Cryogenic Materialtests Karlsruhe
CryoMaK

Mechanical Testing – Cryogenic Material Characterization

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Cryogenic material laboratory within ITEP

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- Characterize materials at operational temperatures → 400 K – 4.2 K

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- Advantage of combination of test methods in one laboratory with expertise of about 30 years

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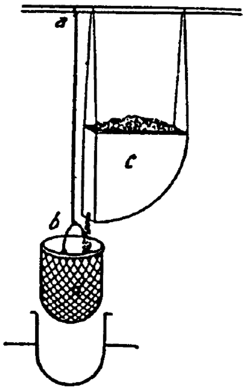
Content

- Motivation:
  - Structural and Functional Materials
  - Example: ITER Cryogenic Magnet System
- Loads to be considered:
  - Thermal Expansion
  - Thermal Conductivity
  - Lorentz Forces
- Material Tests:
  - Tensile Machines
  - Sensors
- Methods:
  - Tensile Test
  - Fracture Toughness
  - Fatigue Crack Growth Rate
  - Low Cycle Fatigue
  - Impact Test


www.vivoscuola.it

Leonardo da Vinci
(1452-1519)



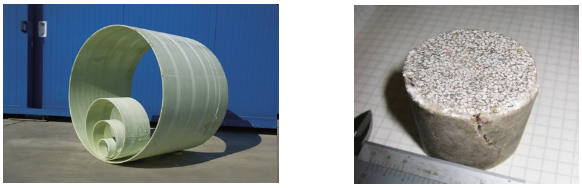
Lund, Byrne; Civil. Eng. and Env. Syst., Vol. 00, pp. 1 ± 8

Structural and Functional Materials

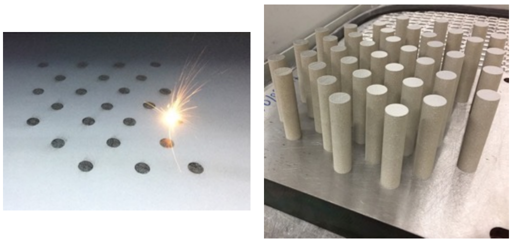
- Effect of material fabrication and processing
  → isotropic or anisotropic properties

e.g. classical metal casting/forging…

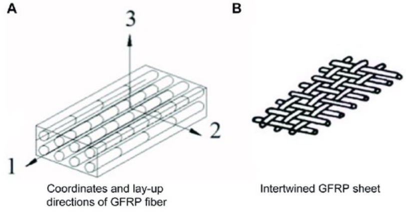
e.g. pure or filled polymers …



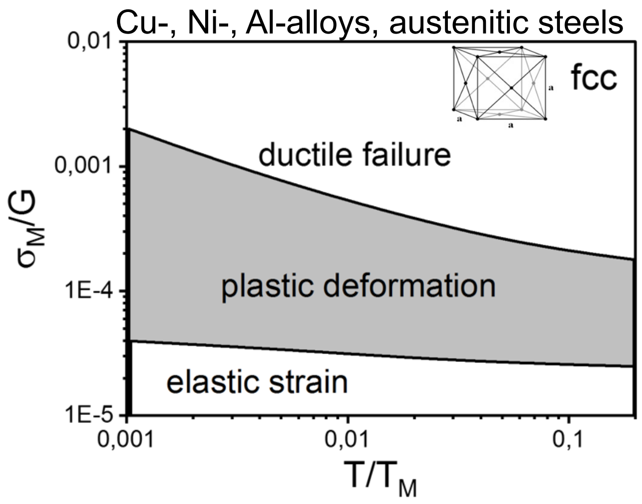
to advanced manufacturing SLM/DED…

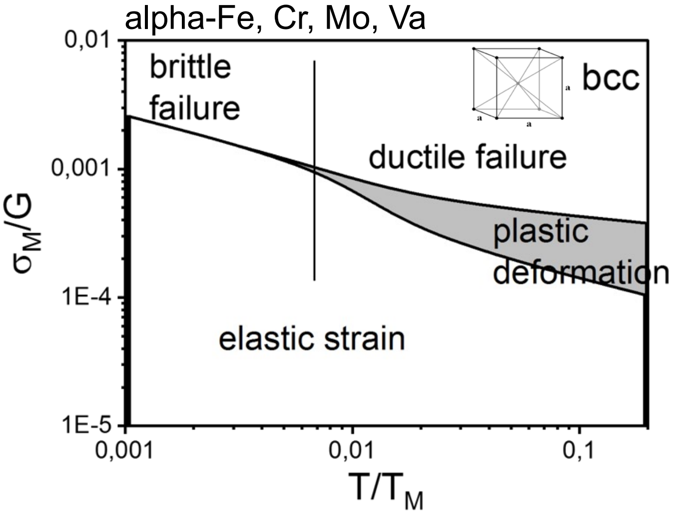


carbon or glass fibers
glass spheres / quartz powder …



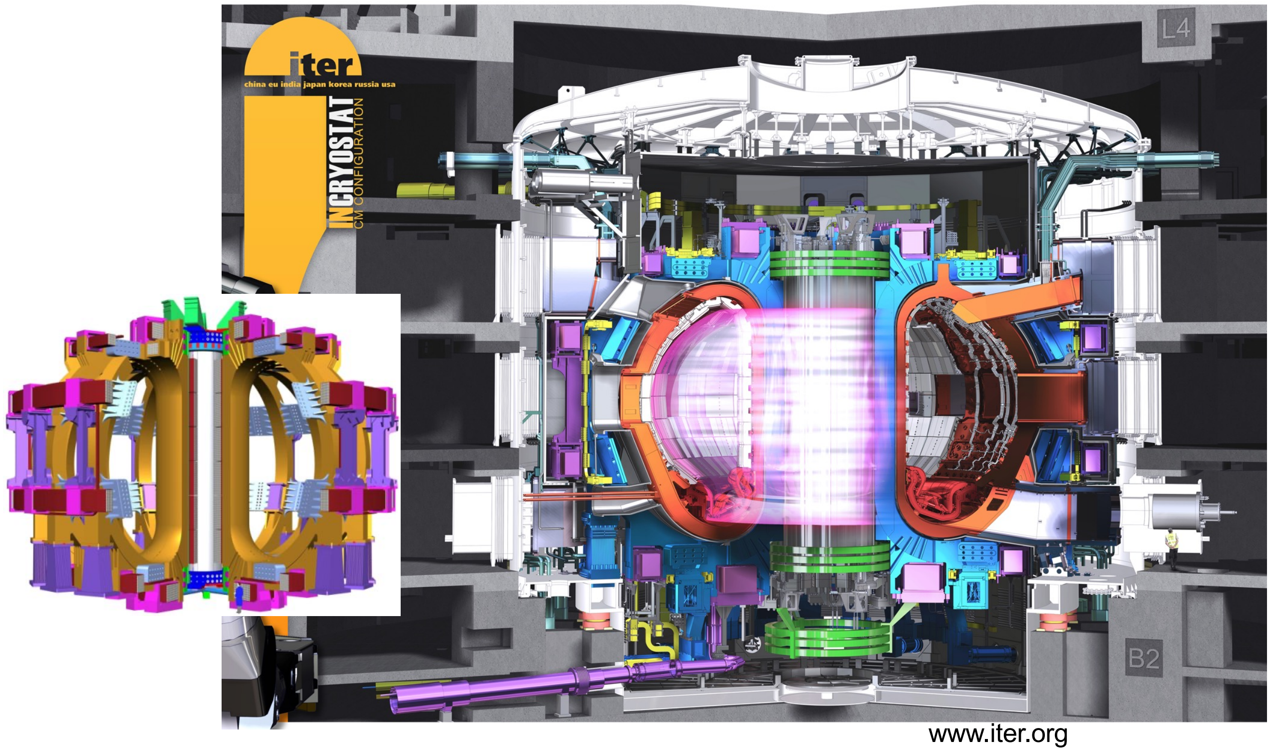
Structural and Functional Materials





Adjustment of mechanical properties via grain-size, precipitation, solution hardening
Alloys can show complex behaviour

Example: ITER Cryogenic Magnet System

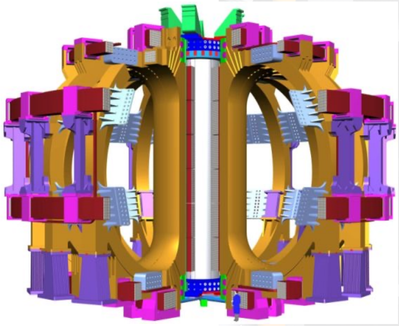


www.iter.org

Example: ITER Cryogenic Magnet System

The cold mass of the magnet system contains:

structural material (mainly austenitic steel) and
the superconducting cable (copper, Nb3Sn, electrical insulation, steel)
… and many, many joints



Loads to be considered:

- Gravitational forces
  due to the mass of the system
- Thermal forces
  due to cool down of the coils
- Lorentz forces
  due to the magnetization

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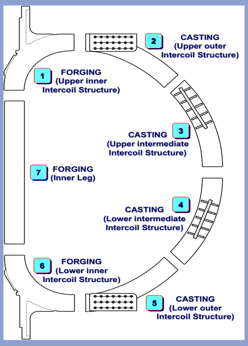
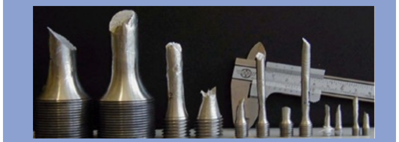
Example: ITER Cryogenic Magnet System

Structural material



Modified 316LN
Cast, forged& rolled plates



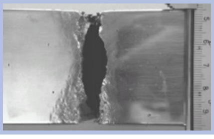
22 Ø – 4 Ø specimen

Superconducting cables

- Conduit
  Type 316LN
  Incoloy 908
  Aluminium

- Stabilizer
  OFHC copper
- Insulation
  GFRP / Epoxy
- Superconductor
  Nb_3Sn TF/CS
  NbTi / PF
  HTSC for current leads

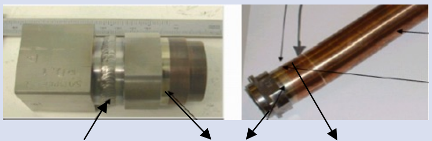
CS conduit (51 mm x 51 mm) fatigue tests



Joints

- Welding
- Solder
- Adhesive bonding

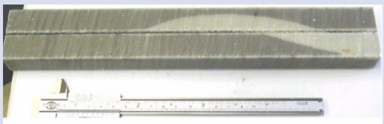
e.g. cable joints



316LN/ 316L TIG

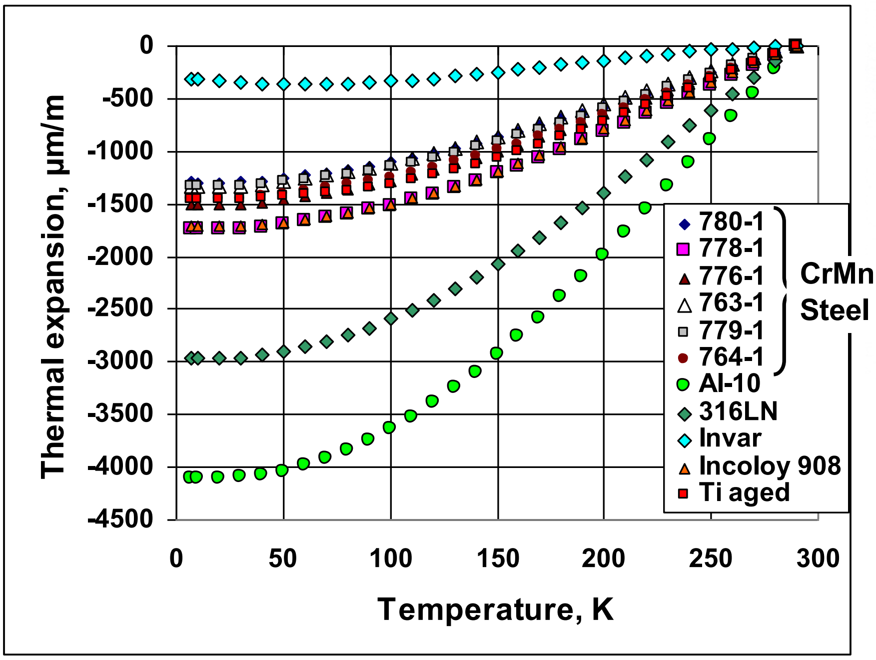
316L/Cu friction weld

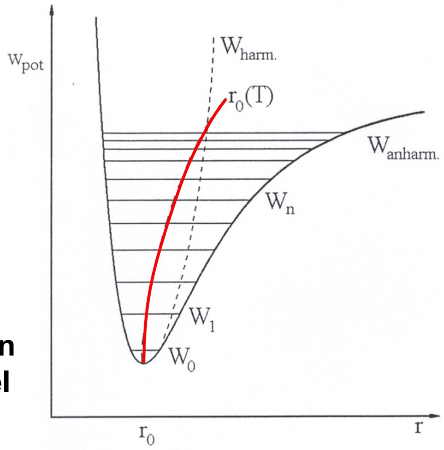
CuCrZr/ Cu brazed joint



3-pont bending of insulationsmaterial

Thermal Expansion





TE 290 K - 4 K:

PA 13.500 µm/m
Polyamide

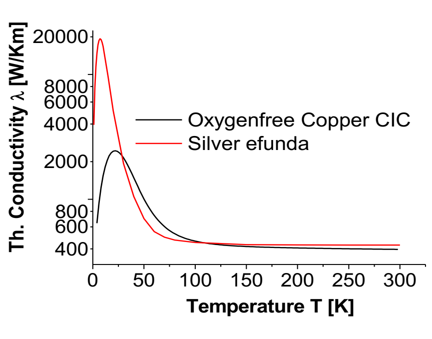
PEEK 10.200 µm/m
Polyetheretherketone

Thermal Conductivity

Typical temperature dependences of thermal conductivity

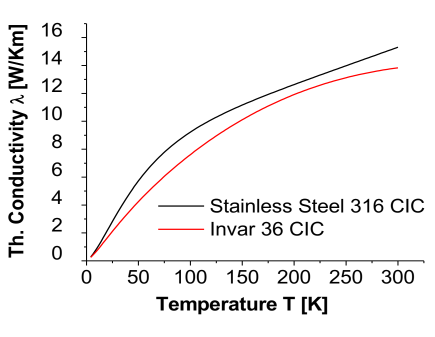
High thermal conductivity

caused by
- electrons
- phonons



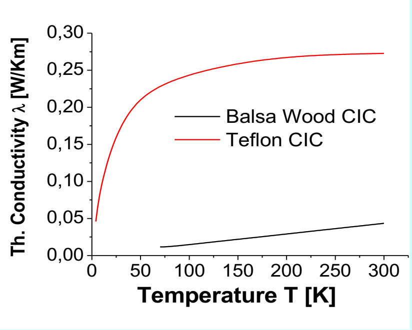
Medium thermal conductivity

Electrons & phonons exist but are blocked by scattering



Low conductivity

No electrons
& almost no phononic components



Lorentz Forces

The Force on a conductor in a magnetic field results from $\boldsymbol{F} = l \cdot \boldsymbol{B} \times \boldsymbol{I}$ (Lorentz-Force)

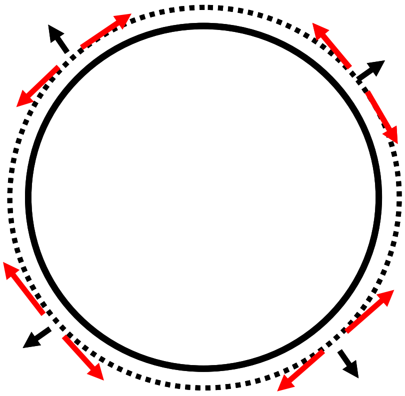
- e.g. for the TF coil: I = 68 kA; B = 11.5 T at the conductor

  this results in a radial force per length
  $F = I \cdot B = 68 \cdot 11.5$ kA T = 782 kA N/(Am)) = 782 kN/m

- to counteract the **radial force**

  the conductor is exposed to a **hoop stress**

  that stretches the conductor.



National & International Standards

DIN 50125	Prüfung metallischer Werkstoffe - Zugproben
DIN EN ISO 6892-1	Metallic materials - Tensile testing - Part 1: Method of test at room temperature
DIN EN ISO 6892-2	Metallic materials - Tensile testing - Part 2: Method of test at elevated temperature
DIN EN ISO 6892-3	Metallic materials - Tensile testing - Part 3: Method of test at low temperature
DIN EN ISO 6892-4	Metallic materials - Tensile testing - Part 4: Method of test in liquid helium
ISO 12135	Metallic materials - Unified method of test for the determination of quasistatic fracture toughness
DIN EN ISO 3506-1	Fasteners - Mechanical properties of corrosion-resistant stainless steel fasteners - Part 1: Bolts, screws and studs
DIN EN ISO 3506-2	Fasteners - Mechanical properties of corrosion-resistant stainless steel fasteners - Part 2: Nuts

National & International Standards

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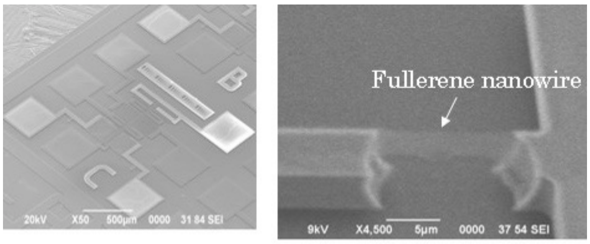
DIN EN ISO 6892-3	Metallic m test at low
DIN EN ISO 6892-4	Metallic m test in liqu
ISO 12135	Metallic m determina
DIN EN ISO 3506-1	Fasteners stainless studs
DIN EN ISO 3506-2	Fasteners stainless

1) Property of interest
2) Read the standard
3) Follow or adapt the procedure to your needs

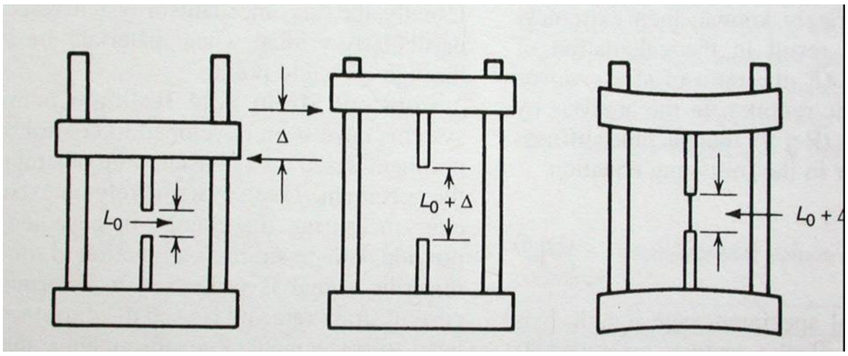
- ASTM E 74 for load verification devices. The primary standards are masses of weights accurate to 0.005% of their values.
- ASTM E 83, “Standard Practice for Verification and Classification of Extensometers”
- ASTM E 1823 “Standard Terminology Relating to Fatigue and Fracture Testing”
- ASTM E 399 “Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials”
- ASTM E 1820 “Standard Test Method for Measurement of Fracture Toughness”
- ASTM E 647 “Standard Test Method for Measurement of Fatigue Crack Growth Rates”
- ASTM E 23 “Standard Test Methods for Notched Bar Impact Testing of Metallic Materials”

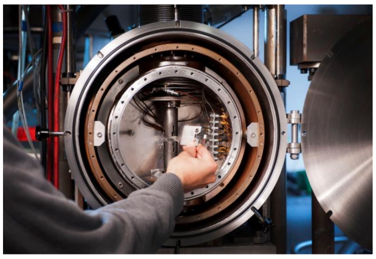
Tensile Machines

Piezo-electrical,
electro-mechanical or
servo-hydraulic test facilities
for applied loads ranging from Nano- up to Giga-Newton



Tensile Machines

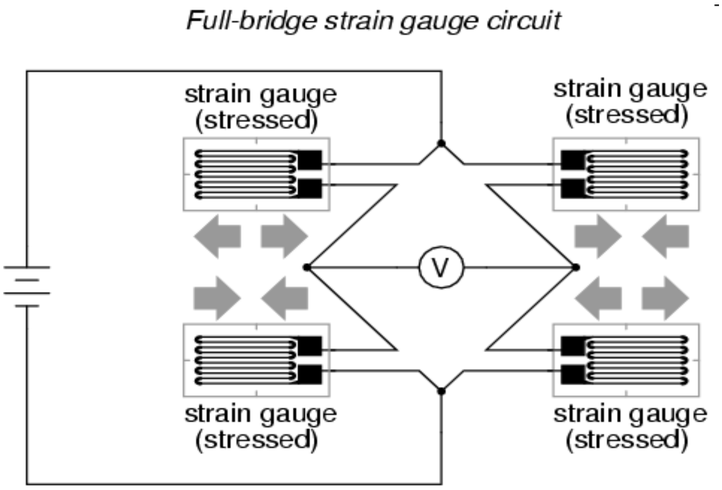


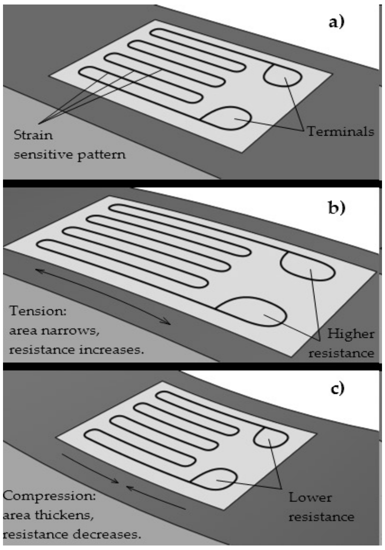


- stiffness of facility
- alignment of load-line and specimen
- mounting of sensors:
  load cell in series (possible bias by bellows)
  extensometer in parallel on or close to specimen
  (possible bias by facility stiffness or thermal exp.)

- force free mounting of specimen
  (possible bias by cooling/heating)
- maintain stable temperature during test

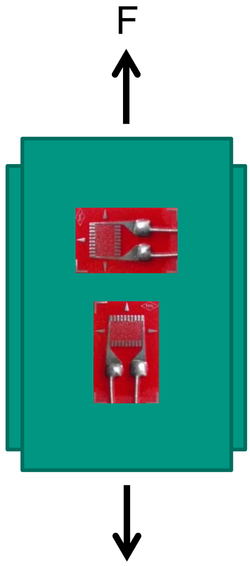
Sensors: Strain Gauge

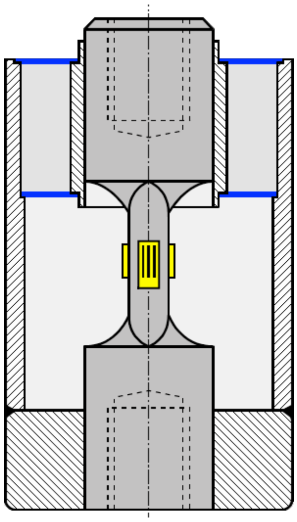




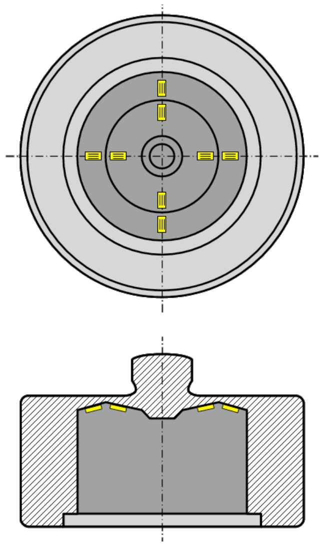
Sensors: Load Cell

- Using elastic behavior of materials (e.g. CuBe, steel alloys…) strain gauges are used for load cell application





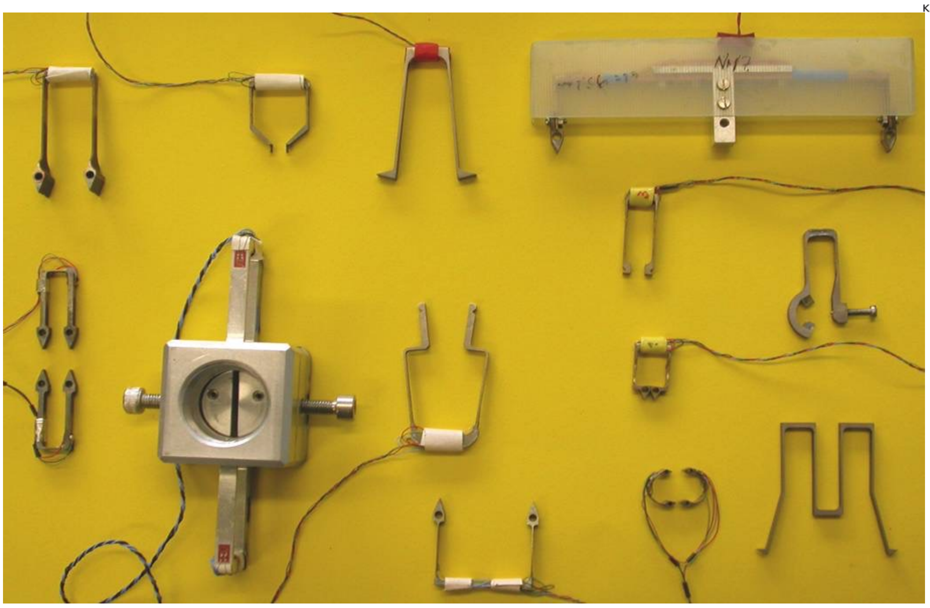
cylindrical rod - elastic body



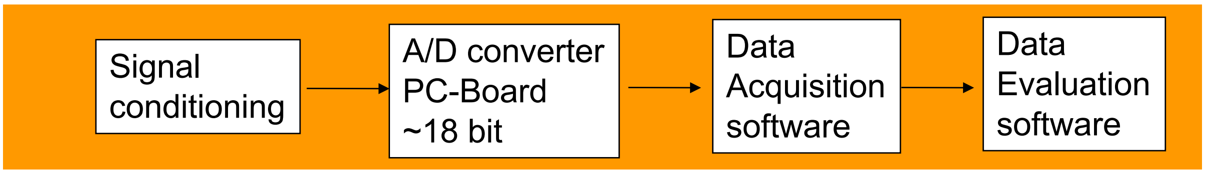
membrane - elastic body

Sensors: Extensometer and Data Acquisition

Physical world

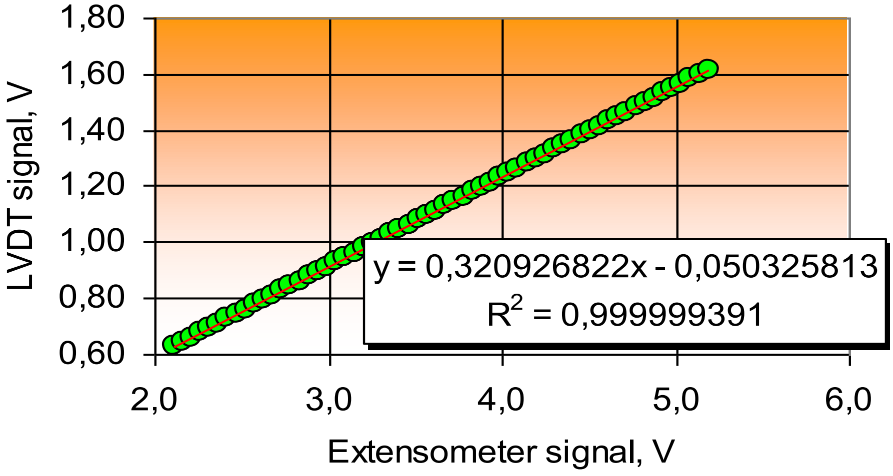


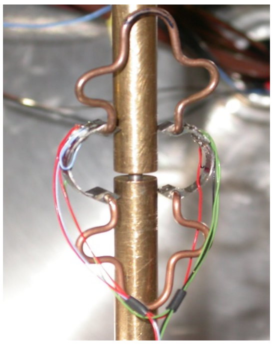
Signal conditioning



Signal conditioning → A/D converter PC-Board ~18 bit → Data Acquisition software → Data Evaluation software

Sensors: Extensometer Calibration

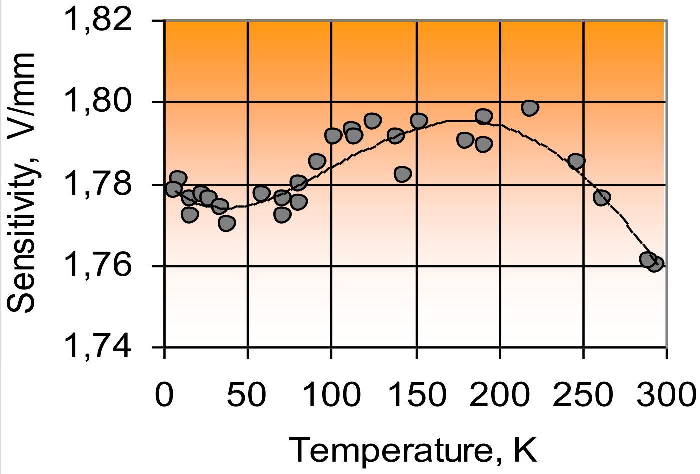


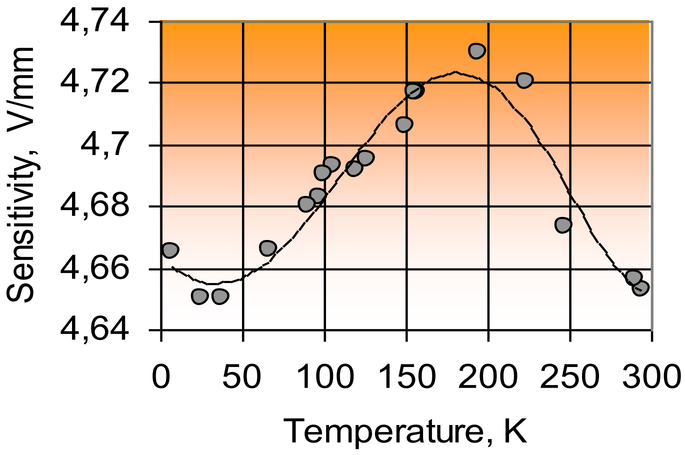


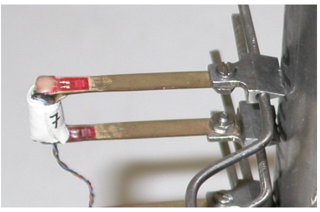
Extensometer under calibration with 12 mm starting length (mass = 0.5 g).

Diagram shows LVDT versus extensometer signal during defined displacement of tensile machine

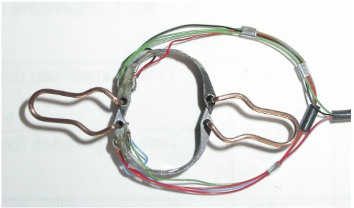
Sensors: Temperature Influence on Calibration





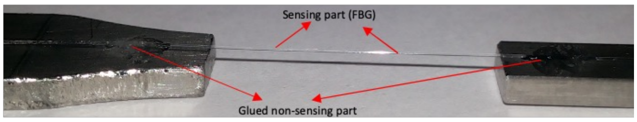


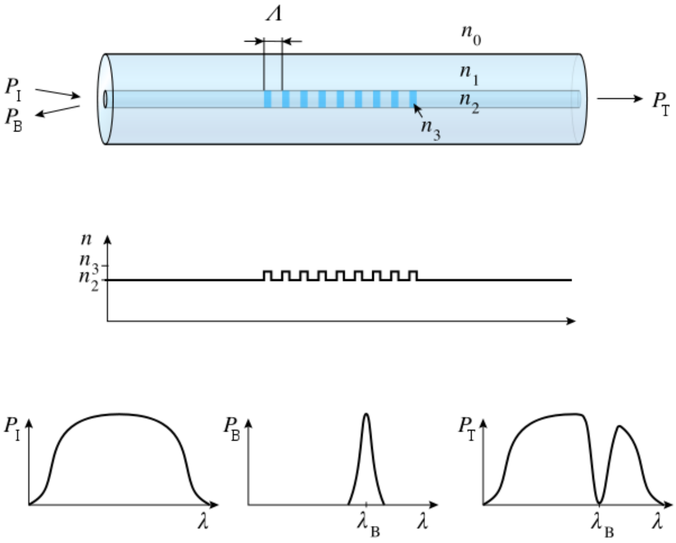
Type A



Type I

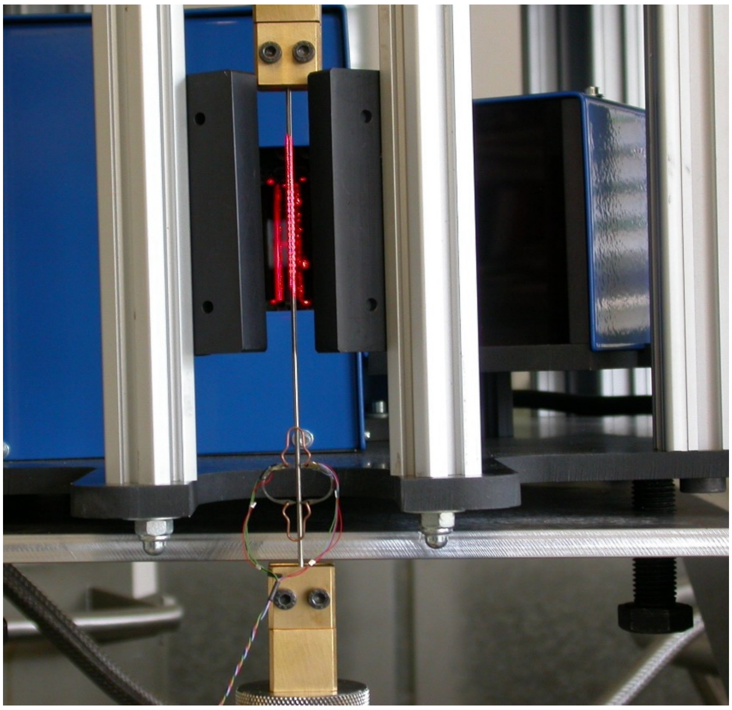
Sensors: Fiber Bragg Optic for Strain Measurement





Parameter	Specification
Company	FBGS
FBG type	DTG-LBL-830_1550
FBG diameter (coated)	195 µm
Initial Bragg wavelength	~1550 nm
Braggmeter accuracy	± 2 pm
Glue used	M-Bond 610 Epoxy-phenol adhesive

Sensors: Double Laser Beam for Strain Measurement

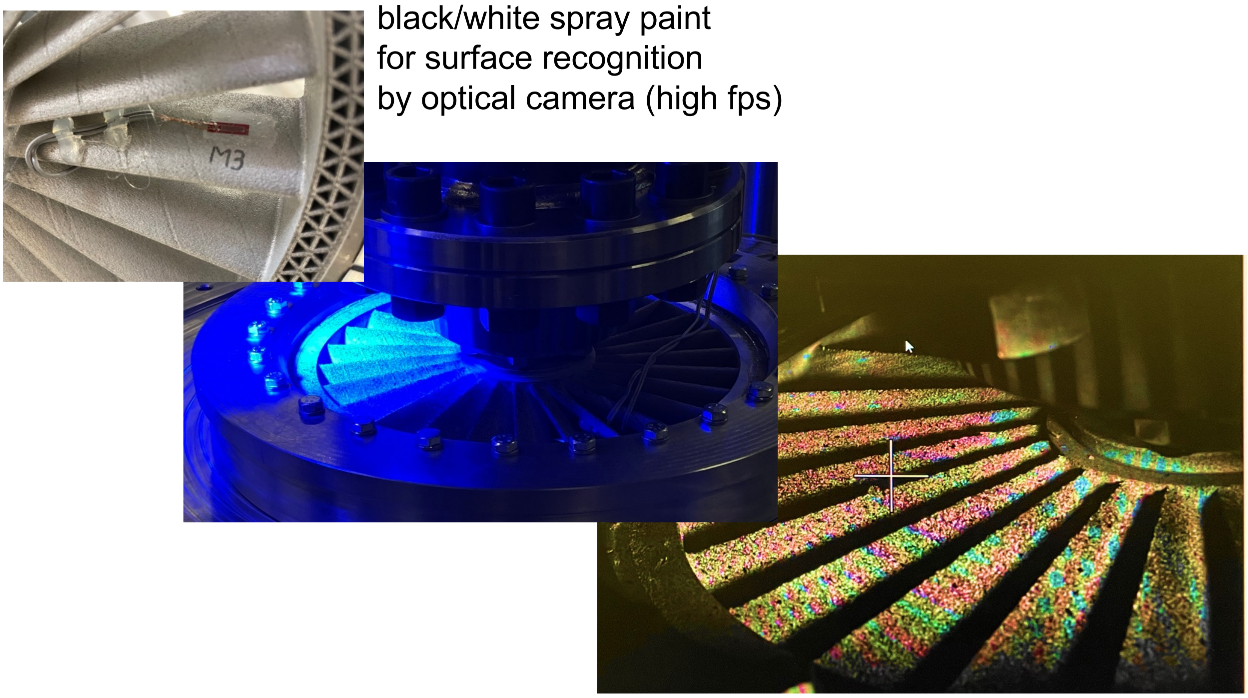


Macroscopic stepwise change of reflectivity (dark/bright)

Sensors: Digital Image Correlation (DIC)

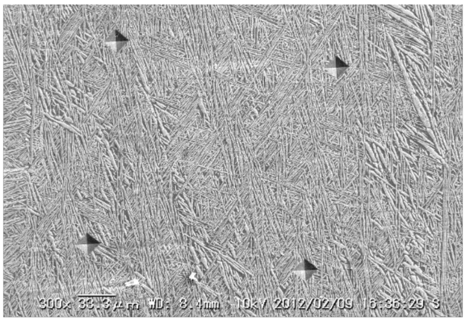
1D Laser Beam → 2D/3D Differential Imaging Correlation

black/white spray paint
for surface recognition
by optical camera (high fps)



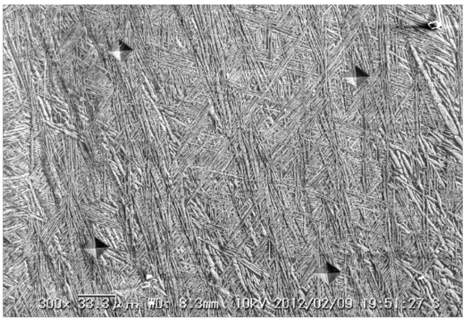
Sensors: Digital Image Correlation (DIC)

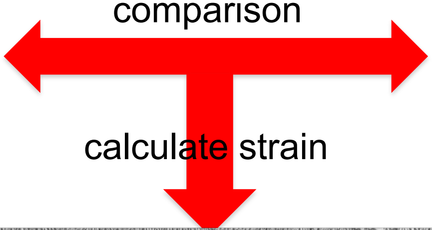
before deformation



SEM image of same area

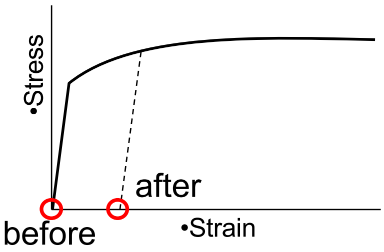
after deformation

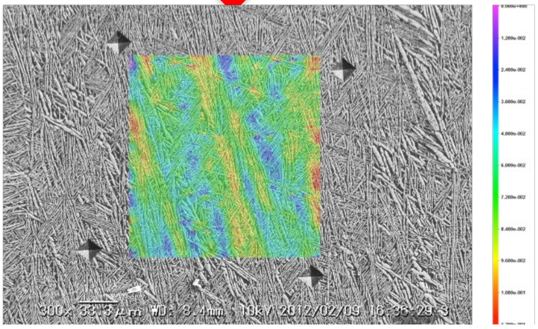




comparison

calculate strain



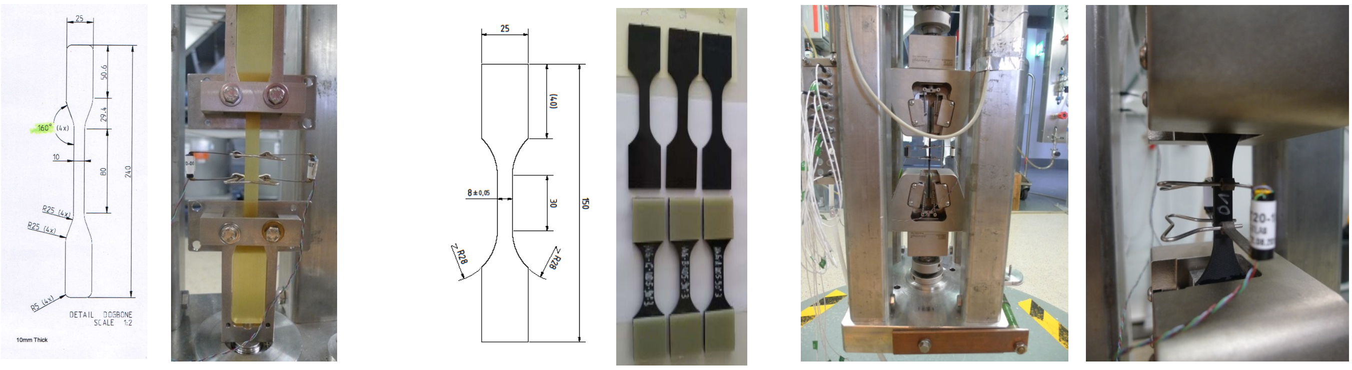


resolved local strain

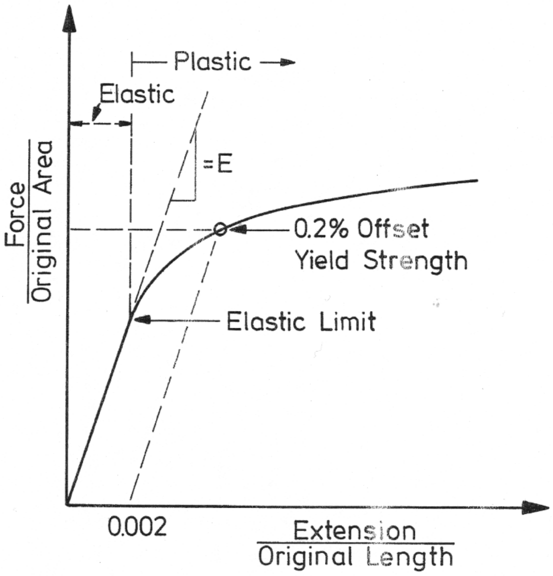
Tensile Test

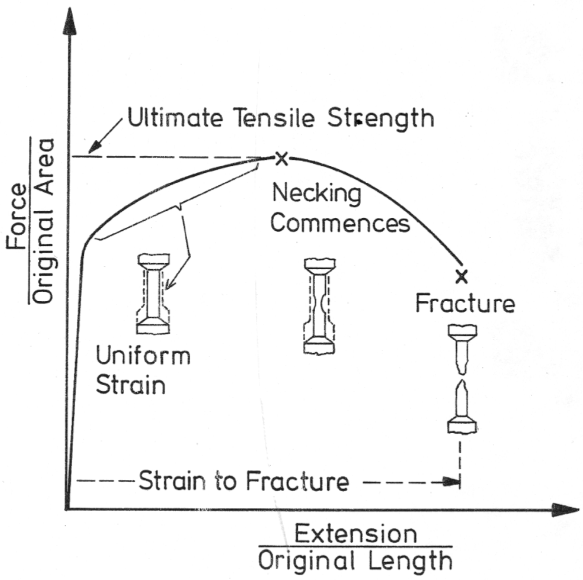
- ISO 6892 / ASTM E8/E8M specimen size metallic materials

- ISO 527 & ASTM D638 plastic & D3039/D3039M fiber reinforced tensile



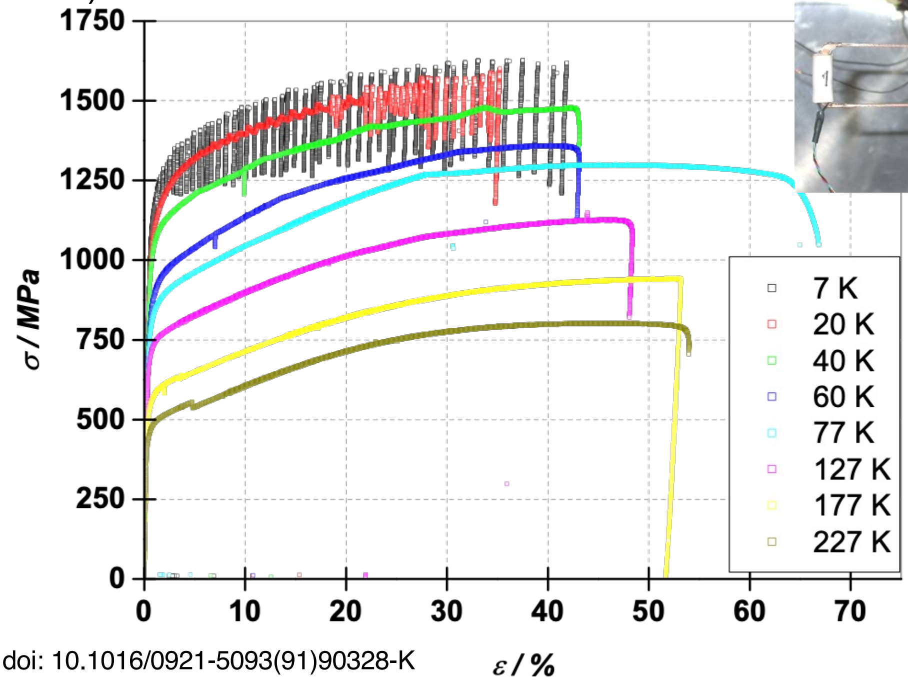
Tensile Test

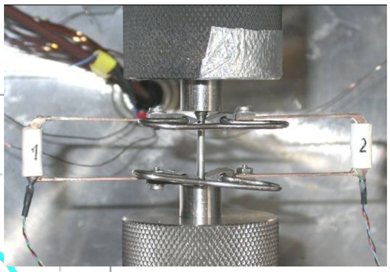


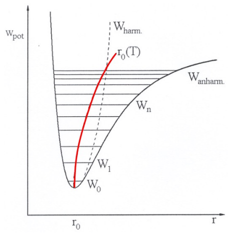


Tensile Test

316LN (1.4429) tensile test series

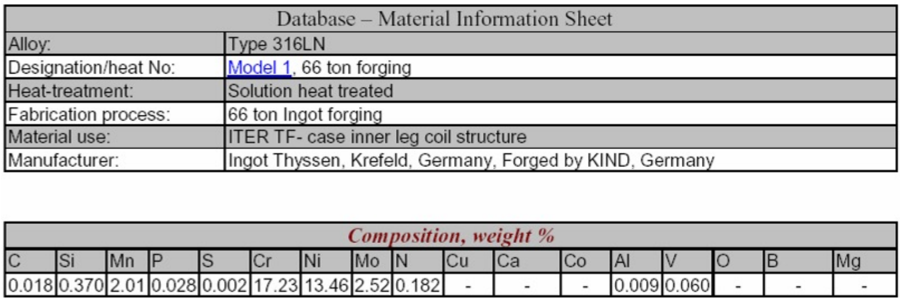






Obst, Nyilas doi: 10.1016/0921-5093(91)90328-K
Tirulinai et al doi: 10.3390/met12030514

Tensile Test



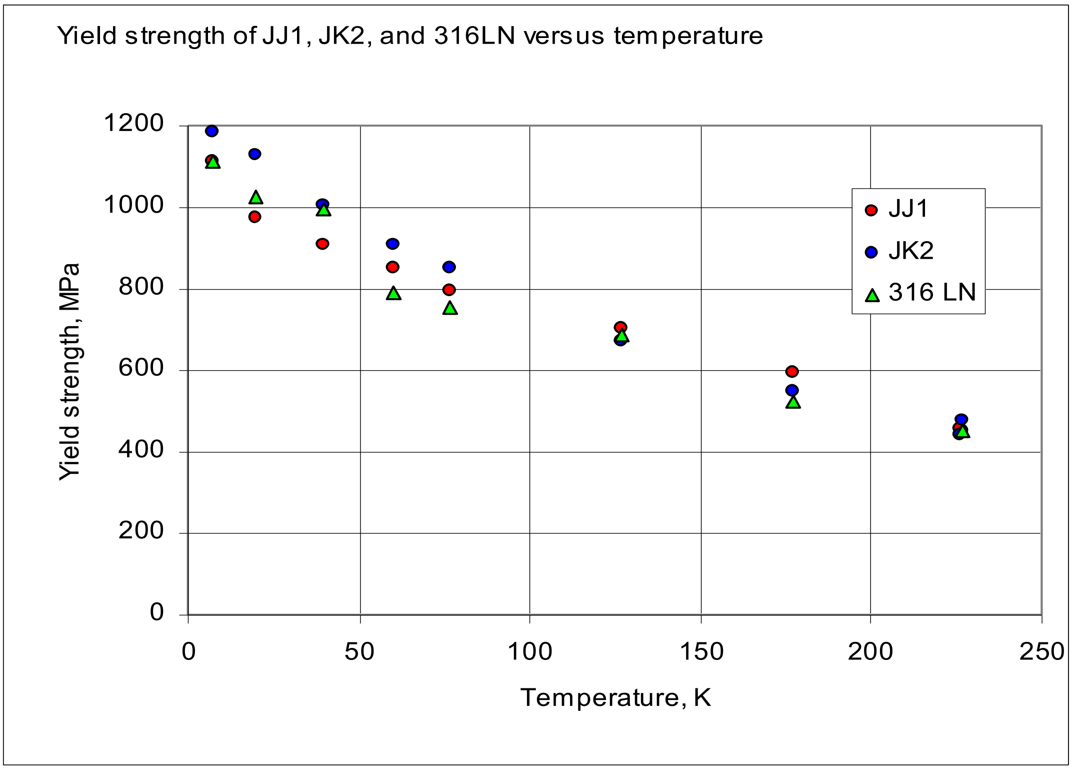
Database – Material Information Sheet	
Alloy:	Type 316LN
Designation/heat No:	Model 1, 66 ton forging
Heat-treatment:	Solution heat treated
Fabrication process:	66 ton Ingot forging
Material use:	ITER TF- case inner leg coil structure
Manufacturer:	Ingot Thyssen, Krefeld, Germany, Forged by KIND, Germany

Composition, weight %

C	Si	Mn	P	S	Cr	Ni	Mo	N	Cu	Ca	Co	Al	V	O	B	Mg
0.018	0.370	2.01	0.028	0.002	17.23	13.46	2.52	0.182	-	-	-	0.009	0.060	-	-	-

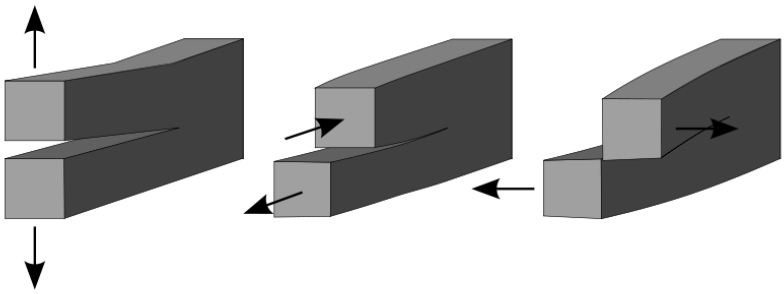
File & heat	T K	Young's Modulus GPa	Yield Strength MPa	UTS MPa	Total elongation %	Reduction of area %
KIND-227	**227**	**175**	**453**	**824**	**58,3**	
KIND-177	**177**	**186**	**521**	**943**	**53,2**	
KIND-127	**127**	**185**	**686**	**1125**	**49,9**	**73,7**
KIND-77	**77**	**185**	**755**	**1268**	**66,5***	**65,5**
KIND-60	**60**	**187**	**790**	**1326**	**43,4**	**66,9**
KIND-40	**40**	**193**	**996**	**1480**	**42,8**	**60,9**
KIND-20	**20**	**193**	**1028**	**1600**	**35,7**	**47,4**
KIND-7	**7**	**197**	**1111**	**1628**	**41,9**	**43,8**

Tensile Test



Fracture Toughness

Concept of fracture mechanics
Crack shapes and geometry factors



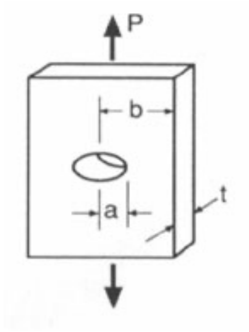
Mode I:
in plane

Mode II:
shear

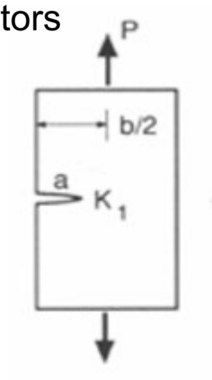
Mode III:
torsion

Fracture Toughness

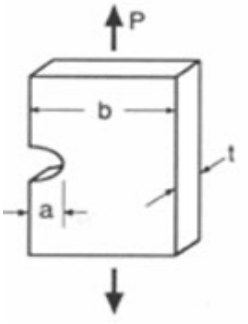
Concept of fracture mechanics
Crack shapes and geometry factors



Interior crack
Y = 1.00



through-thickness
surface crack
Y = 1.12



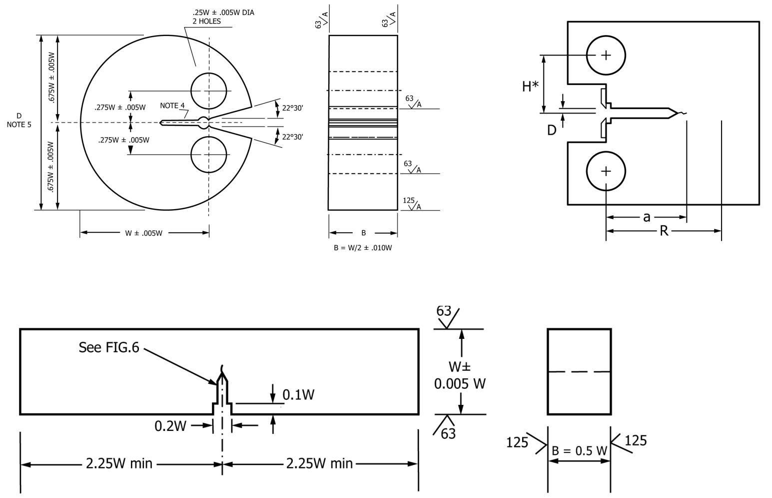
half-circular
surface crack
Y = 0.73

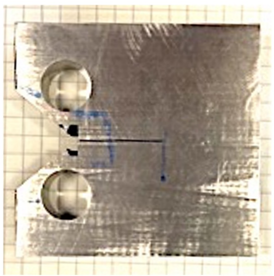
Stress intensity

$$K_I = Y \cdot \sigma \sqrt{\pi \cdot a}$$

Fracture Toughness / Fatigue Crack Growth Rate

- ISO 12135 / ASTM E1820 fracture toughness

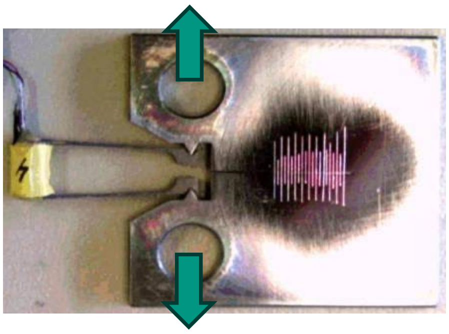


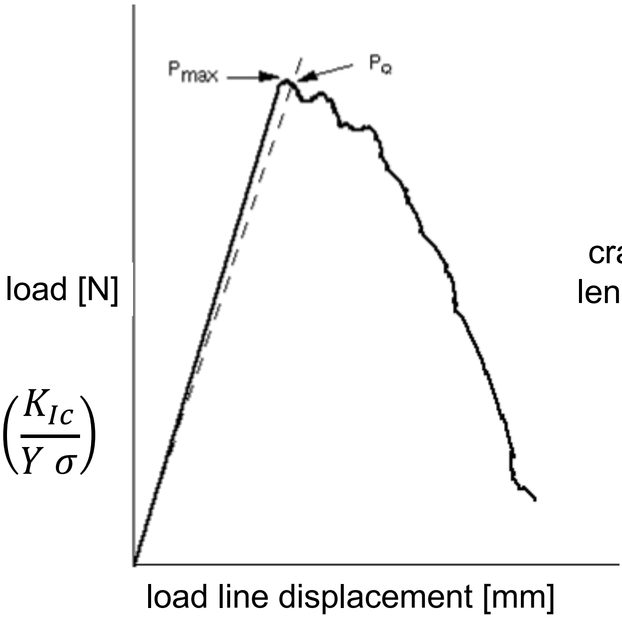


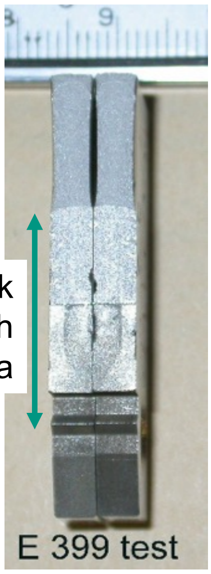
CT specimen,
43 x 45 x 15 (mm)

Fracture Toughness

LEFM - linear elastic fracture mechanics [K-concept], ASTM Standard E 399
Quasi-static loading until sudden failure





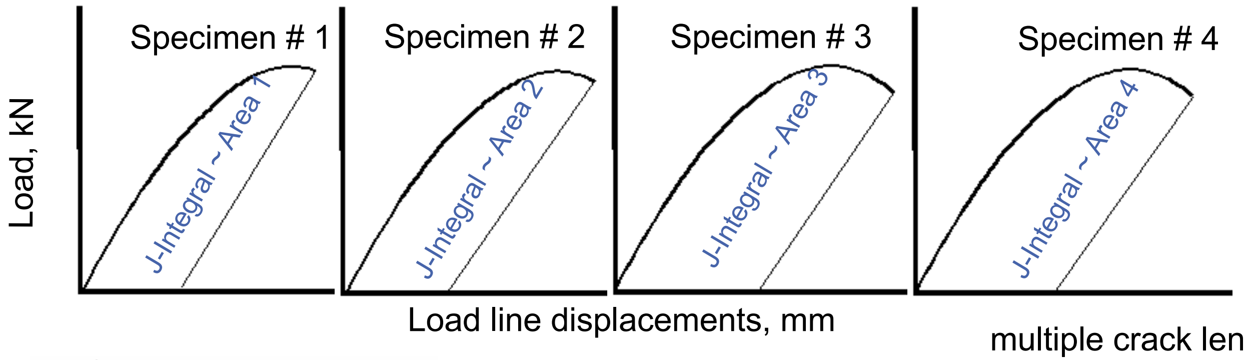


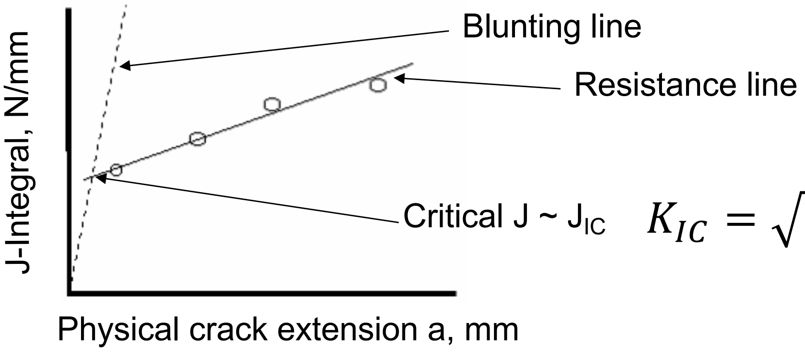
$$K_{Ic} = Y\,\sigma_c\sqrt{\pi\, a} \qquad a_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{Y\,\sigma}\right)$$

geometry factor	Y
stress at failure	$\sigma_c = P_Q / A$
crack length	a

Fracture Toughness

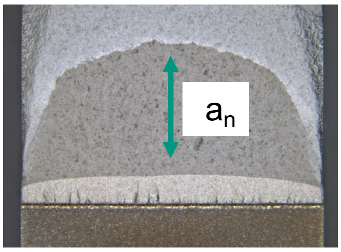
Elastic plastic fracture mechanics [J-concept], ASTM E1820 multi specimen method





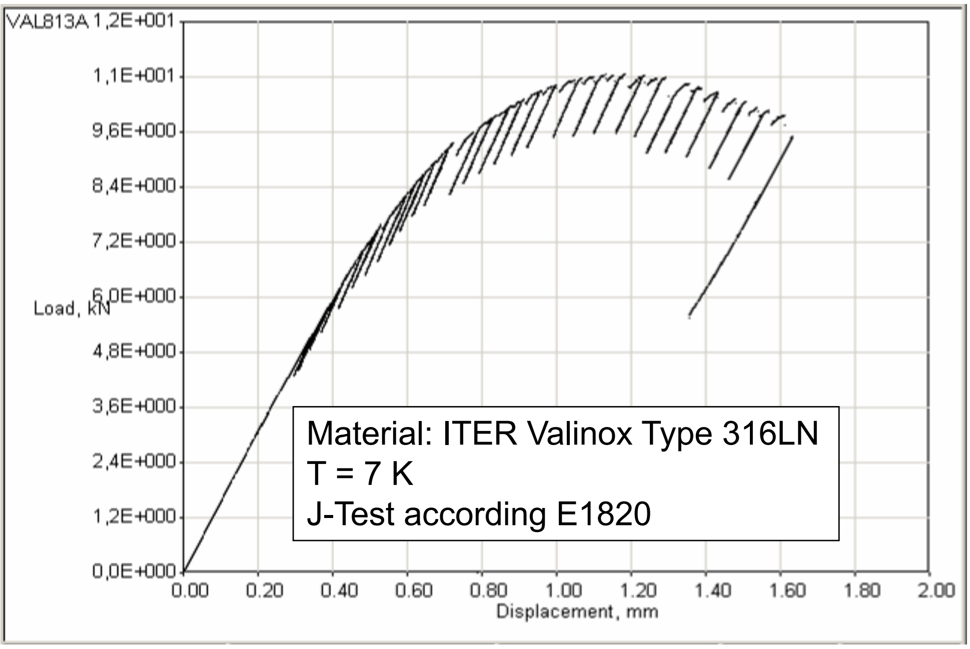
$$K_{IC} = \sqrt{E \cdot J_{IC}}$$

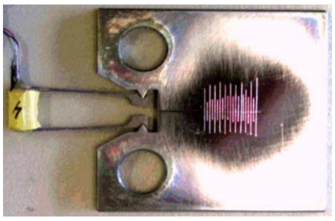
multiple crack lengths
a_0, a_1, a_2, …



Fracture Toughness

Elastic plastic fracture mechanics [J-concept], ASTM E1820 single specimen method





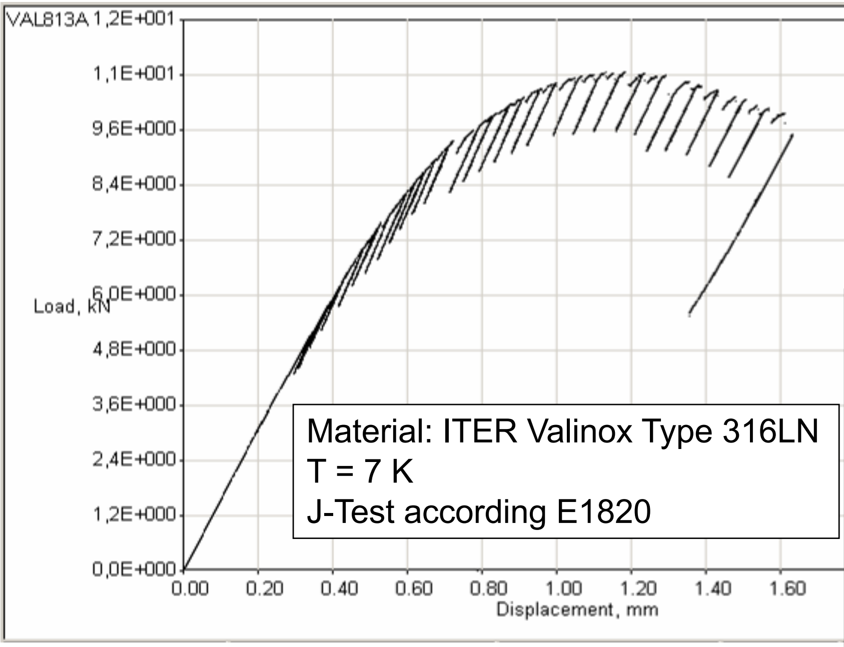
slope kN/mm
of each unloading
→ crack length $a_0, a_1, a_2, \dots$

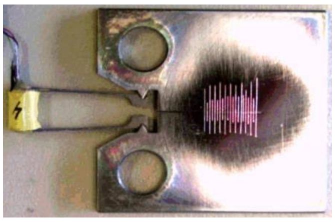
curve area
at each unloading
→ integral $J_1, J_2, J_3, \dots$

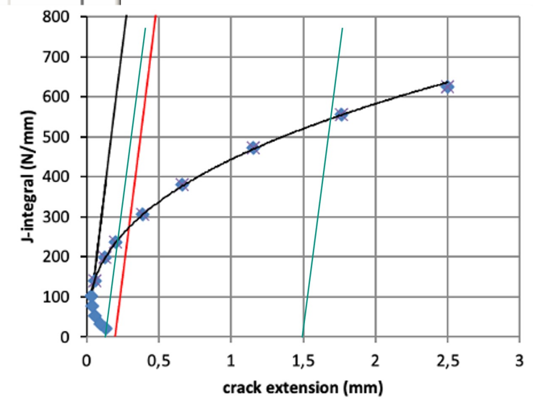
Fernández-Pisón et al doi: 10.1016/j.engfracmech.2021.108042
Weiss, Nyilas doi: 10.1111/j.1460-2695.2006.00963.x

Fracture Toughness

Elastic plastic fracture mechanics [J-concept], ASTM E1820 single specimen method





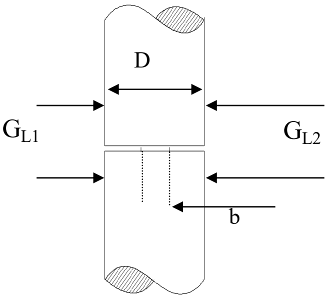


Fernández-Pisón et al doi: 10.1016/j.engfracmech.2021.108042
Weiss, Nyilas doi: 10.1111/j.1460-2695.2006.00963.x

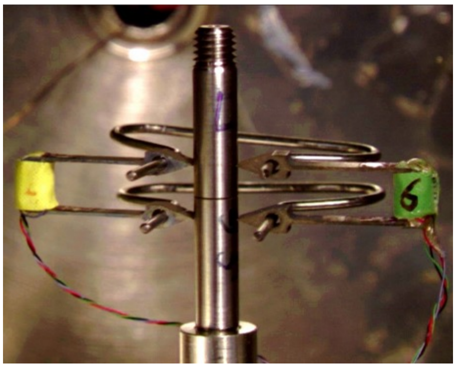
Fracture Toughness: J Evaluation on Tensile Test (JETT)

Elastic plastic fracture toughness test method
developed based on a fundamental solution on J Evaluation on Tensile Test

J. R. Rice et al., Some further results of J Integral analysis and estimates, in: " ASTM Special Technical Publications 536", (1973) p. 231

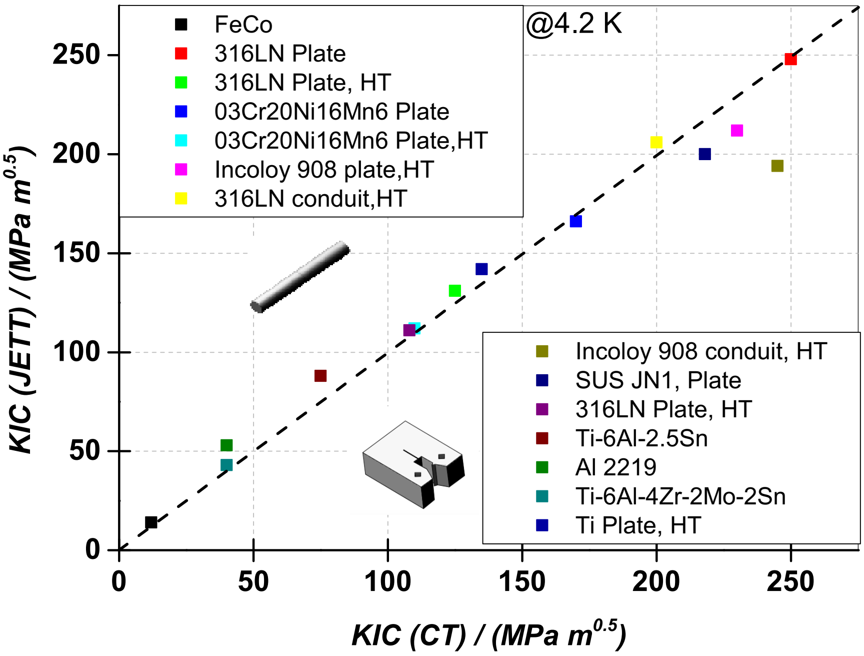


D = round bar diameter
b = net section diameter
d_{ex} = extensometer reading
d_{nc} = elastic displacement
$d_c = d_{ex} - d_{nc}$



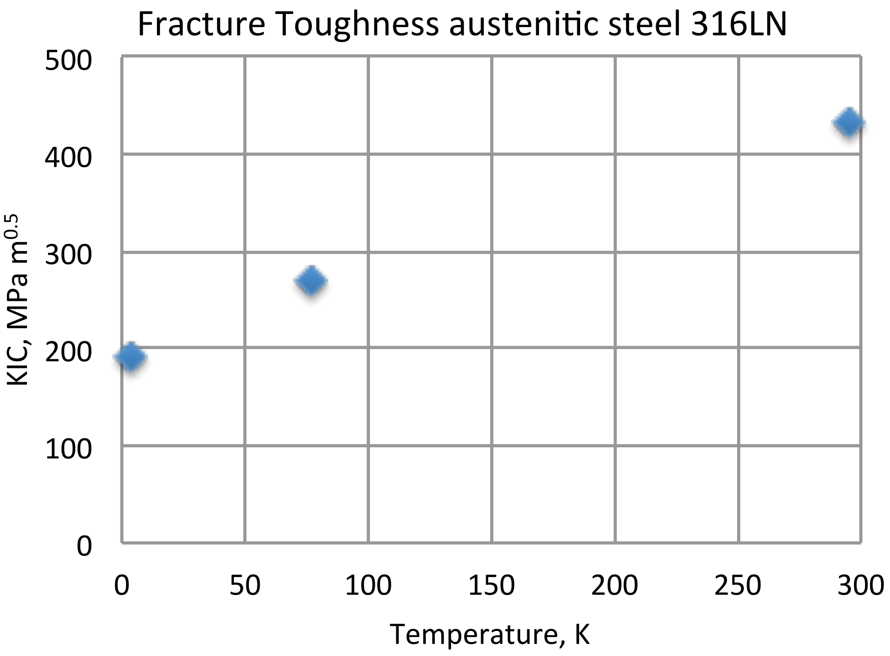
$$J = \frac{1}{2\cdot\pi\cdot b^{2}}\left[3\cdot\int_{0}^{dc} P\cdot d(dc) - P\cdot dc\right]$$

Fracture Toughness: J Evaluation on Tensile Test (JETT)



Correlation between JETT test results of various materials and valid ASTM tests

Fracture Toughness

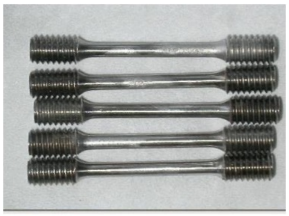


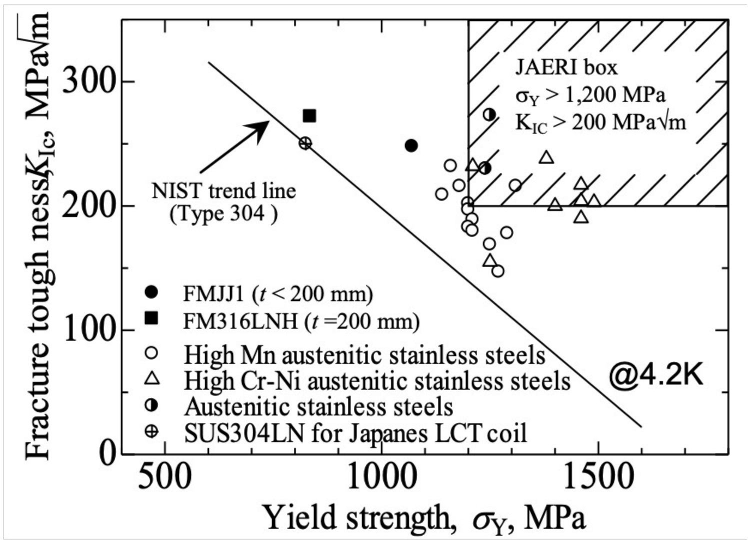
Tensile & Fracture Toughness: High Strength Materials

- Combining *quasi-static* mechanical performance of materials

- Tensile test (strength)
  → σ_Y (MPa)

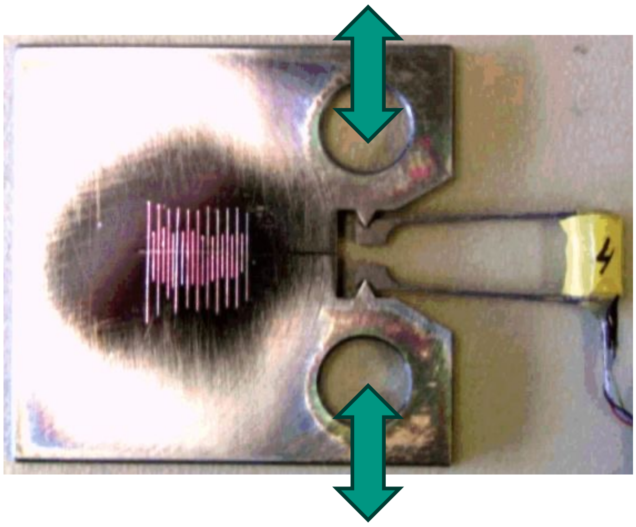
- Fracture toughness (ductility)
  → K_{Ic} (MPa$\sqrt{m}$)



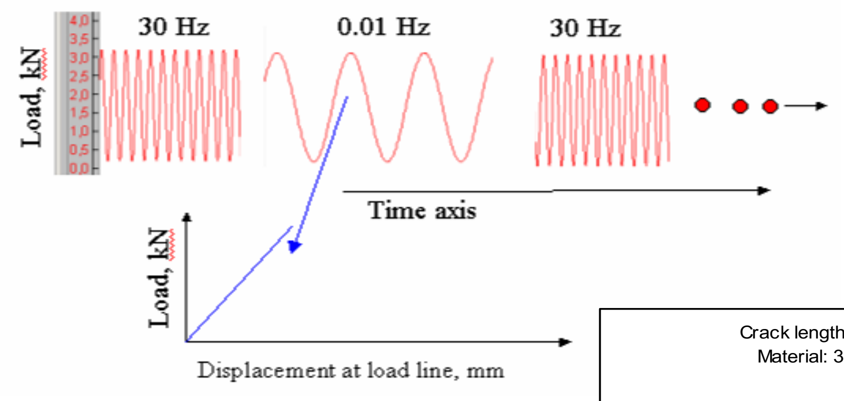


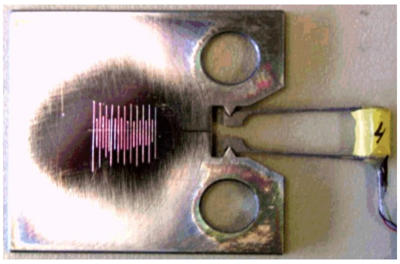
Nishimura, AIP Conference Proceedings 1574, 333 (2014)

Fatigue Crack Growth Rate (FCGR)



Fatigue Crack Growth Rate (FCGR)





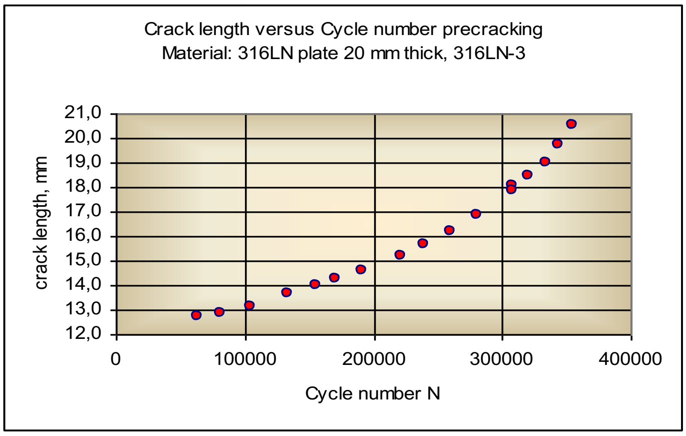
CT specimen, 43 x 45 x 4

Start cycling with Δσ = const and 30 Hz

$$\Delta K = Y \Delta\sigma \sqrt{\pi\, a(N)}$$

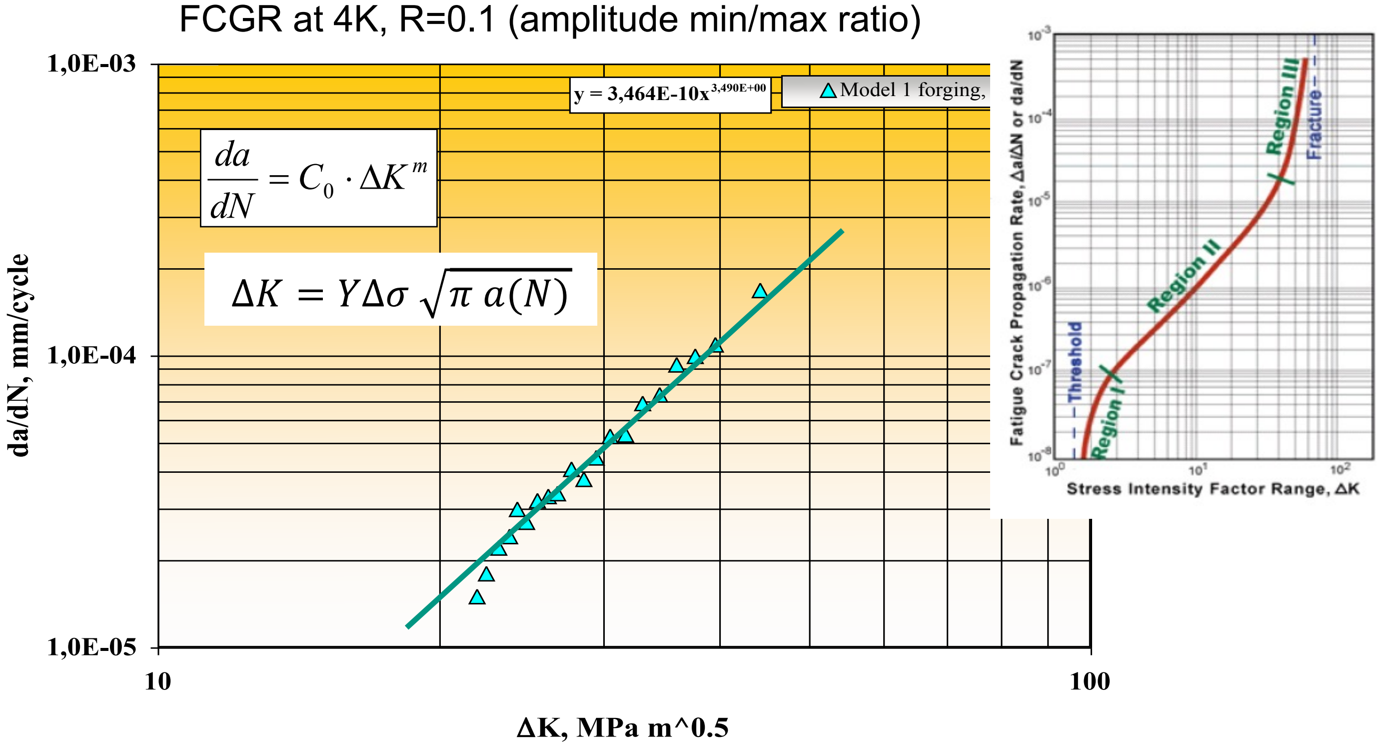
For each 1000 cycles
acquisition of compliance

→ Function crack length versus
cycles and da/dN



Fatigue Crack Growth Rate (FCGR)

FCGR at 4K, R=0.1 (amplitude min/max ratio)



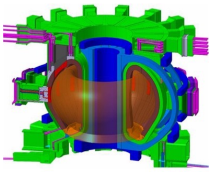
$$\frac{da}{dN} = C_0 \cdot \Delta K^m$$

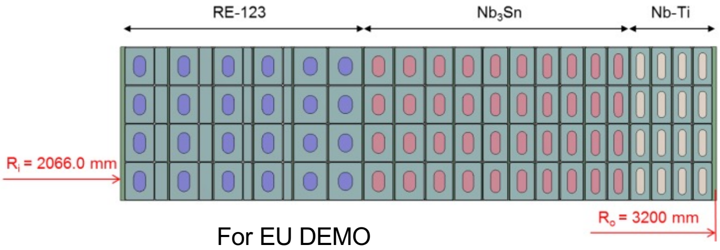
$$\Delta K = Y \Delta\sigma \sqrt{\pi\, a(N)}$$

Fatigue Crack Growth Rate (FCGR)

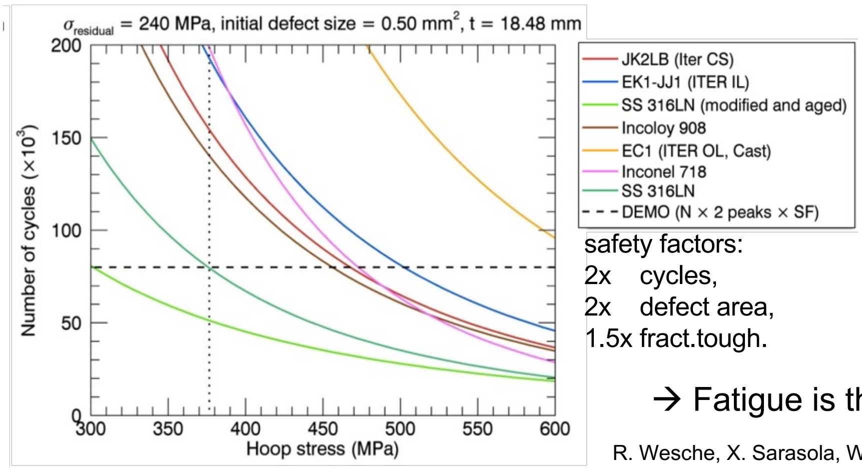
Example from one of the DEMO Central-Solenoid magnet designs

After how many cycles N
the critical crack length a_c
of jacket thickness t
is reached?





SC+SS graded design



safety factors:
2x cycles,
2x defect area,
1.5x fract.tough.

For EU DEMO
20,000 plasma cycles x 2 x 2 = **80,000 cycles**
the hoop stress needs to be reduced
to ≈375 MPa in case of SS 316LN.

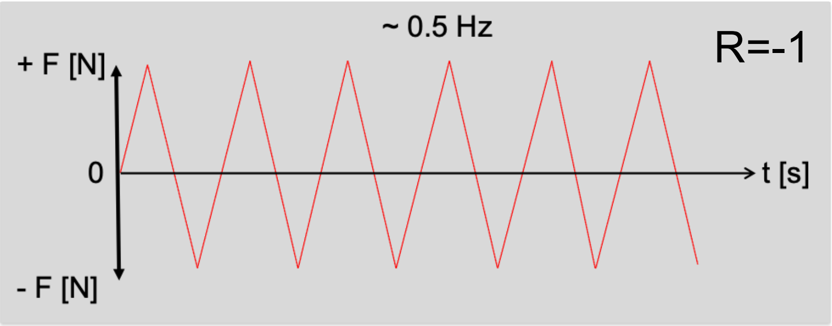
For higher loads or higher cycle numbers, other materials have to be used or even developed.

For a future fusion power plant with planned
156,000 cycles x 2 x 2 = **624,000 cycles**
even with EC1 material the hoop stress
should be < 325 MPa.

→ Fatigue is the main driver that limits the design

R. Wesche, X. Sarasola, WPMAG Final Meeting, Garching, February 12-14, 2019

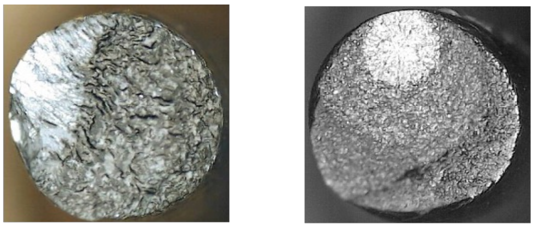
Low Cycle fatigue (LCF)

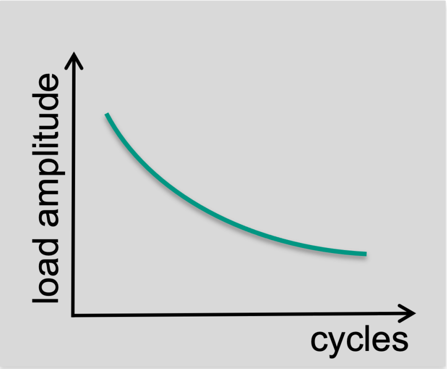


Start with +/-F and ~0.5 Hz until failure of specimen

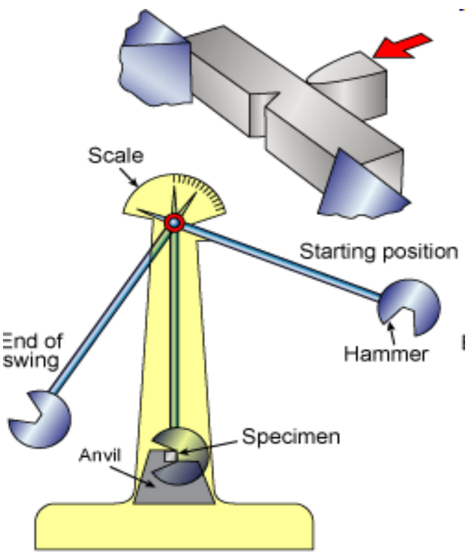
change load level for each specimen

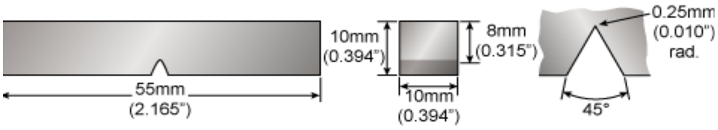
→ lifetime curve (Wöhler curve)

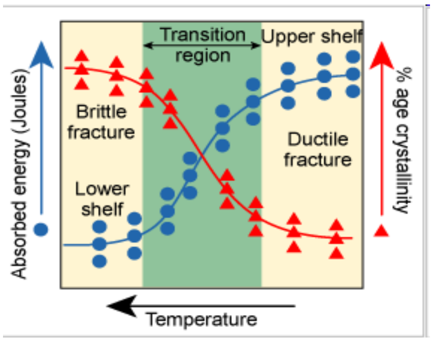




Impact Test







Fast and easy test to examine ductile/brittle transition by absorbed impact energy

Drawback:	results at cryogenic temperature <77K only comparable under same test condition/geometry, but no basic material property!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Thanks for listening!


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Dr. Klaus-Peter Weiss
klaus.weiss@kit.edu

Cryogenic Materialtests Karlsruhe
CryoMaK

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