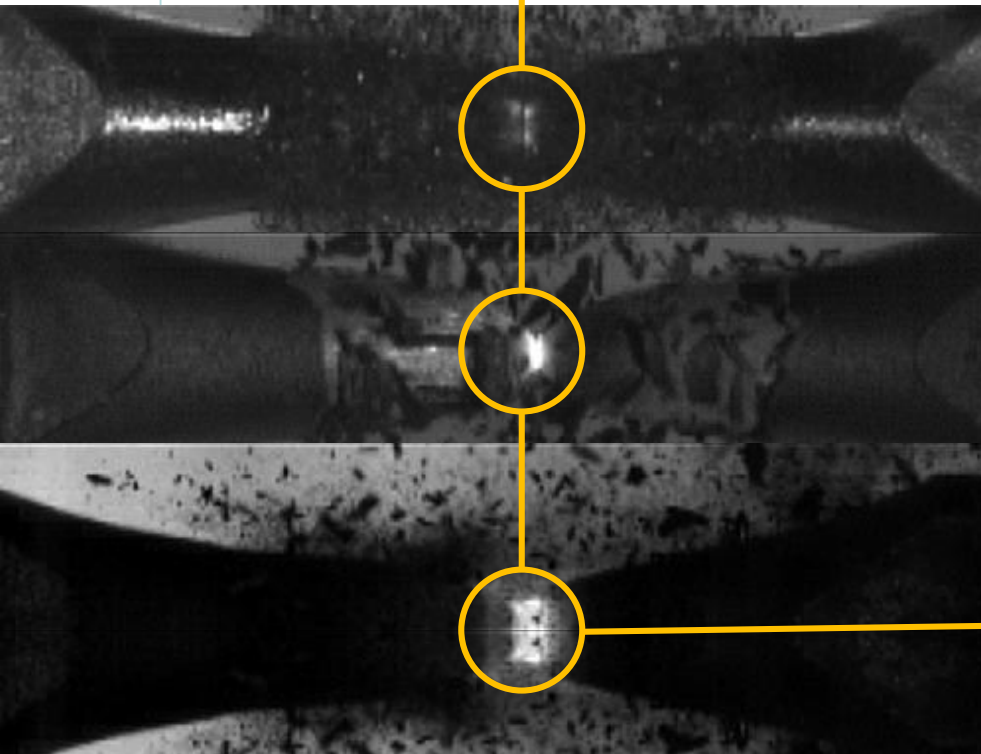
300000 fps
1/2713000 sec
320 x 56
frame : 0
+0.000000 ms
Date : 2016/1/20
Time : 16:11

800°C

W Plansee – Dynamic tests

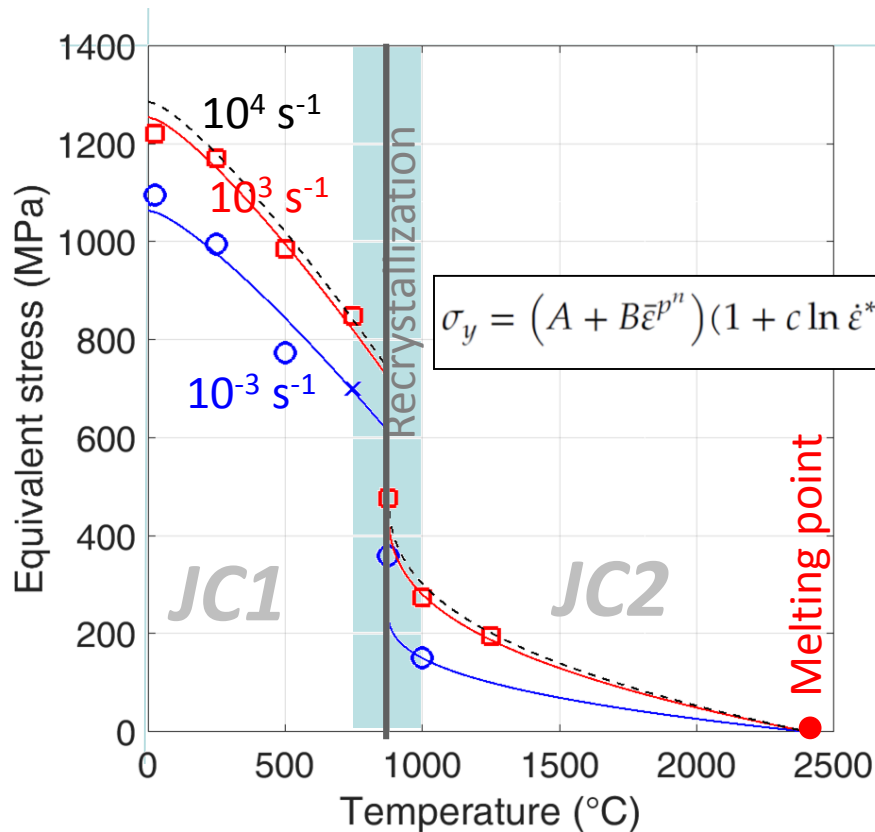


It is possible to appreciate the considerable increase in temperature due to the conversion of the plastic work into heat



This phenomenon is much more observable in tests performed at ultra-high strain-rate and high temperature

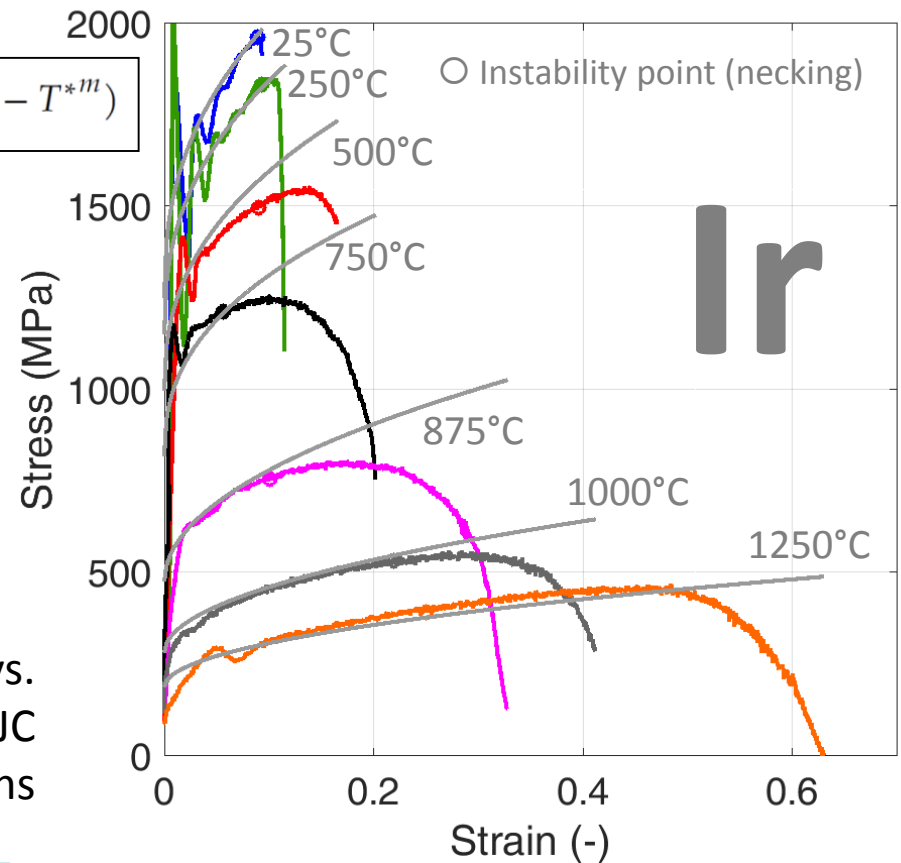
Thermal softening – Self Heating



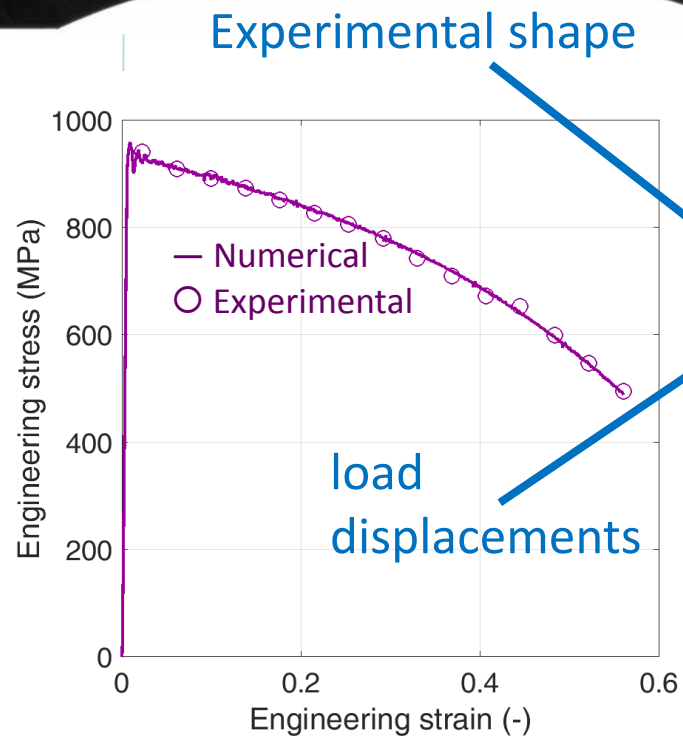
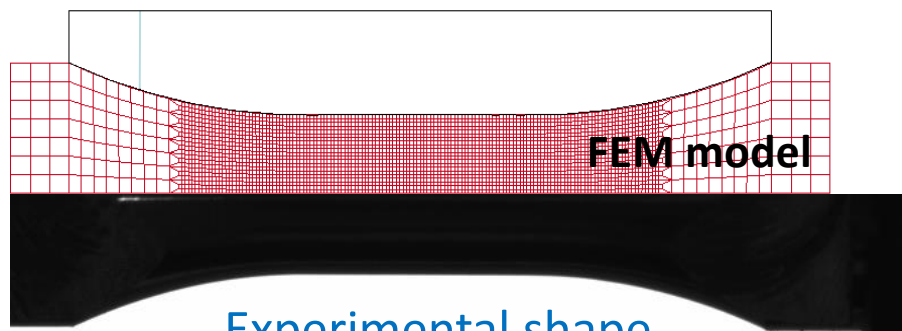
Experimental logarithmic (true) stress vs.
effective plastic strain compared with JC
model previsions

Courtesy of EN-STI CERN Engineering Department

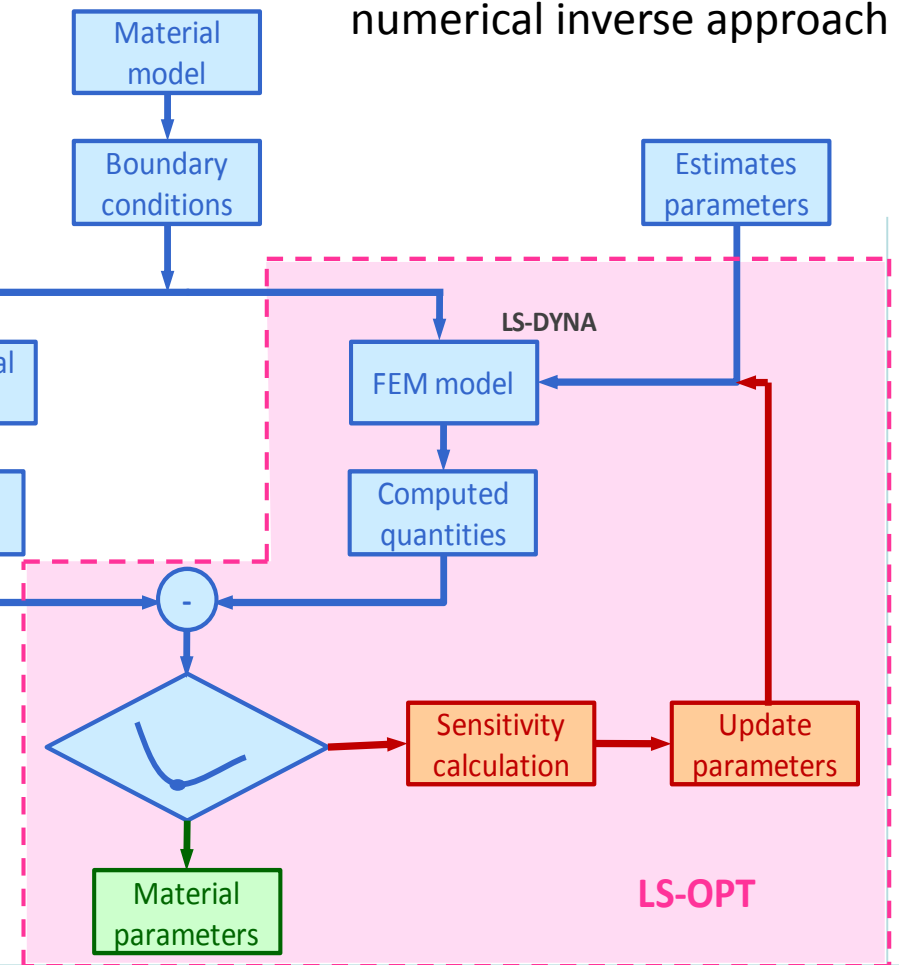
Two different JC models:
JC1 for $25^\circ\text{C} \leq T < 875^\circ\text{C}$ and JC2 for $T \geq 875^\circ\text{C}$



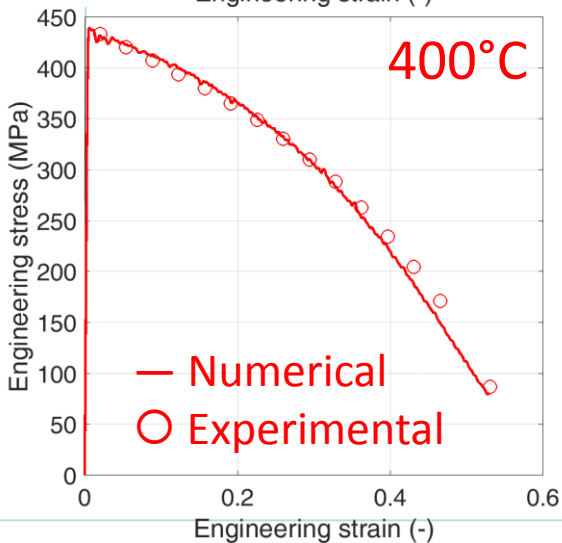
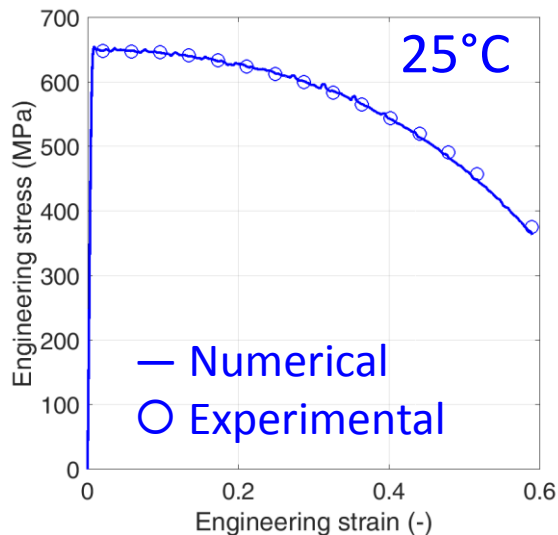
Modelling: Iridium – 2 Regions JC model



Optimization procedure for
numerical inverse approach



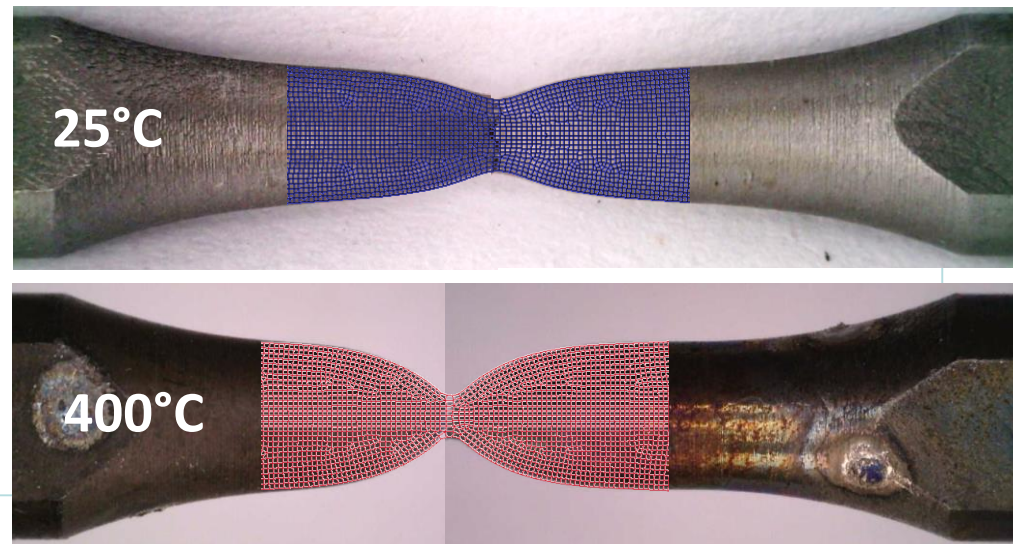
Numerical analysis for model identification



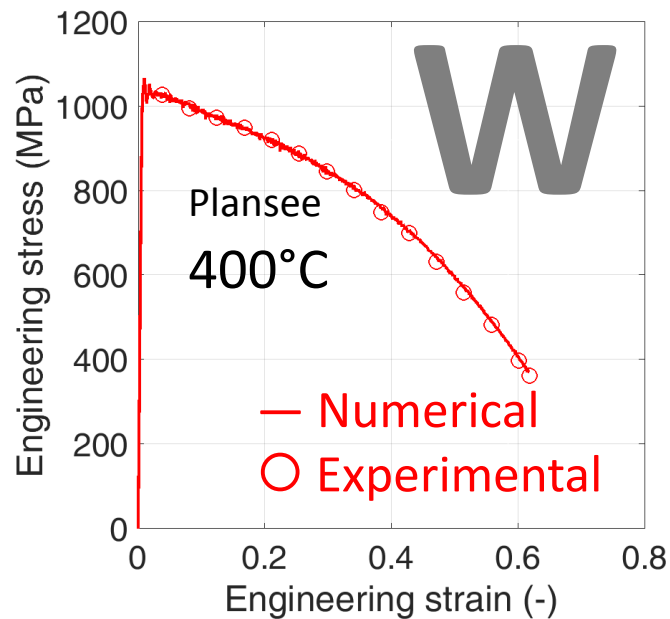
10^{-3} s^{-1}
Mo

Using an numerical inverse approach, in which strain, strain-rate and temperature effects are taken into account, it is possible to reproduce the local material behaviour with a high level of accuracy, both in terms of engineering stress-strain response and deformed shape

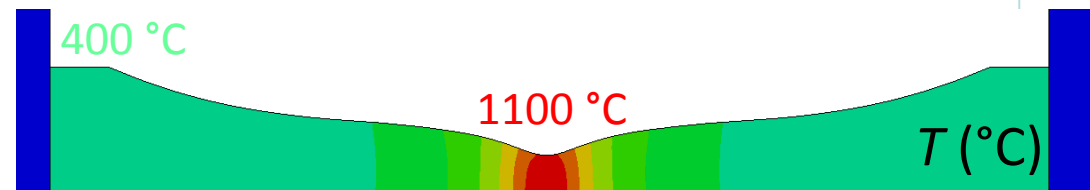
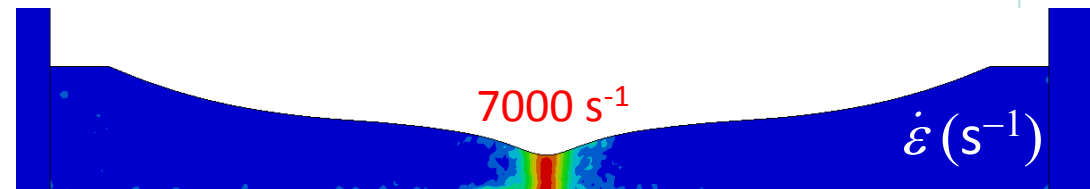
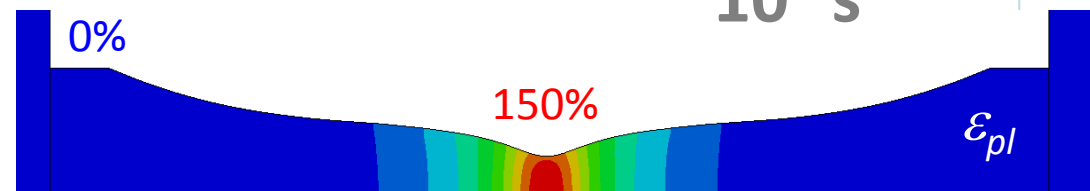
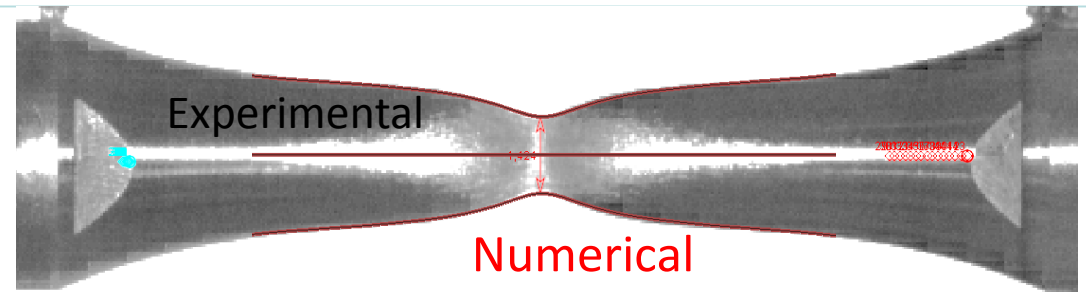
Global remeshing



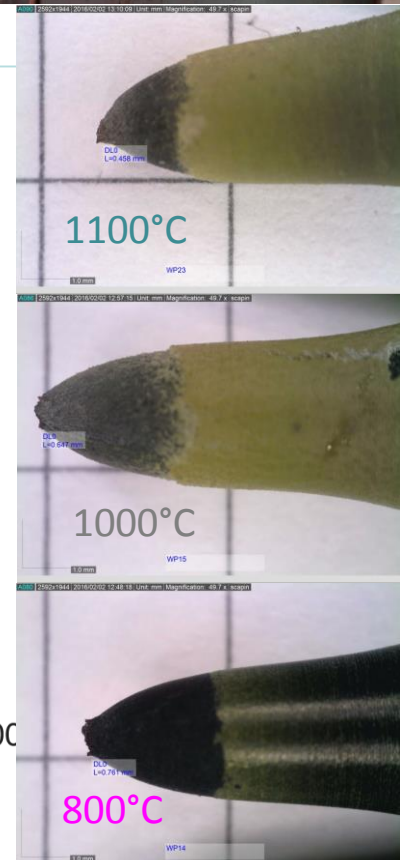
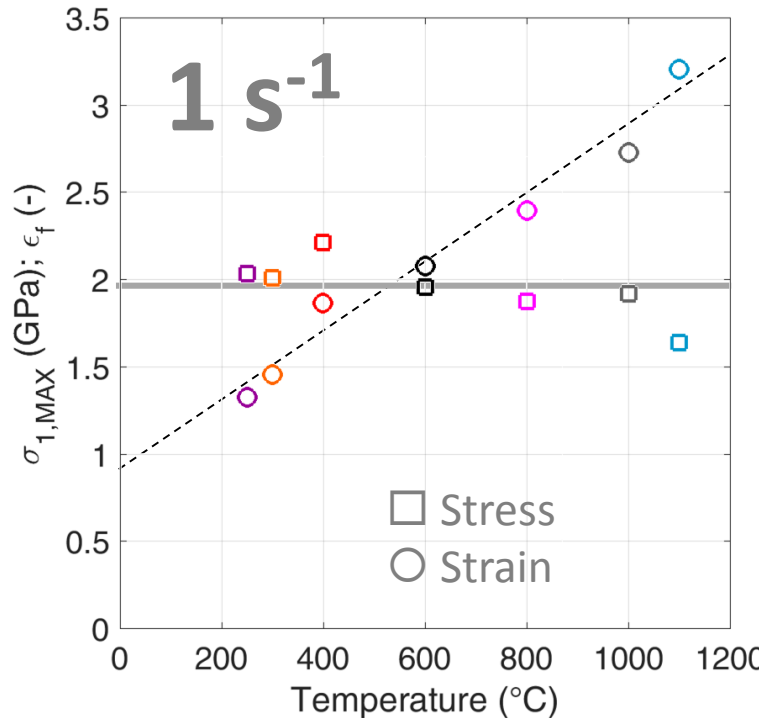
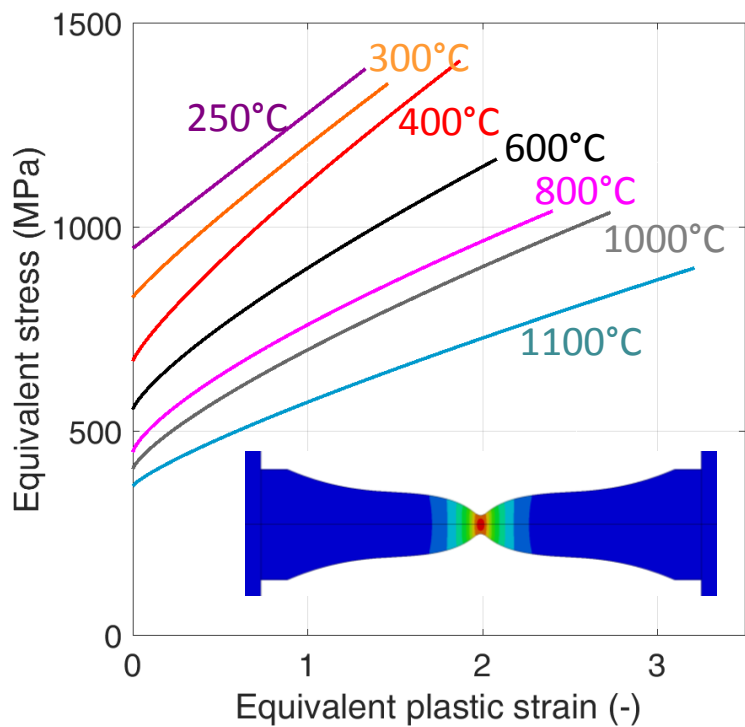
Result analysis: Molybdenum



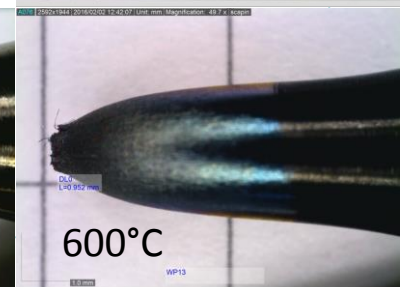
The numerical approach allows to take into account also for the temperature increment during the test (adiabatic condition)



Result analysis: Tungsten



W



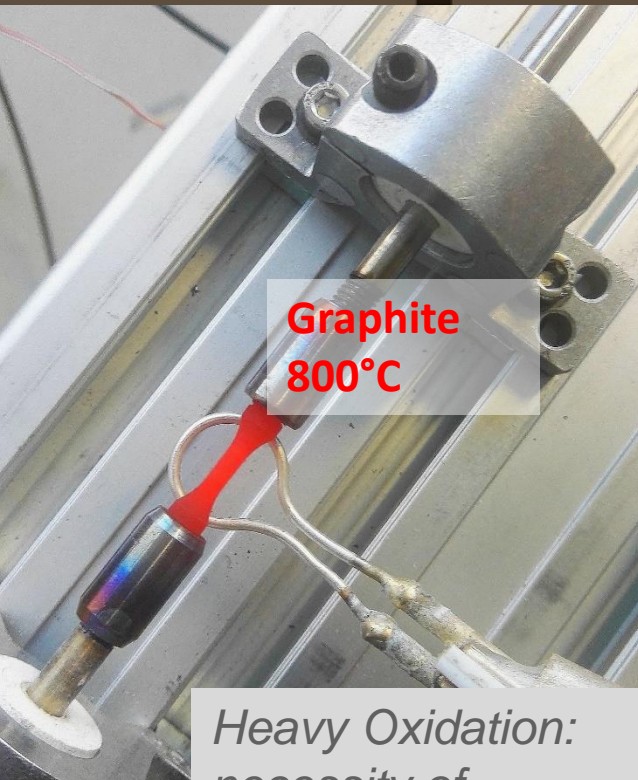
Strain @ failure



- ✓ Copper
- ✓ Glidcop
- ✓ Inermet180
- ✓ Densamet
- ✓ Molybdenum (Plansee – AT&M)
- ✓ Iridium
- ✓ Tungsten (Plansee – TLWM)
- ✓ Niobium (sheets)
- ✓ Copper (sheets)
- ✓ Lead and Lead-Antimony

2013

2016



Graphite
800°C

*Heavy Oxidation:
necessity of
heating in vacuum*



Silicon



Lead

Graphite



MoGr



100000 fps
1/2713000 sec
448 x 144
frame : 46
+0.46 ms

UTS 150 MPa

Graphite 25°C



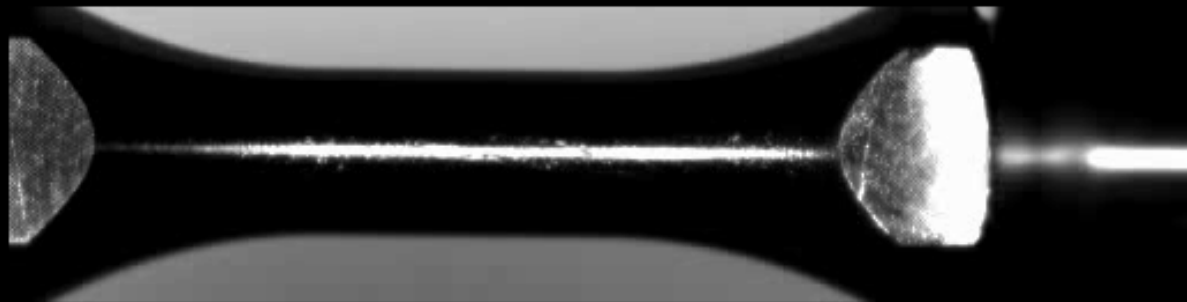
The future: brittle and low strength materials



100000 fps
1/2713000 sec
512 x 128
frame : 30
+0.30 ms
Date : 2016/4/15
Time : 12:42



100000 fps
1/2713000 sec
512 x 128
frame : 30
+0.30 ms
Date : 2016/4/14
Time : 18:08



Silicon and Lead



100000 fps

1/2713000 sec

448 x 144

frame : 25

+0.25 ms

Date : 2016/4/22

Time : 12:06



100000 fps

1/2713000 sec

448 x 144

frame : 30

+0.30 ms

Date : 2016/4/22

Time : 11:45



Graphite



- ✓ The investigation of the mechanical response of refractory metals was performed, in last years, at different temperatures and strain-rates.
- ✓ A methodology for testing materials at high strain-rate at various temperatures was presented. The methodology consists of performing dynamic tensile tests using a SHTB setup and heating the specimen using an induction coil system.
- ✓ The heating system is properly design to concentrate the heat flux in the gage length of the specimen: the investigated range in temperature was from room temperature up to 1250 °C (in the next future >1500°C). Vacuum protection is necessary in the future.
- ✓ An improvement in the setup allows the fast video recording of the test at high temperature and strain-rates; a miniaturized setup was developed in order to reach strain-rates greater than 10^4 s^{-1} .
- ✓ The experimental data obtained from quasi-static and dynamic tensile tests are processed via a numerical inverse method based on FEM numerical simulations in order to perform the material model identification.

Thank you for your attention



**POLITECNICO
DI TORINO**

Mechanical and Aerospace Engineering Department

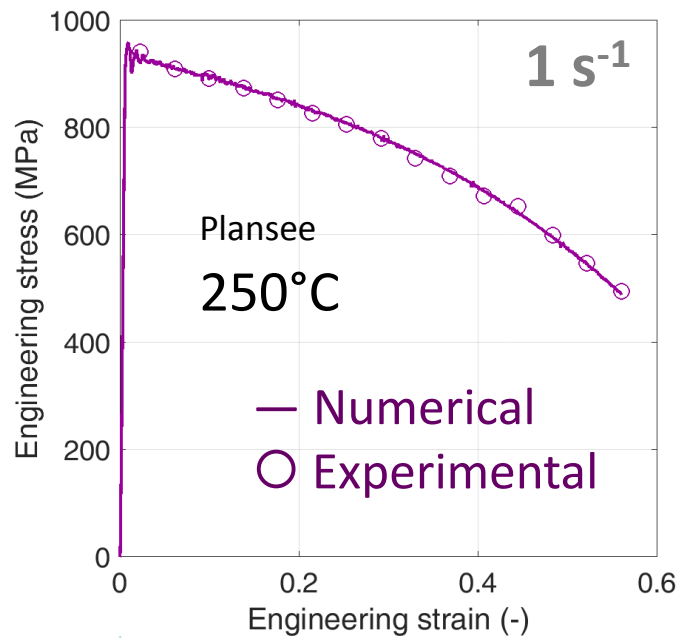
3rd EuCARD-2 Annual Meeting, 26-28 April 2016, University of Malta

Backup slides

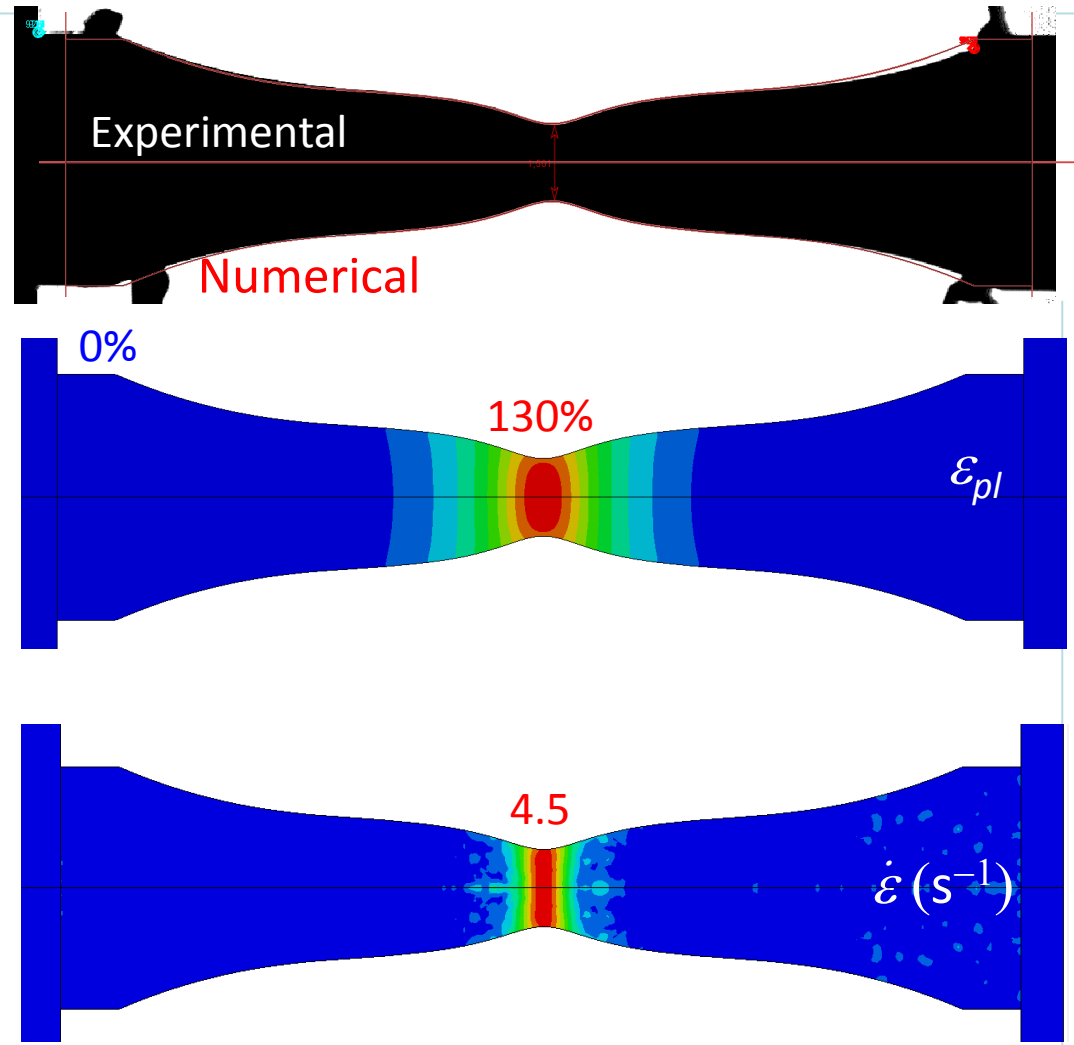


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DI TORINO**

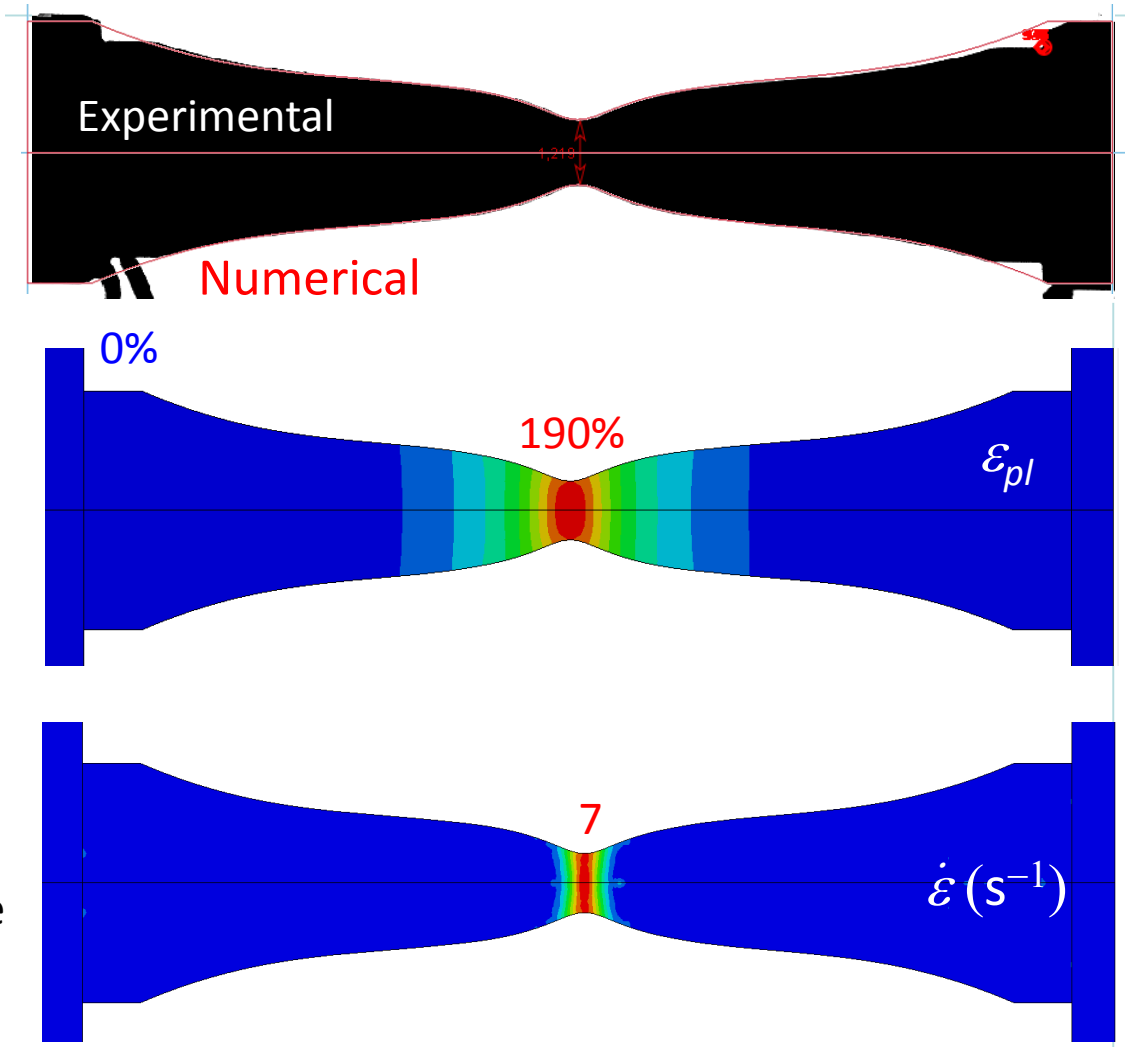
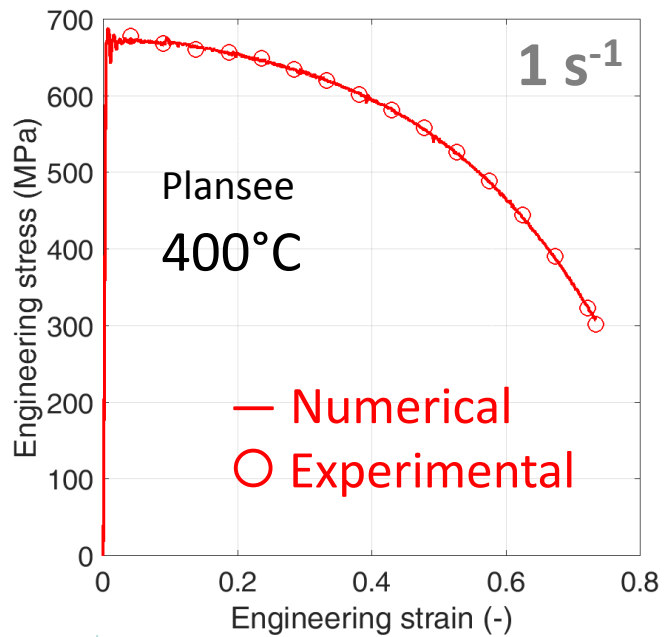
Mechanical and Aerospace Engineering Department



Using an numerical inverse approach, in which strain, strain-rate and temperature effects are taken into account, it is possible to reproduce the local material behaviour with a high level of accuracy, both in terms of engineering stress-strain response and deformed shape

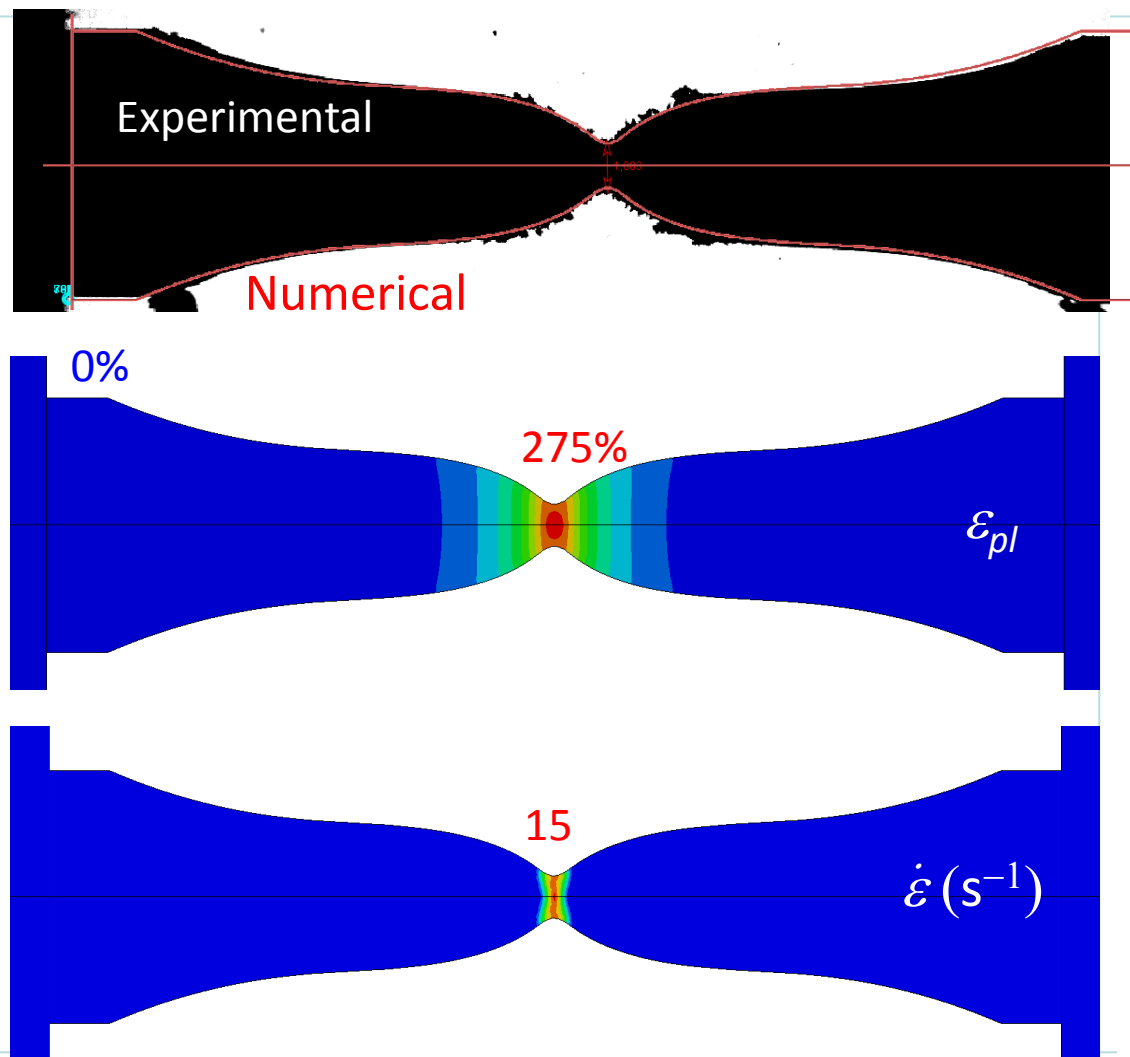
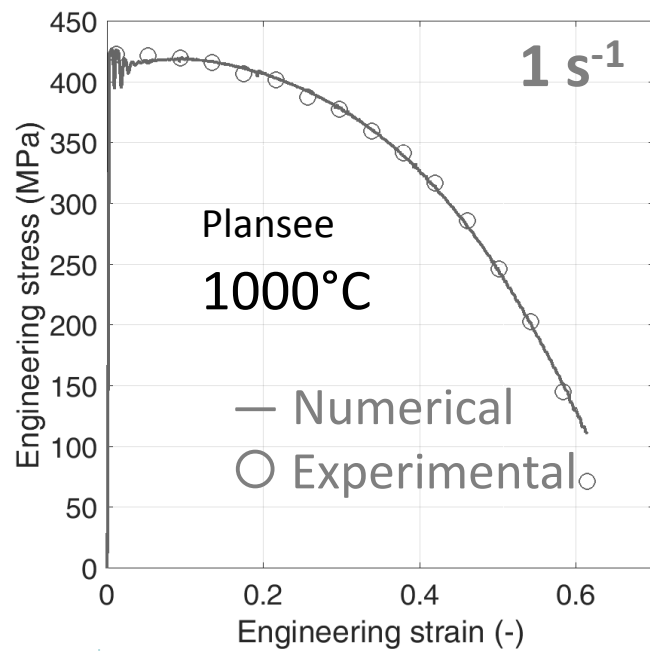


Result analysis

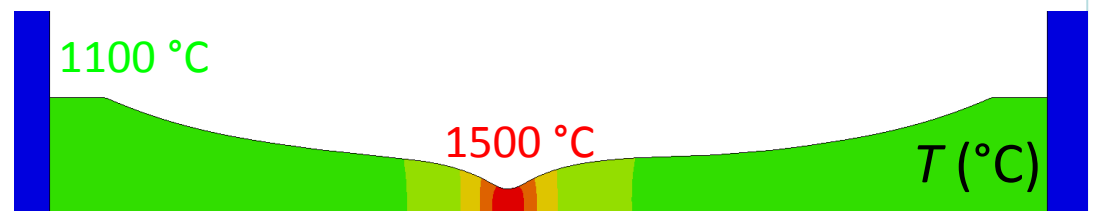
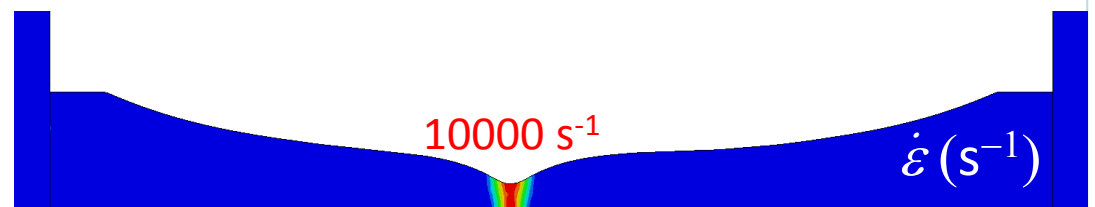
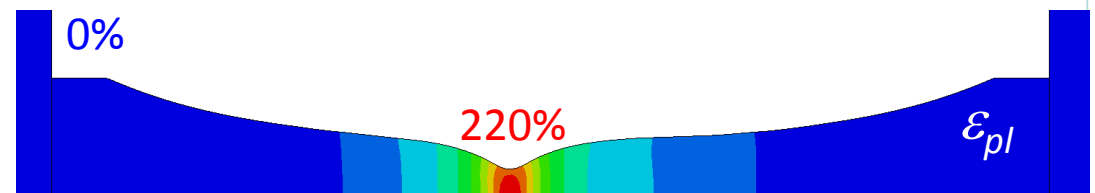
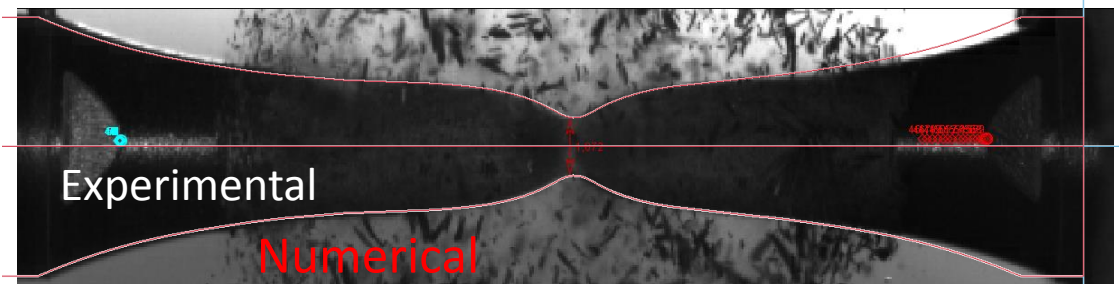
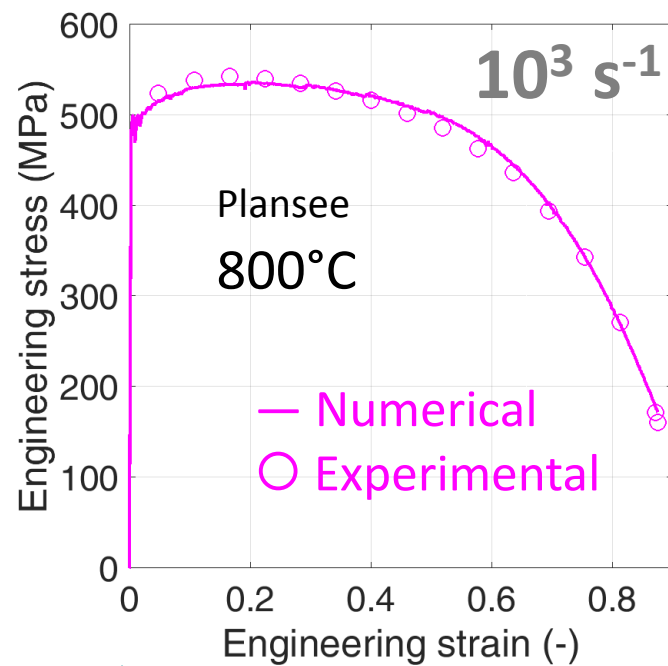


The numerical approach allows to take into account for the strain-rate increment during the test

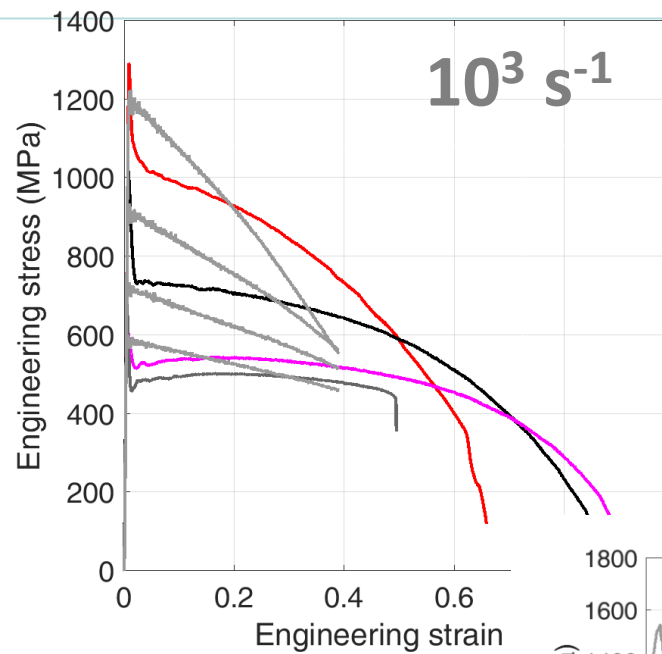
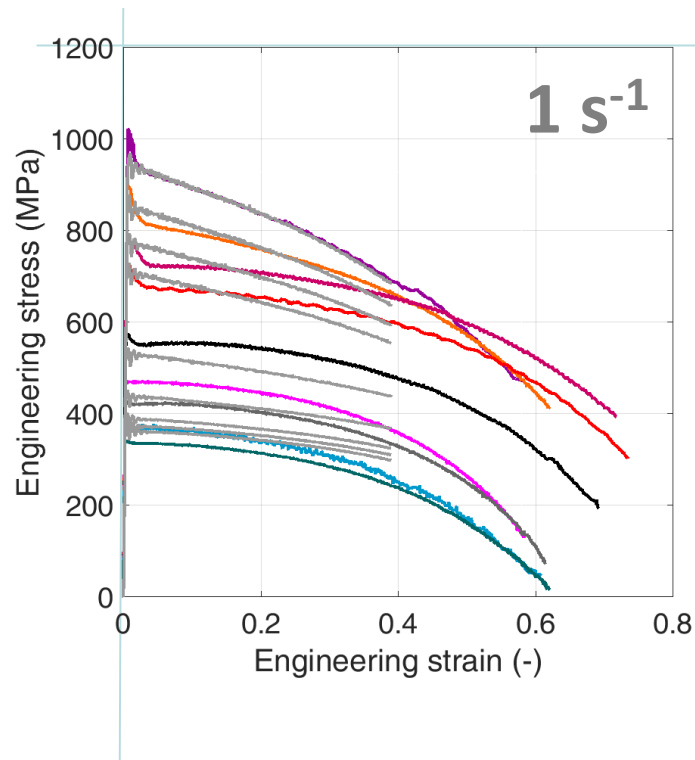
Result analysis



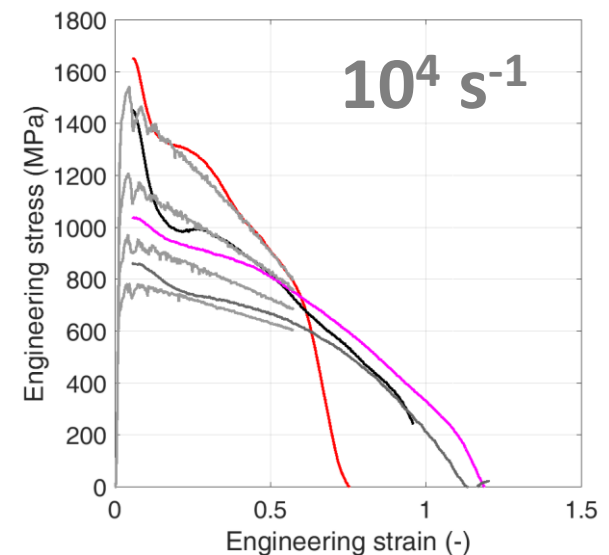
Result analysis



Result analysis



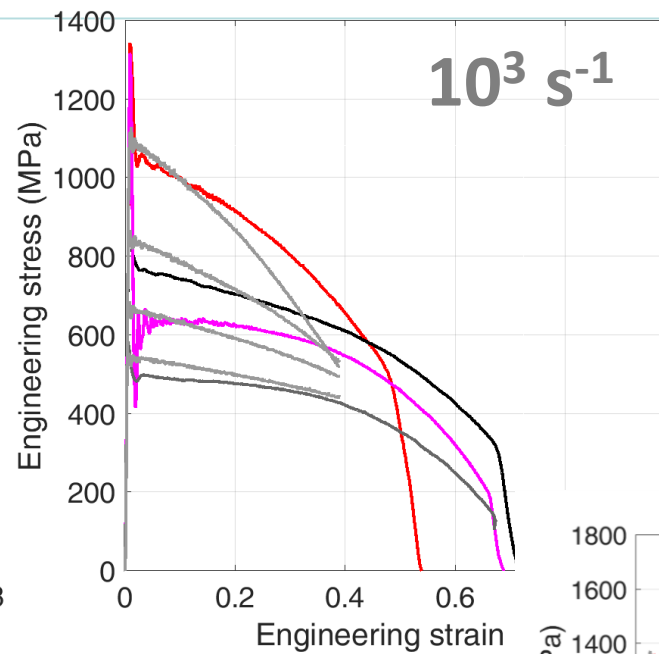
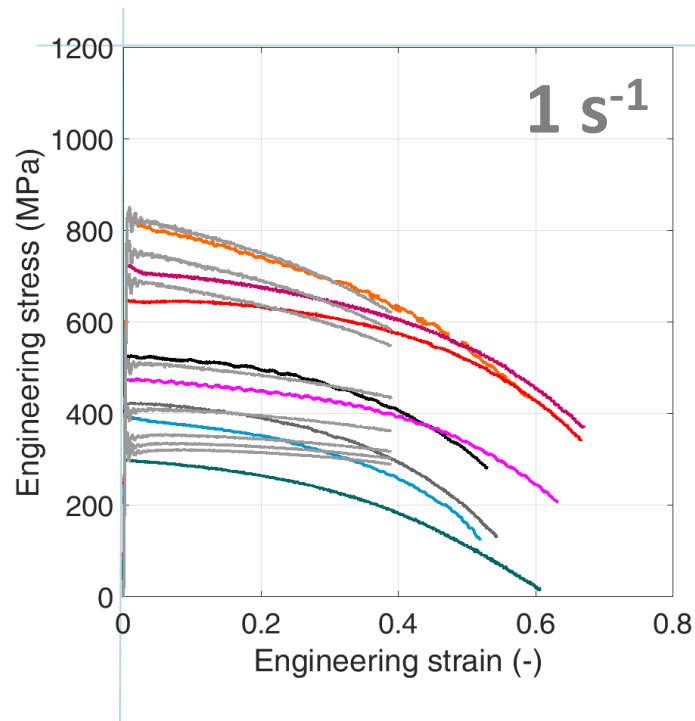
$$\begin{aligned} C_1 &= 331.4 \text{ MPa} \\ C_2 &= 3221.6 \text{ MPa} \\ C_3 &= 3.117 \times 10^{-3} \text{ 1/K} \\ C_4 &= 1.742 \times 10^{-4} \text{ 1/K} \\ C_5 &= 242.2 \text{ MPa} \\ n &= 0.9771 \end{aligned}$$



Zerilli- Armstrong for BCC metals

$$\sigma_y = C_1 + C_2 e^{[-C_3 + C_4 \ln(\dot{\epsilon}_{pl})]T} + C_5 \epsilon_{pl}^n$$

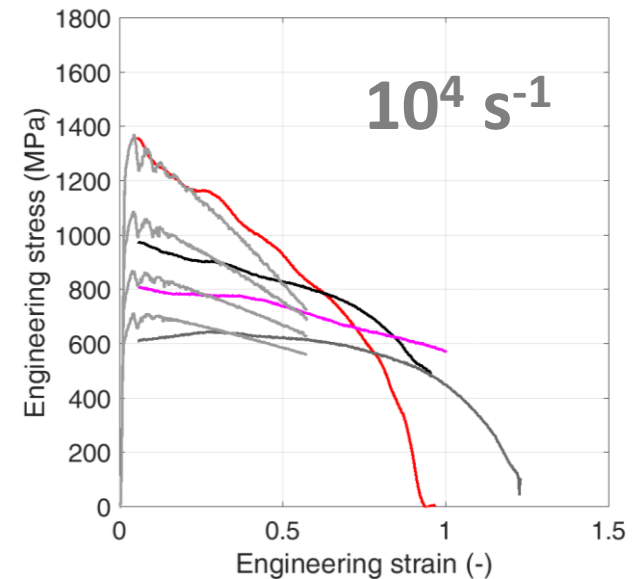
Z-A global strength model - Plansee



$$\begin{aligned} C_1 &= 268.9 \text{ MPa} \\ C_2 &= 2778.3 \text{ MPa} \\ C_3 &= 2.751 \times 10^{-3} \text{ 1/K} \\ C_4 &= 1.436 \times 10^{-4} \text{ 1/K} \\ C_5 &= 233.4 \text{ MPa} \\ n &= 0.8053 \end{aligned}$$

For both the materials, the obtained global Z-A models are able to predict the behaviour, even if in some cases the error could be significant

The Z-A model was not proposed to cover so wide range in strain, strain-rate and temperature: the accuracy should be better by focusing on limited range

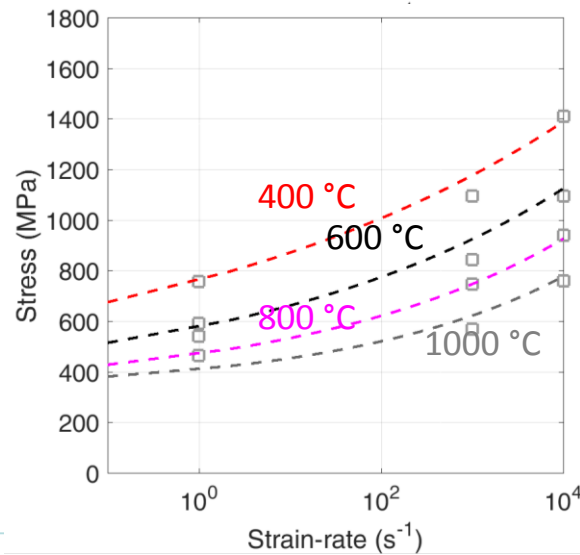
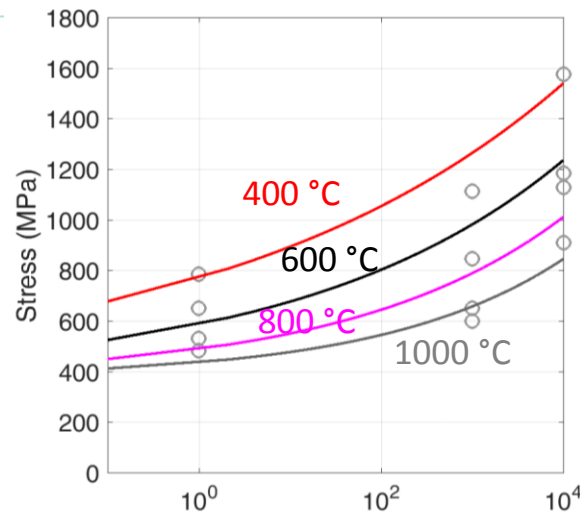
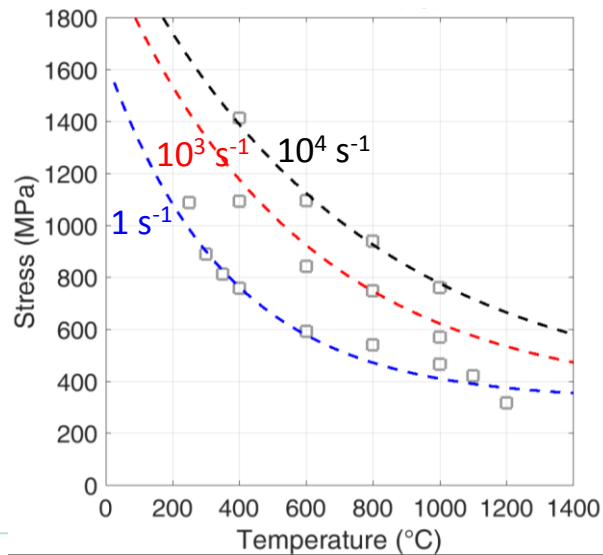
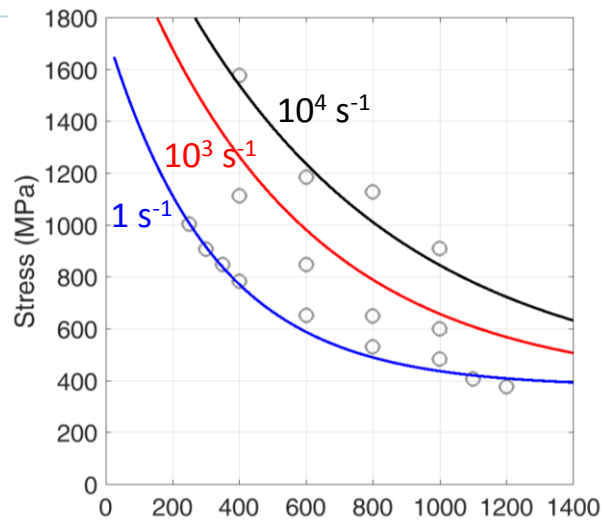


Z-A global strength model - TLWM



Plansee

TLWM



Z-A model previsions
compared with
experimental data at
a fixed value of
strain

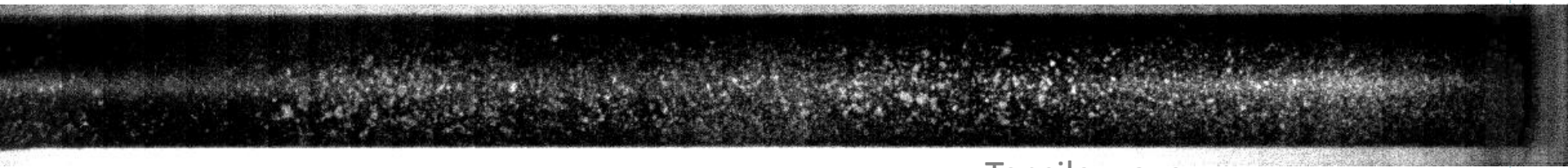
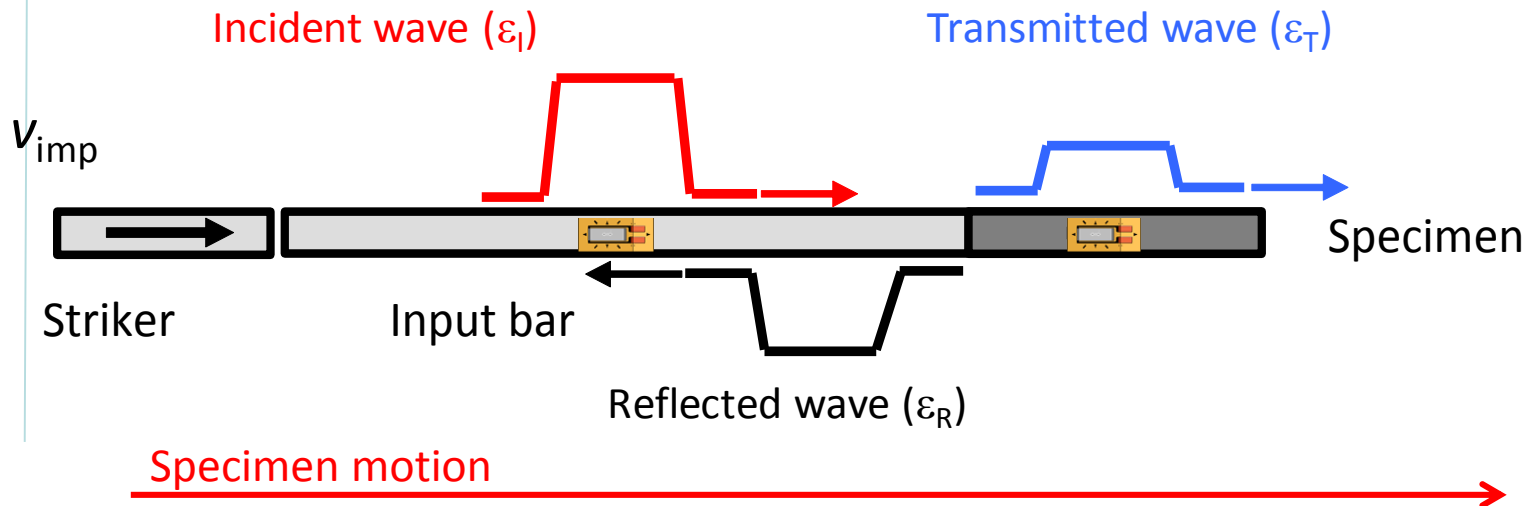
$$\varepsilon_{eng} = 20\%$$

Z-A global strength model



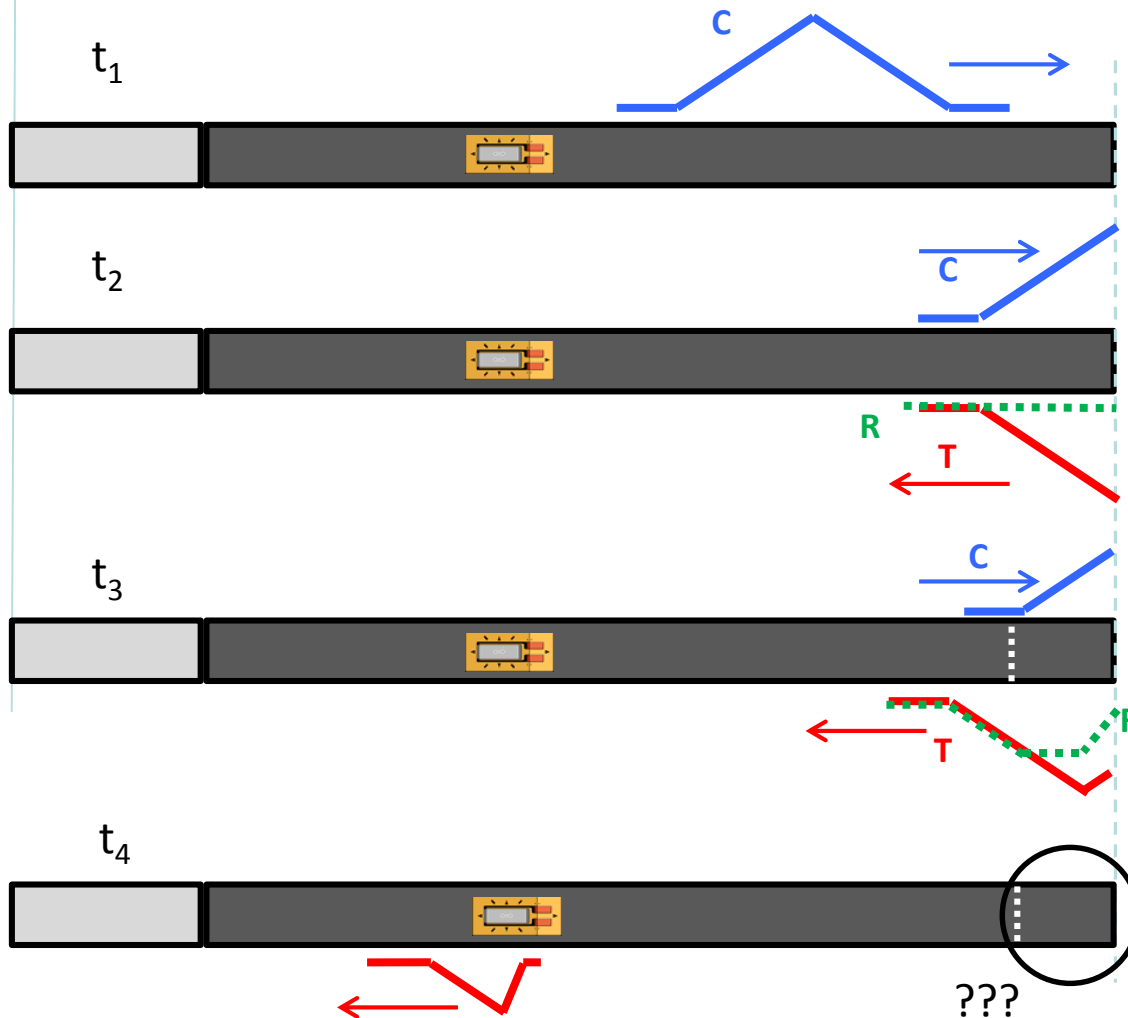
The SHPB setup is **modified in order to permit dynamic tensile tests on brittle material (graphite)**, to evaluate the rupture strain at high strain rates.

The compressive wave reflects on the free surface and turns into a **rarefaction wave**.



← Tensile wave →

SHPB Spalling test (I)



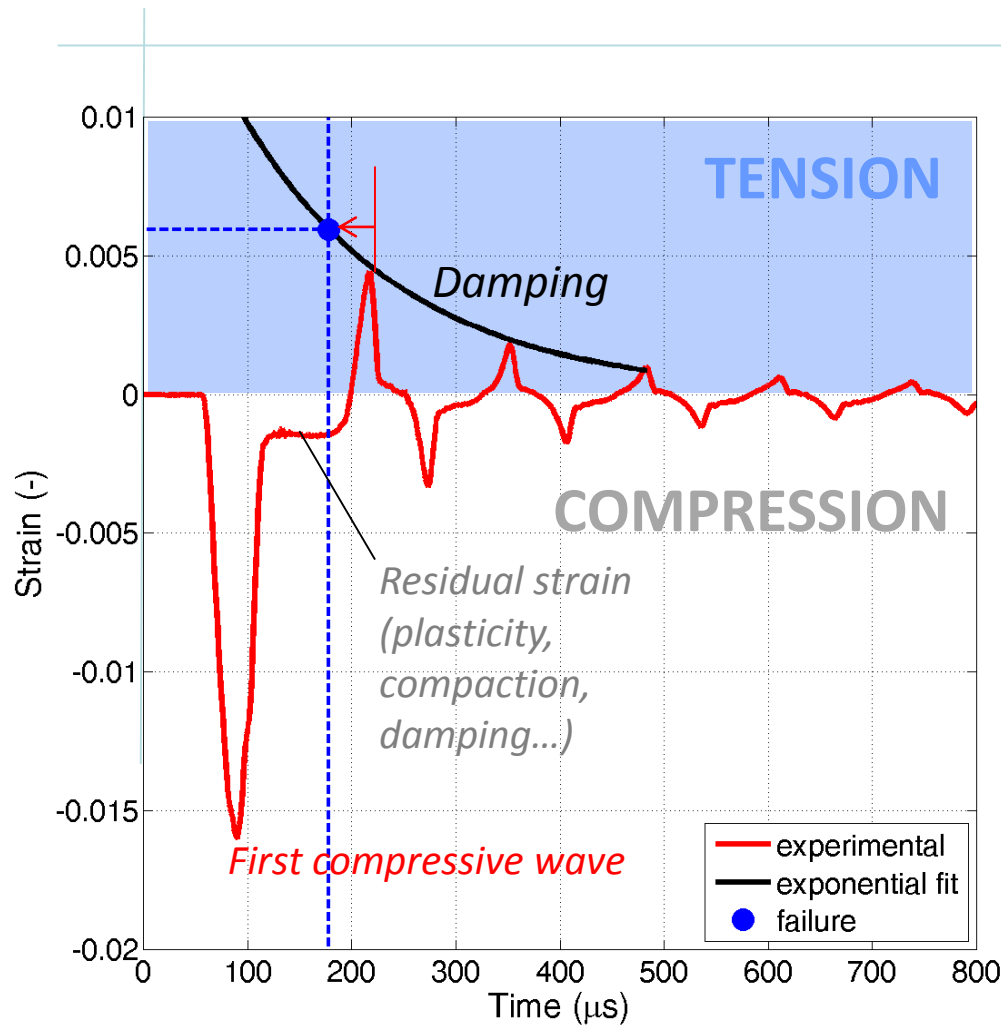
The compressive wave (C) of length L is transmitted into the specimen and travels until reaching the free surface

At the free surface the compressive wave is reflected back as tensile wave (T), which grows in amplitude: when $T = C$, the resultant $R = 0$ and the specimen is completely unloaded.

When the resultant $R = T - C$ reaches the ultimate stress of the material, it generates a fracture surface.

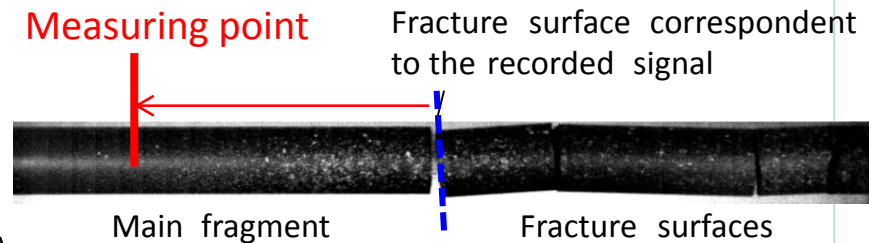
The wave travelling inside the left main fragment is limited in amplitude by the ultimate stress of the material, and cannot generate other fractures (unless inhomogeneities are present). Further fracture could occur in the right fragment.

SHPB Spalling test (II)



Evaluation of the rupture strain

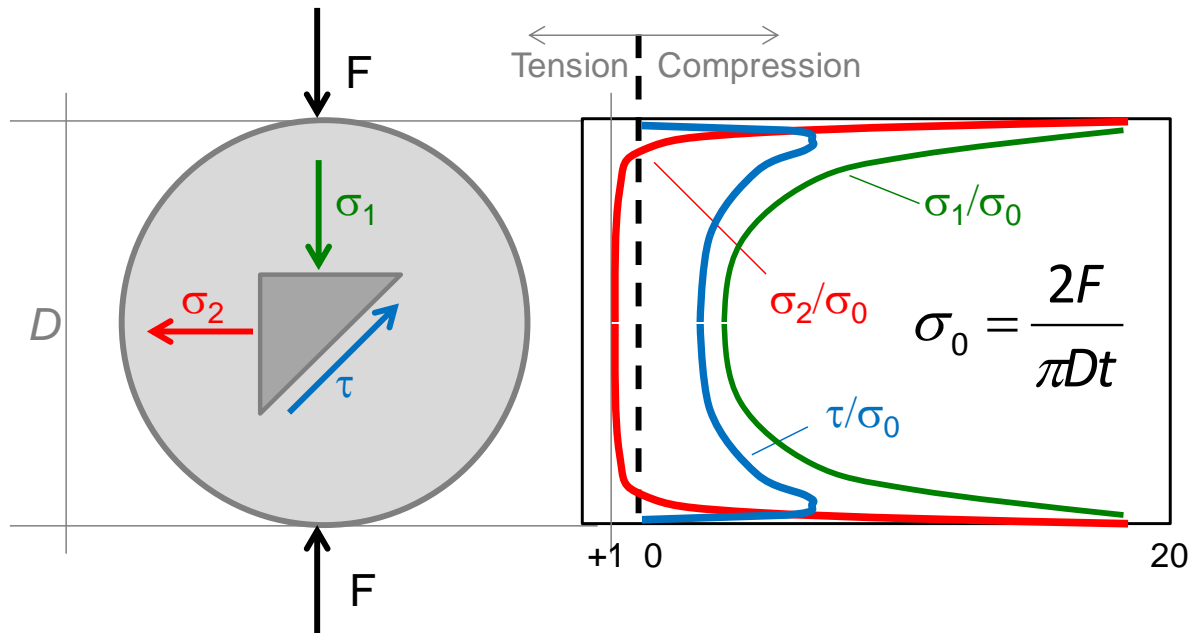
- ✓ Strain gauge is reached by the tensile wave only after rupture has already occurred: given to material damping, the **rupture strain is therefore higher than what registered by the gauge!**
- ✓ Rupture strain estimated with an **exponential model** ($\epsilon = Ae^{-Bt}$)



SHPB Spalling test (III)



Experimental technique alternative to the classic tensile and compression tests, used for the evaluation of tensile strength of brittle and hard materials (like rocks, glass and ceramics).

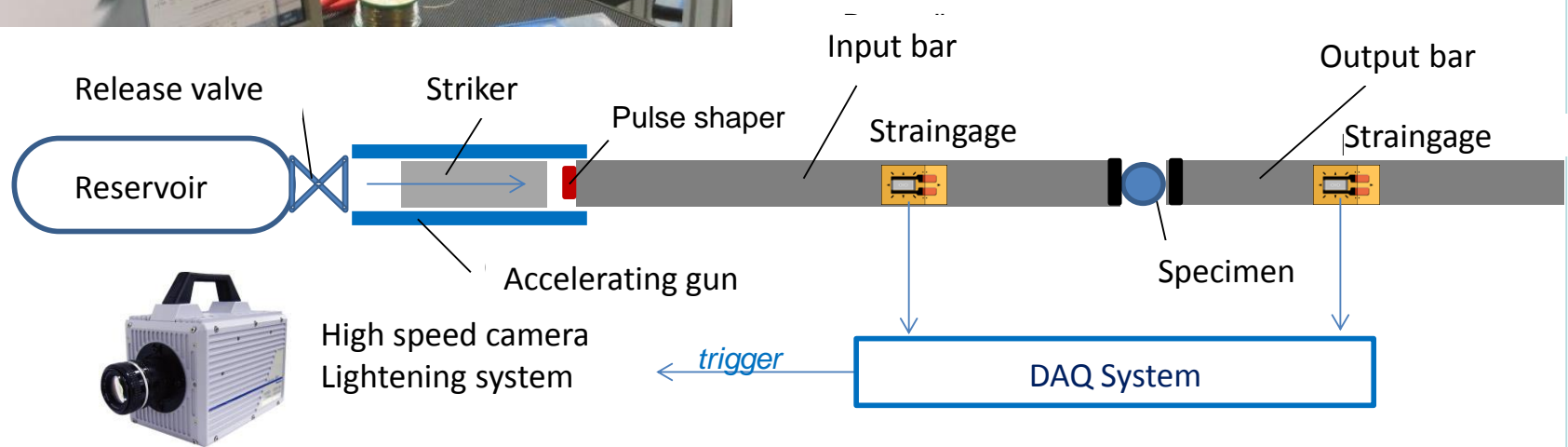
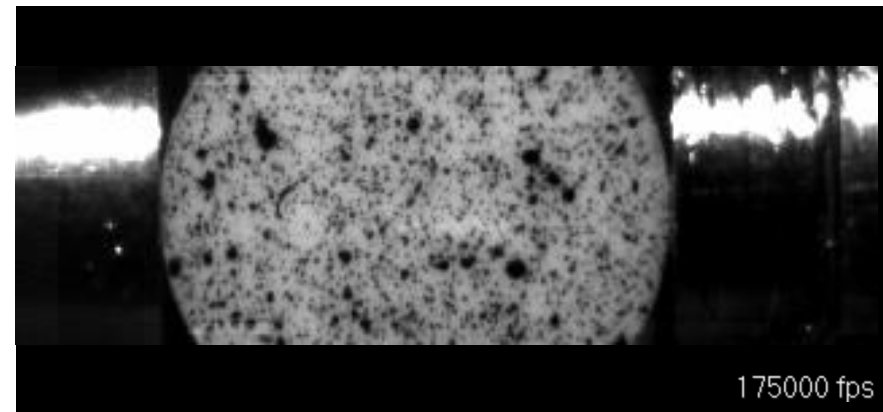


Test execution:

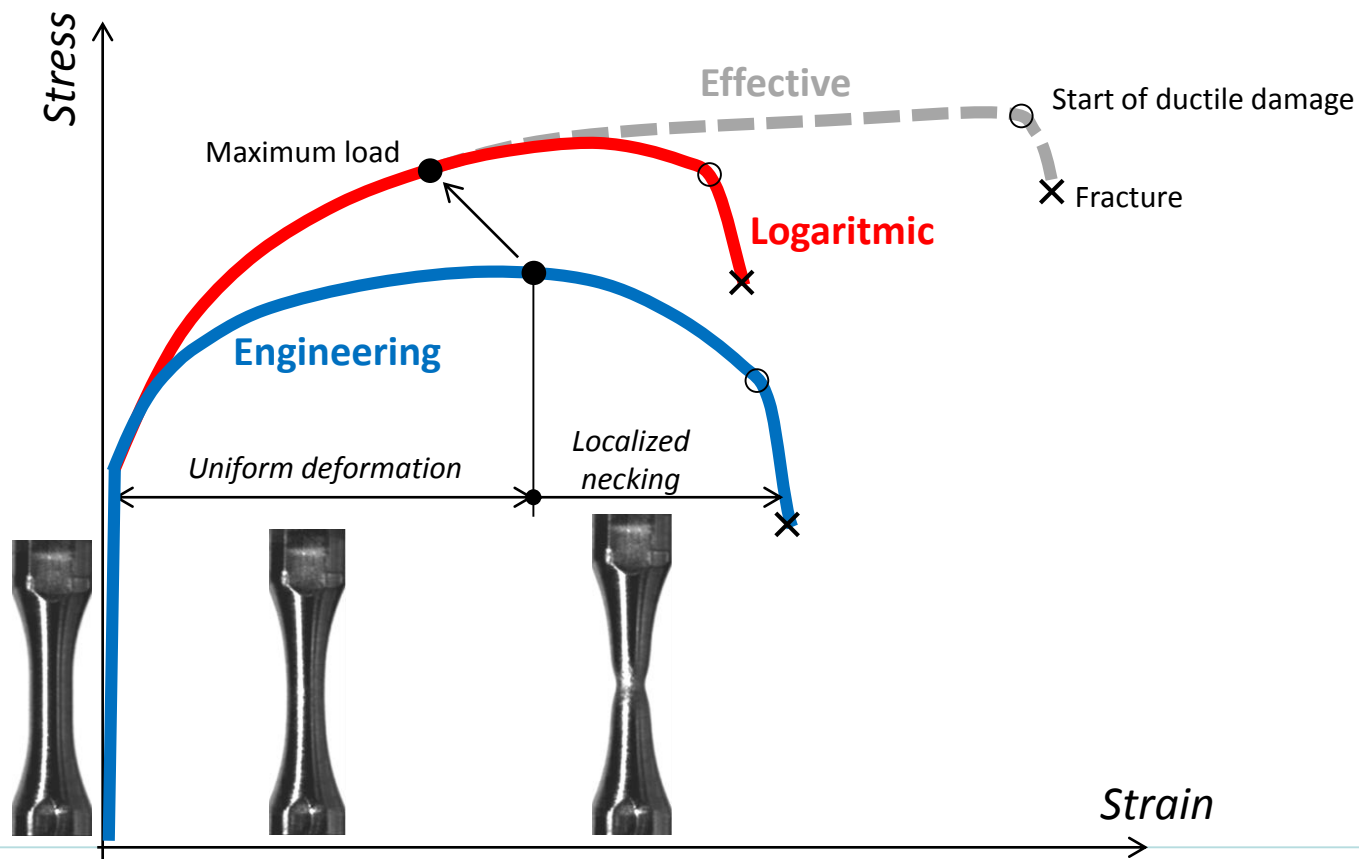
- ✓ Diametric compression of a cylinder (diameter D , thickness t) which generates a maximum tensile stress in the middle of the specimen, perpendicular to the applied load.
- ✓ The standard test is valid only if the fracture happen in the



SHPB Brazilian test



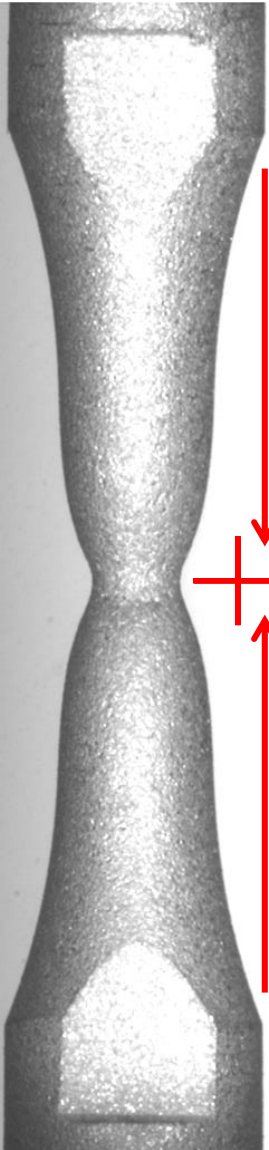
Brazilian test (II)





The shape of the specimen during the test (static or dynamic) is the consequence of the complex spatial and temporal distribution of stress, strain, strainrate and temperature in the necking region: it could be useful for the evaluation of the material strength model

The necking profile is easily evaluable trough the digital image analysis of the test

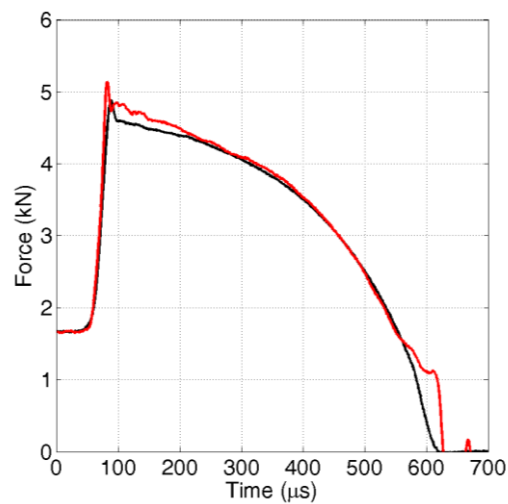
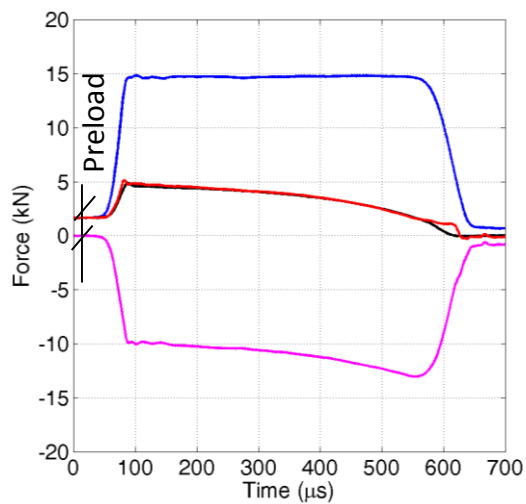


Stress & strain

Triaxiality
Strainrate
Temperature

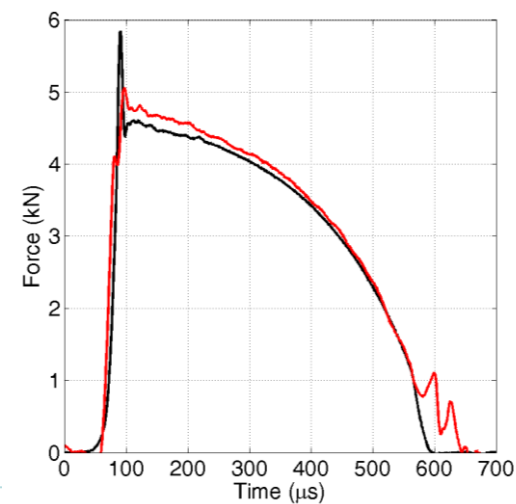
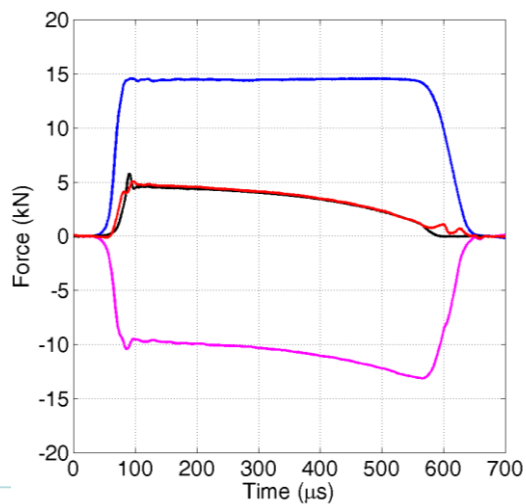


Necking profile analysis



With preload

Mo @ 300°C



Without preload

Preload



Johnson-Cook

$$\sigma_y = \left(A + B \bar{\epsilon}^{p^n} \right) (1 + c \ln \dot{\epsilon}^*) (1 - T^{*m})$$

Zerilli- Armstrong for BCC metals

$$\sigma = C_1 + C_2 e^{[-C_3 + C_4 \ln(\dot{\epsilon}^*)]T} + [C_5 (\epsilon^p)^n + C_6]$$