FUNDAMENTALS ON MECHANICAL TESTING

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  - Tensile
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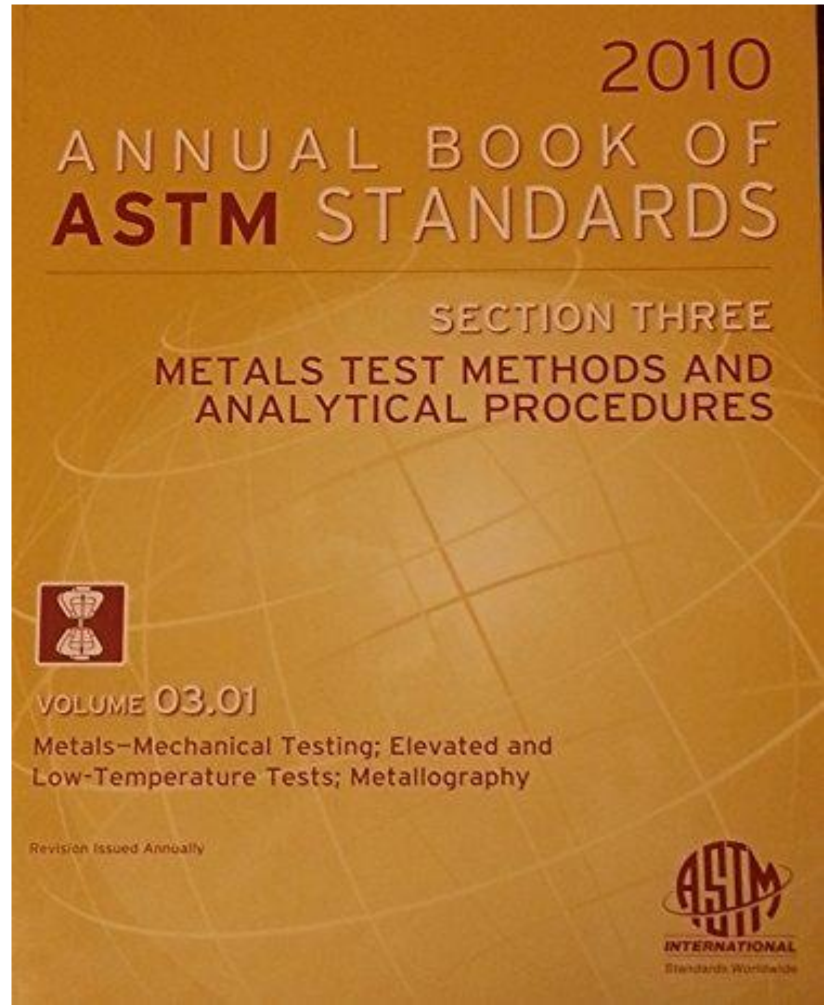
  - Fracture toughness
- Summary

Introduction

- The capability of a material to meet design and service requirements is determined by its mechanical and physical properties.
  - Physical properties are those typically measured by methods not requiring the application of an external mechanical force (or load). Typical examples of physical properties are density, magnetic properties (e.g., permeability), thermal conductivity and thermal diffusivity, electrical properties (e.g., resistivity), specific heat, and coefficient of thermal expansion.
  - Mechanical properties, are described as the relationship between forces (or stresses) acting on a material and the resistance of the material to deformation (i.e., strains) and fracture

Introduction

- Mechanical testing of engineering materials may be carried out for a number of reasons:
  - Provide engineering design data, as well as acceptability, the main purpose of which is to check whether the material meets the specification
  - Simulate the service conditions of a material, so that the test results may be used to predict its service performance.
- Mechanical tests are performed following Testing Standards
  - Specimen geometry
  - Testing procedure
  - Reporting



TESTING TECHNIQUES

Testing techniques

- Acceptance tests for RPV steels are
  - Tensile
  - Charpy
  - Pellini drop-weight
- Test performed within surveillance programmes
  - Tensile
  - Charpy
  - Fracture toughness (not always)
- All this tests and the use of the results are normalized in the design codes (ASME, KTA, RCC-M..) and associated testing standards

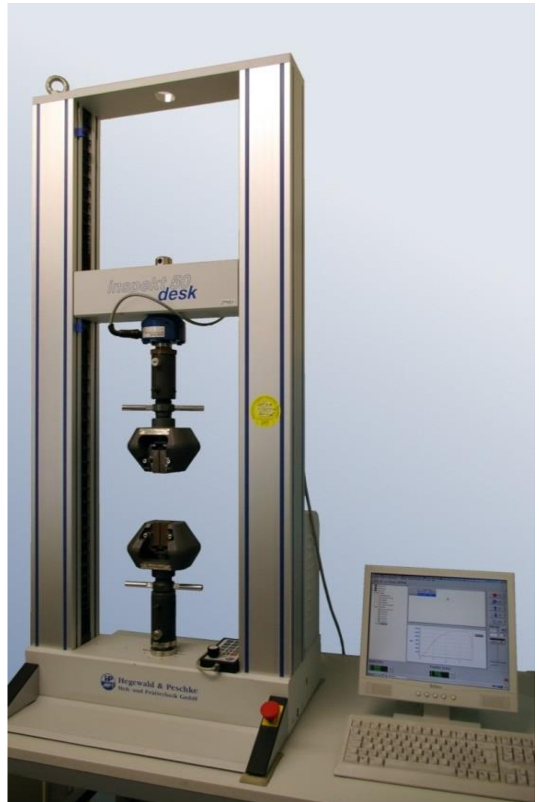
TENSILE TEST

Tensile Test

- It is done by applying an axial load to an normalized specimen with a constant strain rate, until failure
- During the tests both load and strain (or displacement) are measured
- It is a quite simple test, but sometimes preparatory work can becomes very time consuming:
  - Selection of specimen geometry
  - Selection of griping system
  - ..

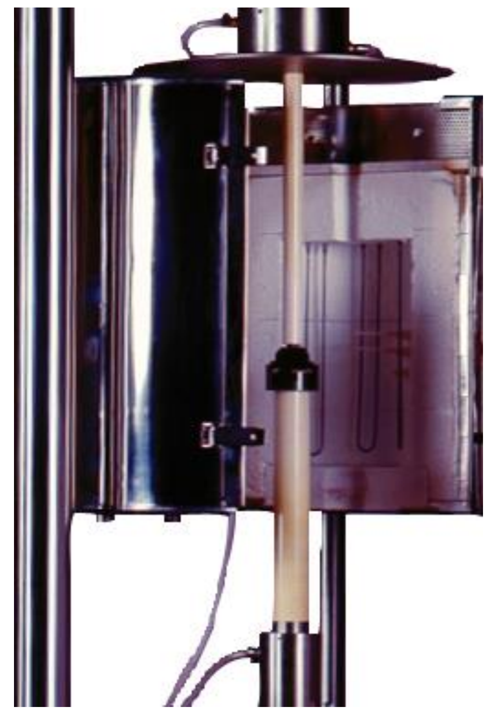
Epsilon axial extensometer

MTS load cell



Tensile test

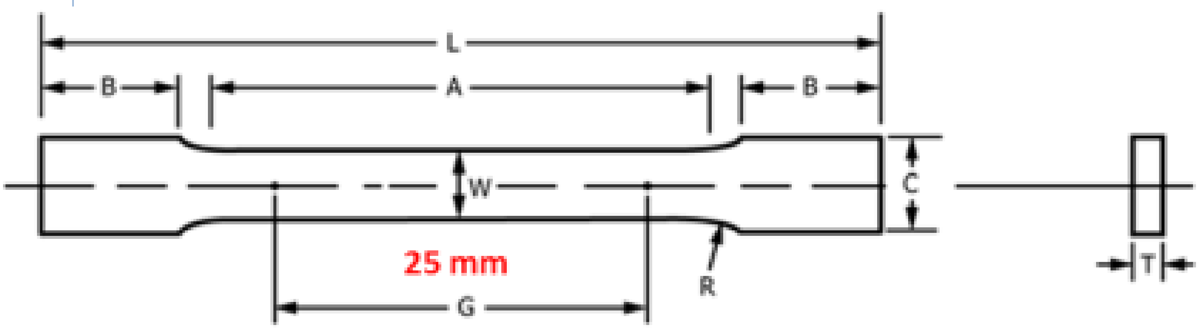
- To perform the test at temperature different from room temperature:
  - Environmental chamber: Temperature < room temperature
  - Furnace: Temperature > room temperature

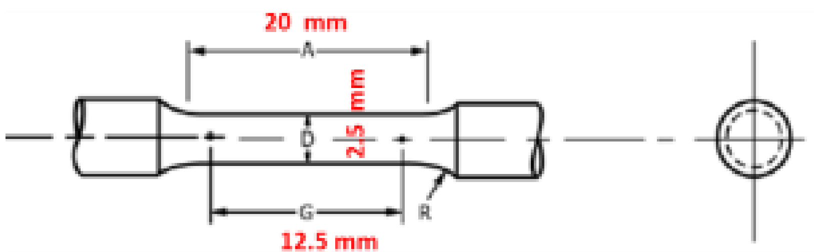


Tensile test

❑ Specimen geometry selection

- Plane or round geometry
- Testing temperature, griping system, extensometer…

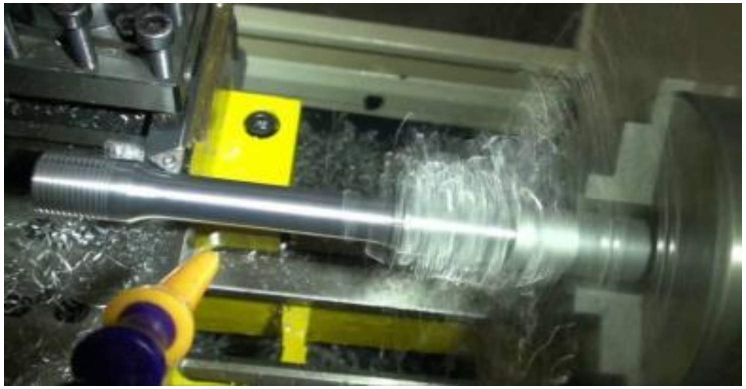


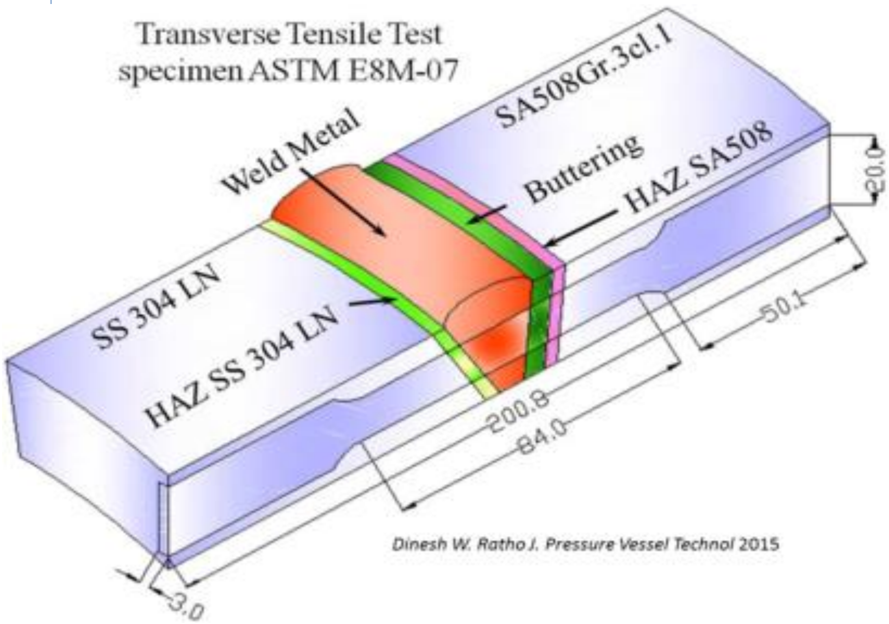


ASTM E8/8M-16 - Standard Test Methods for Tension Testing of Metallic Materials

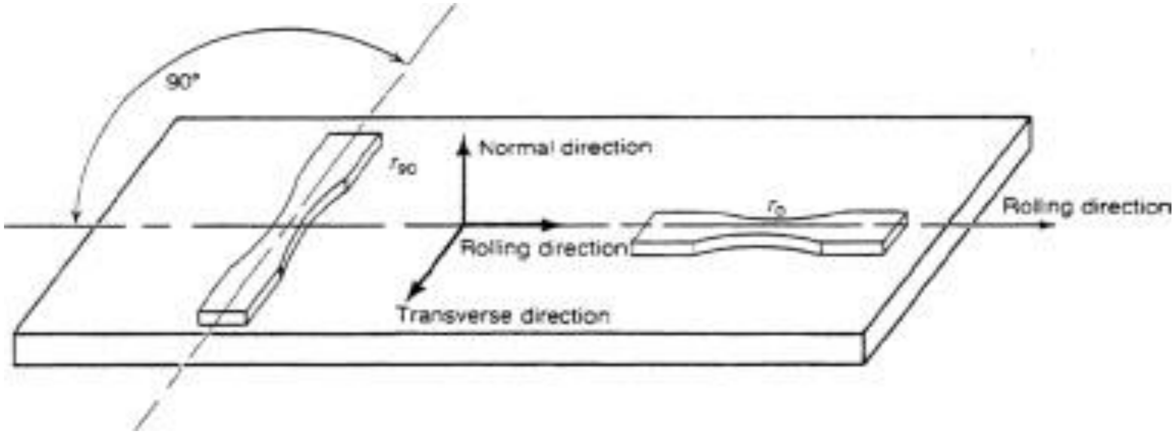
Tensile test

- Specimen mechanization:
  - Location
  - Orientation
  - Surface condition



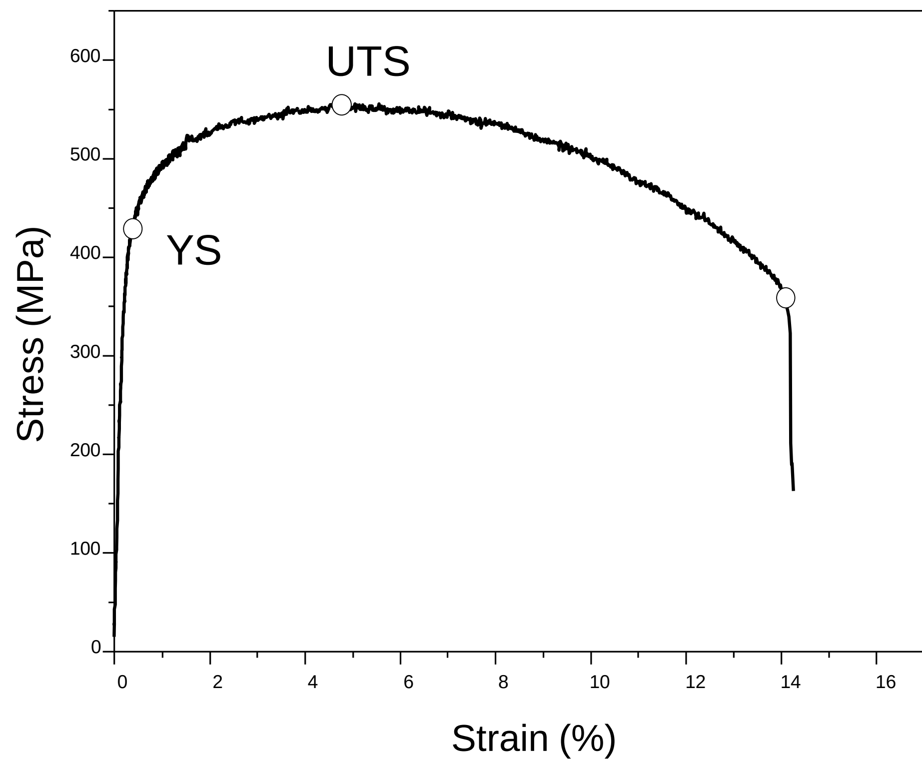


Dinesh W. Rathod J. Pressure Vessel Technol 2015



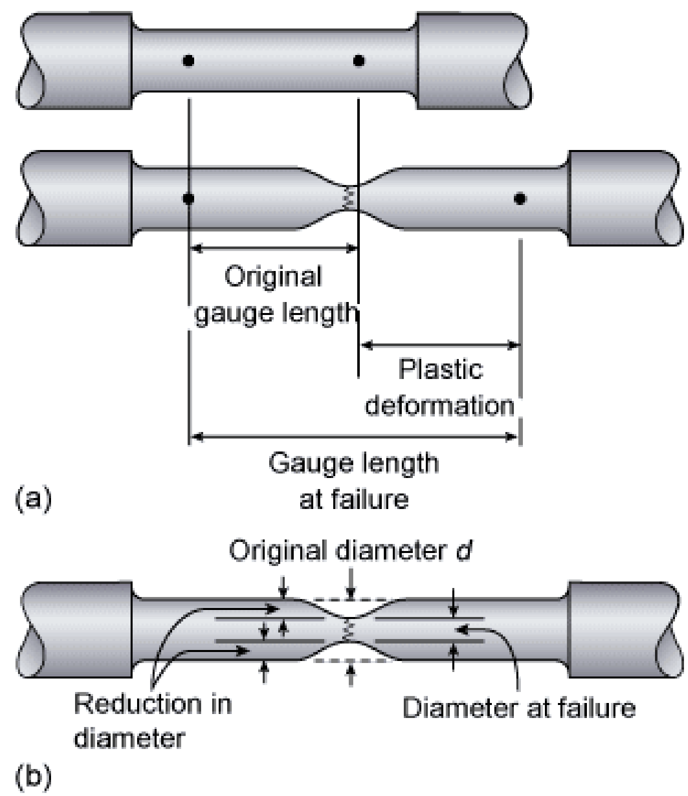
Tensile test

- ❑ The yield strength YS or yield point of a material is defined in engineering and materials science as the stress at which a material begins to deform plastically.
  - A plastic strain of 0.2% is usually used to define the offset yield stress.
- ❑ Ultimate tensile strength (UTS), is the maximum stress that a material can withstand before necking, which is when the specimen's cross-section starts to significantly contract
- ❑ Reduction of area is obtained by measuring the original cross-sectional area of the specimen and relating it to the cross-sectional area after failure.
- ❑ Elongation. The increase in gauge length related to the original length times 100 is the percentage of elongation.



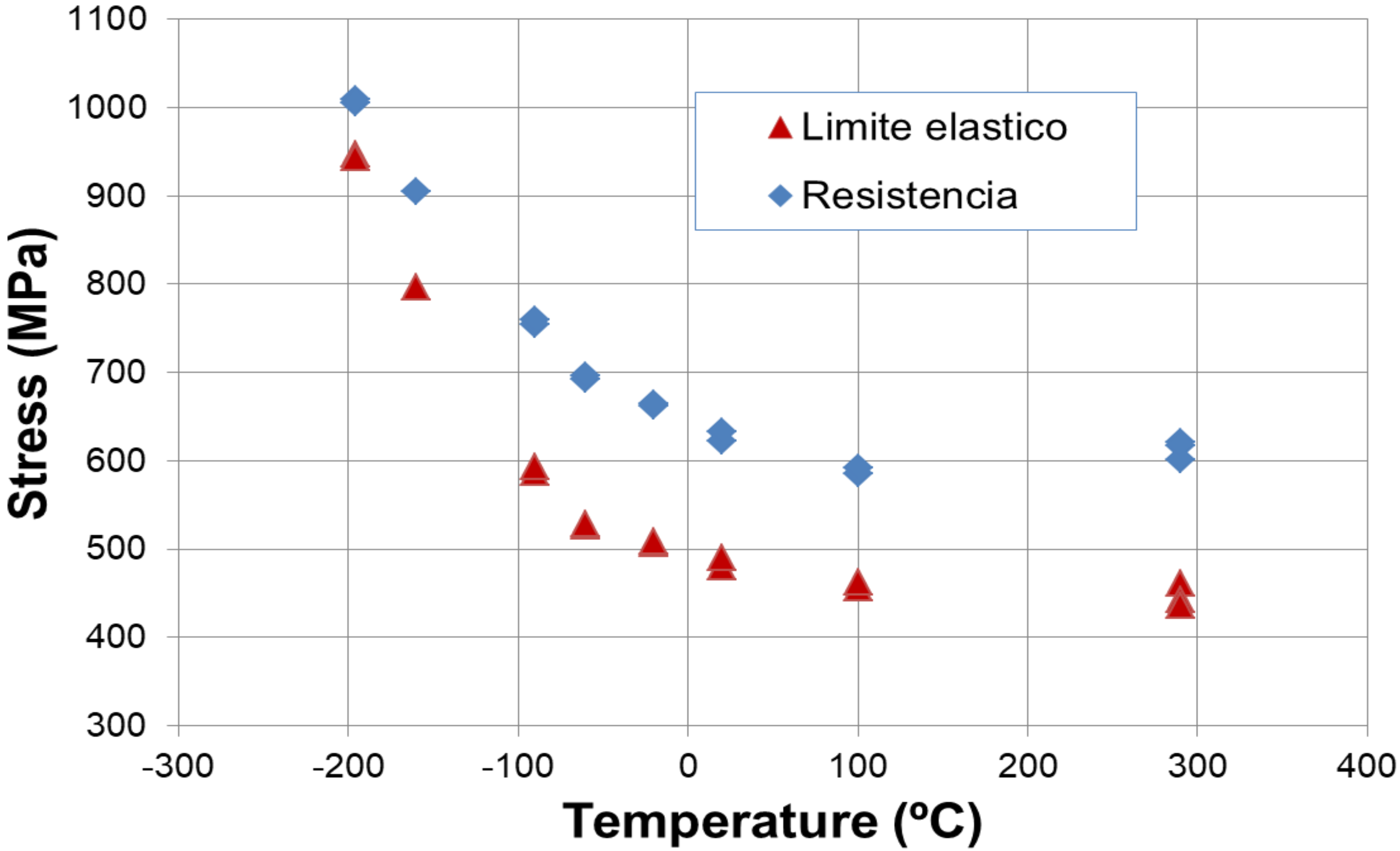
Tensile Tests

- Dimensional control



Tensile Tests

108554PLA **IAEA**

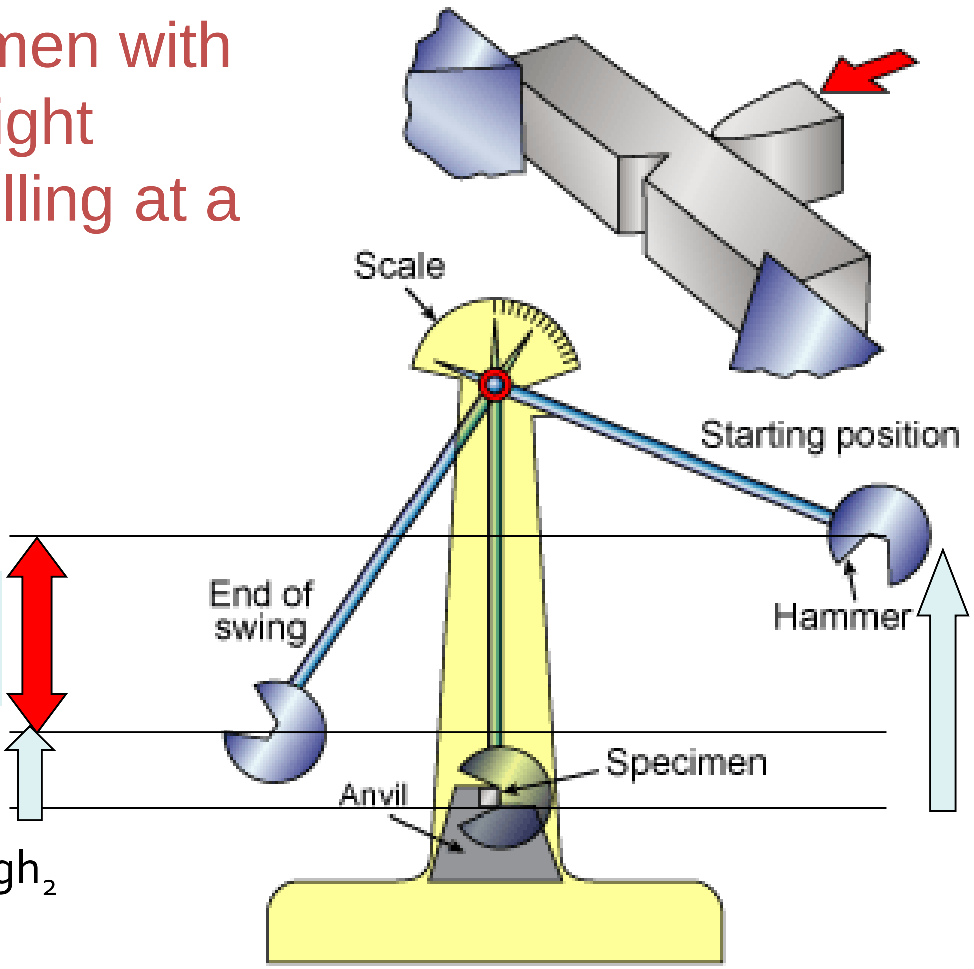


CHARPY IMPACT TEST

Charpy impact test

Higher/Lower temperature

Involve striking a standard specimen with a controlled weight pendulum travelling at a set speed.



Energy absorbed by the specimen

h_1

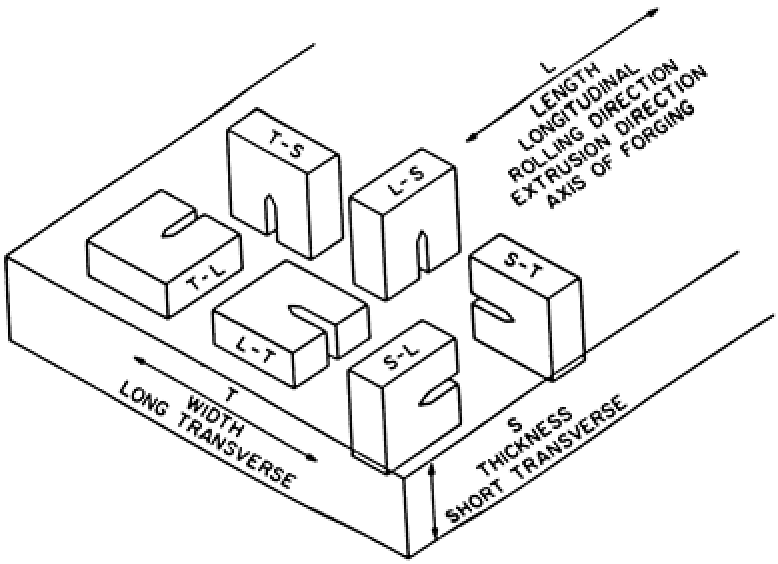
Potential energy=mgh_1

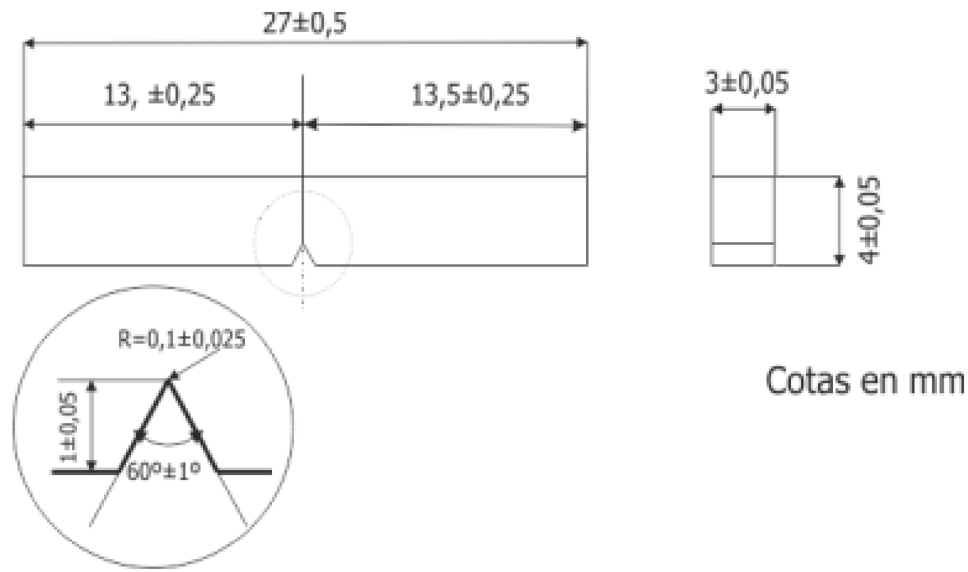
h_2

Potential energy=mgh_2

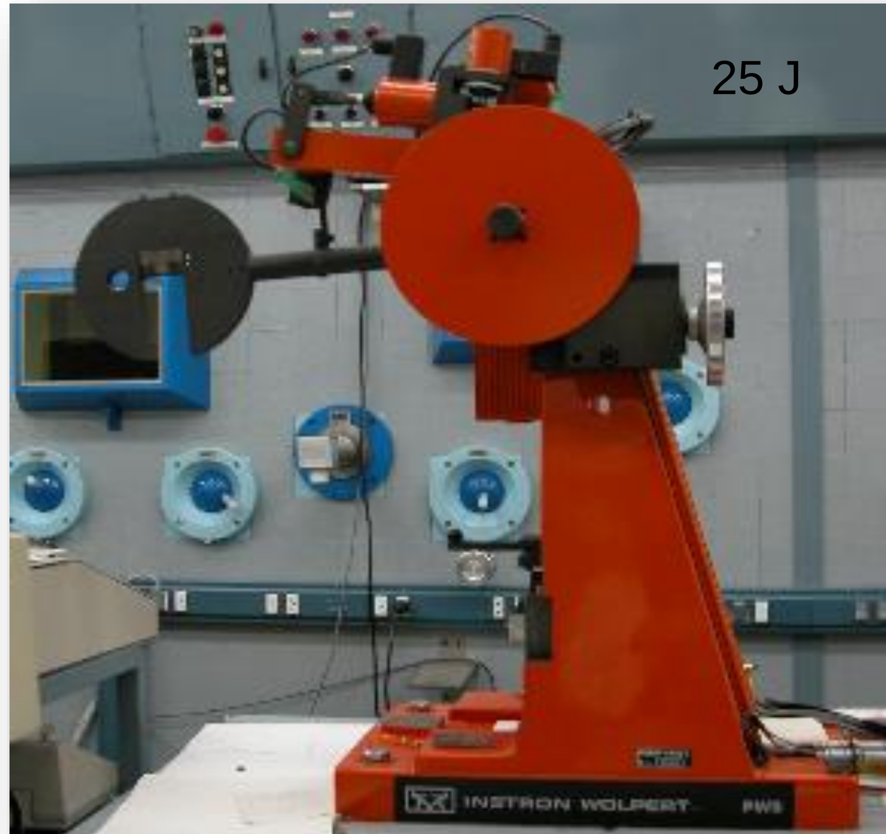
Charpy impact test

- Specimen mechanization





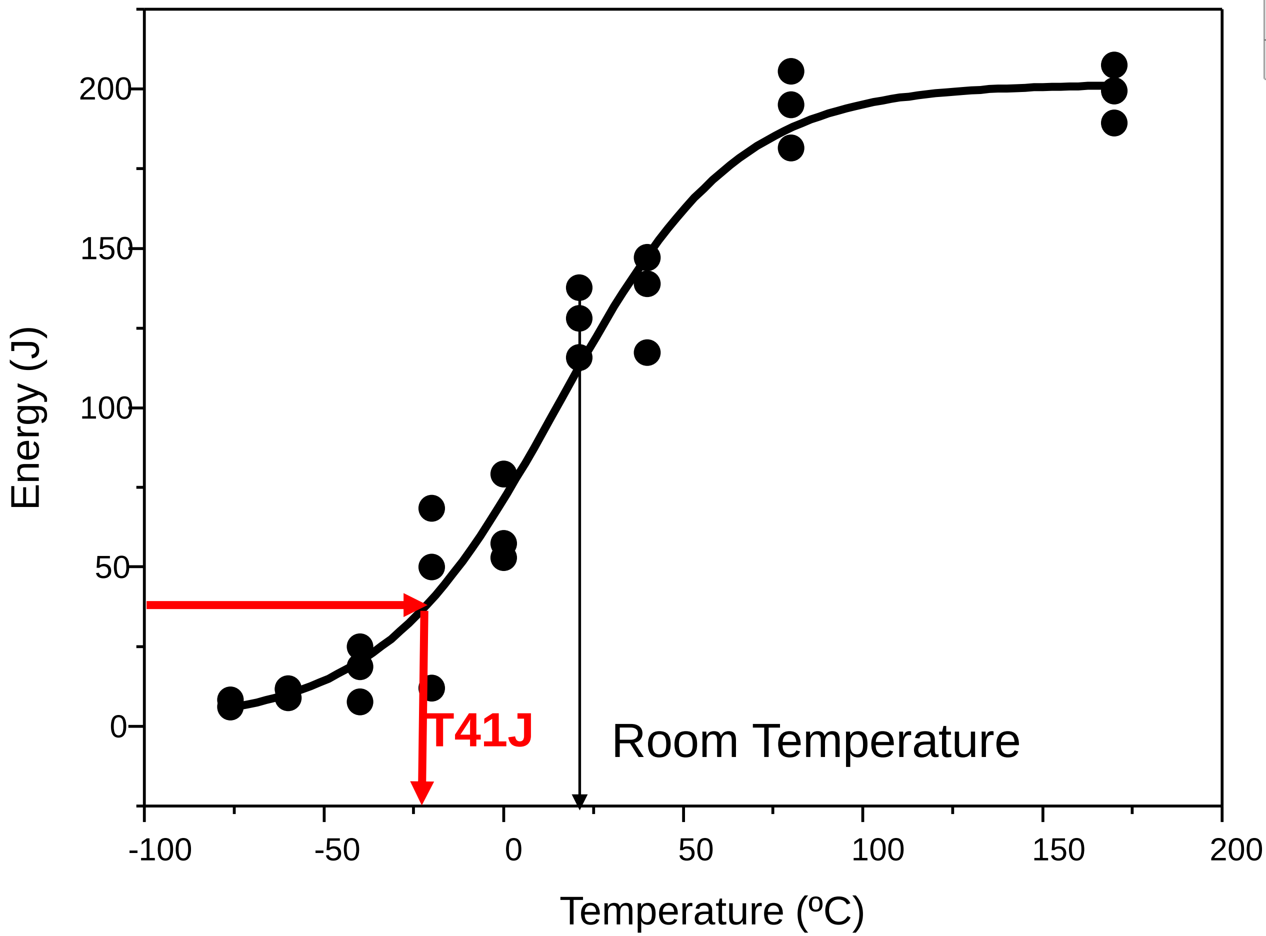
Charpy impact test

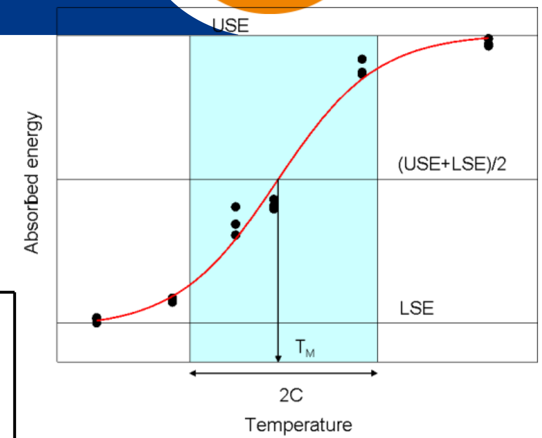


Charpy impact test

- ❑ Charpy test – Absorbed energy

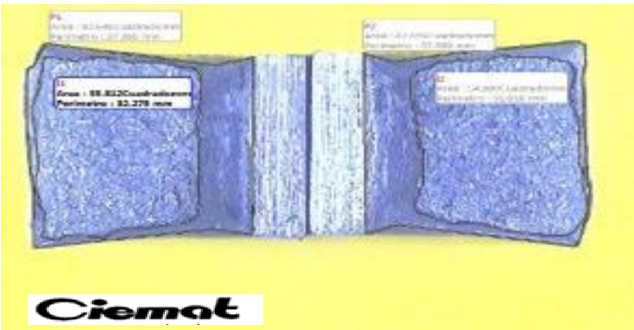
$$E = \frac{USE + LSE}{2} + \frac{USE - LSE}{2}\tanh\left(\frac{T - T_M}{C}\right)$$

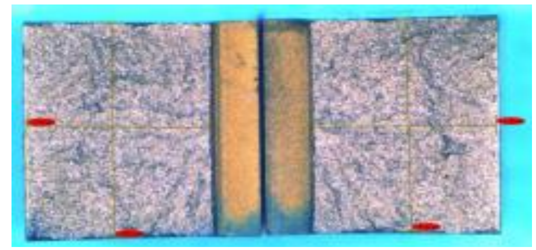




Charpy impact test

❑ Percent of shear fracture





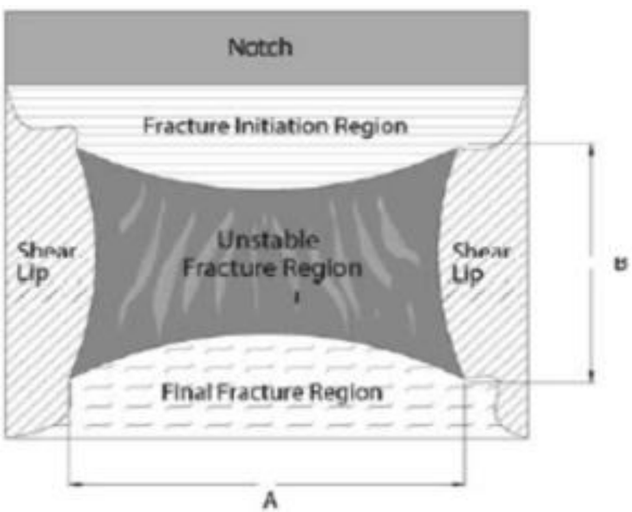


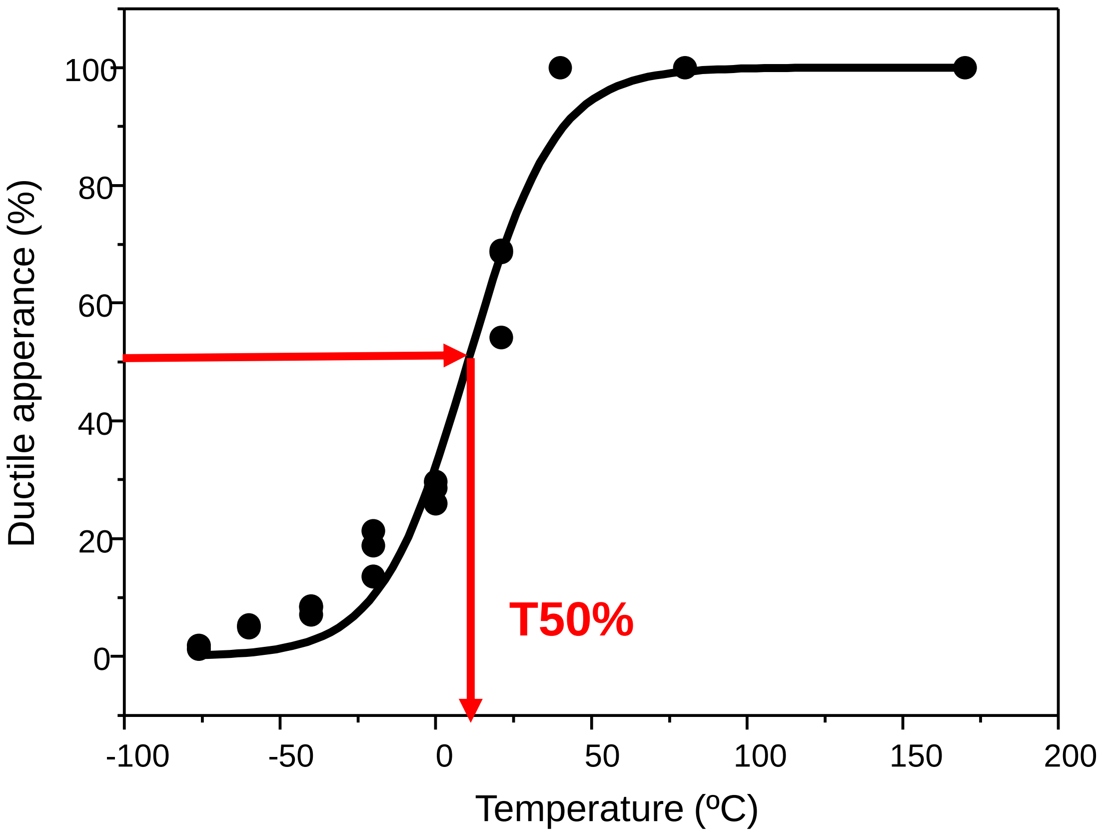
TABLE A6.1 Percent Shear for Measurements Made in Millimetres

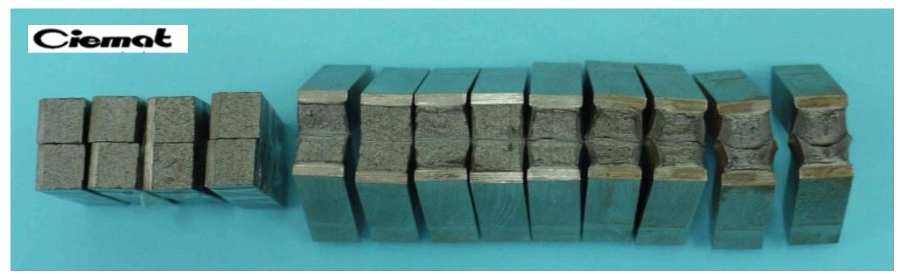
1—100 % shear is to be reported when either *A* or *B* is zero.

nension 3, mm	Dimension *A*, mm																		
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10
1.0	99	98	98	97	96	96	95	94	94	93	92	92	91	91	90	89	89	88	88
1.5	98	97	96	95	94	93	92	92	91	90	89	88	87	86	85	84	83	82	81
2.0	98	96	95	94	92	91	90	89	88	86	85	84	82	81	80	79	77	76	75
2.5	97	95	94	92	91	89	88	86	84	83	81	80	78	77	75	73	72	70	69
3.0	96	94	92	91	89	87	85	83	81	79	77	76	74	72	70	68	66	64	62
3.5	96	93	91	89	87	85	82	80	78	76	74	72	69	67	65	63	61	58	56
4.0	95	92	90	88	85	82	80	77	75	72	70	67	65	62	60	57	55	52	50
4.5	94	92	89	86	83	80	77	75	72	69	66	63	61	58	55	52	49	46	44
5.0	94	91	88	85	81	78	75	72	69	66	62	59	56	53	50	47	44	41	37
5.5	93	90	86	83	79	76	72	69	66	62	59	55	52	48	45	42	38	35	31
6.0	92	89	85	81	77	74	70	66	62	59	55	51	47	44	40	36	33	29	25
6.5	92	88	84	80	76	72	67	63	59	55	51	47	43	39	35	31	27	23	19
7.0	91	87	82	78	74	69	65	61	56	52	47	43	39	34	30	26	21	17	12
7.5	91	86	81	77	72	67	62	58	53	48	44	39	34	30	25	20	16	11	6
8.0	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10	5	0

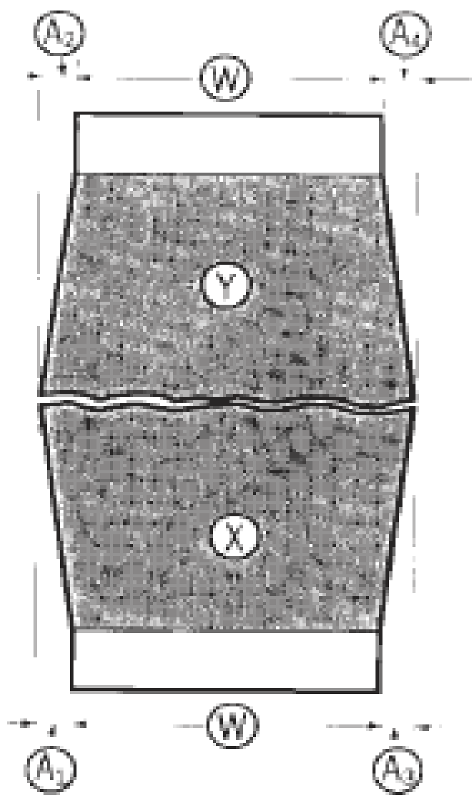
Charpy impact test

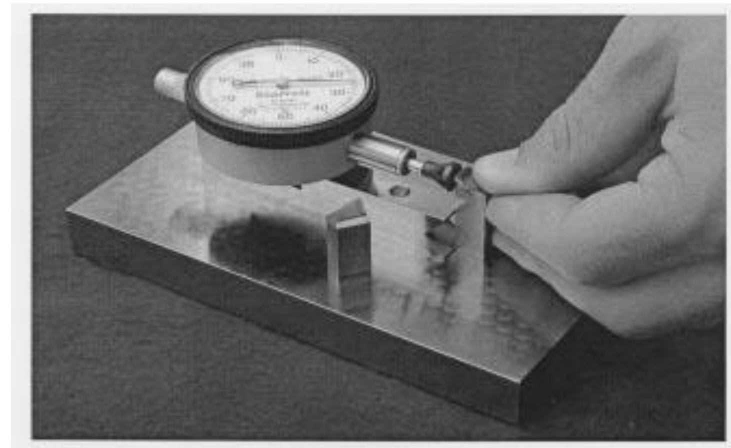
- ❑ Percent of shear fracture

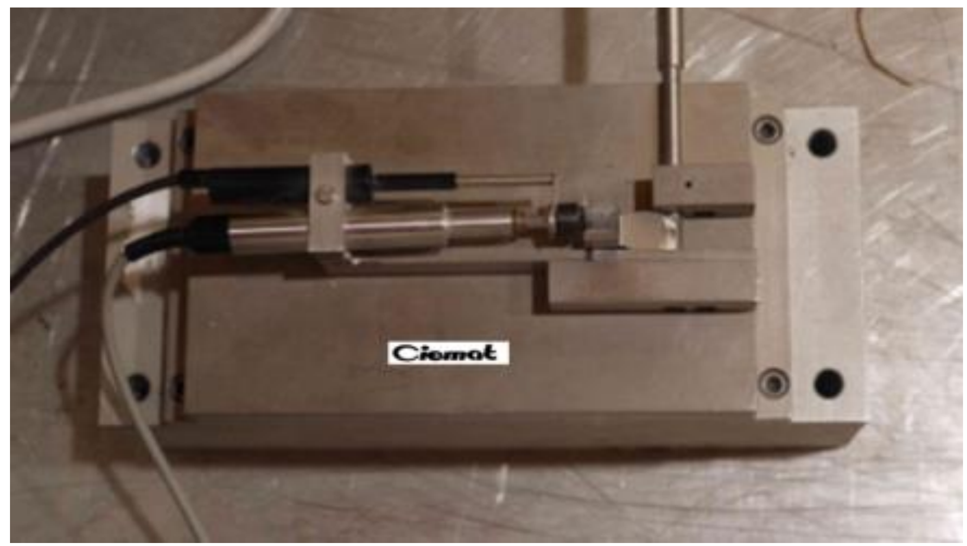




- Lateral expansion: Máx Y + Max X

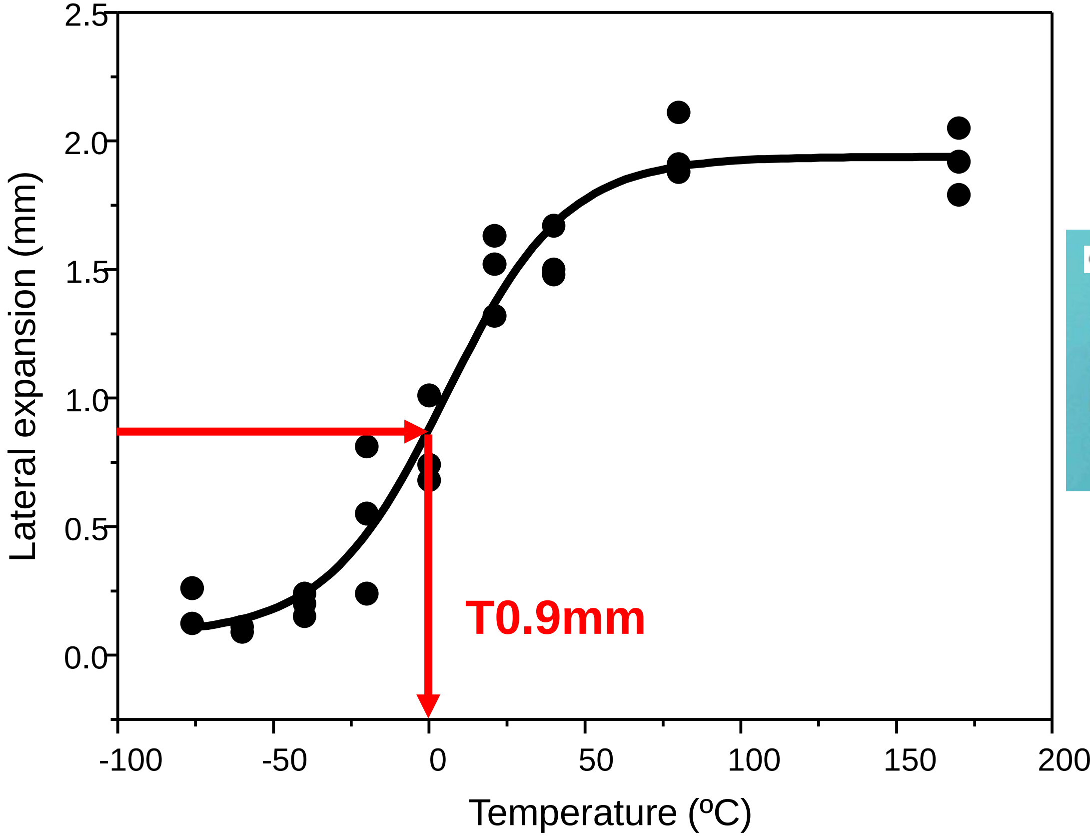


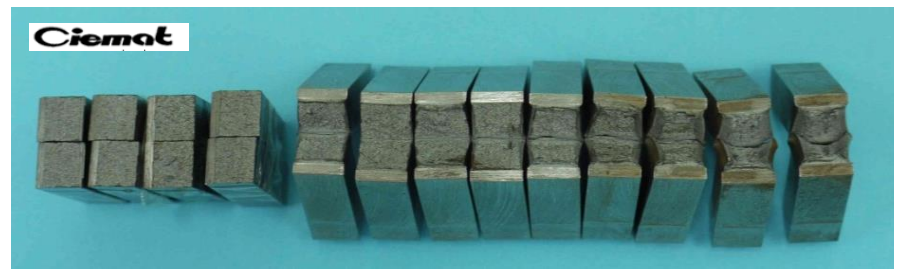




Charpy impact test

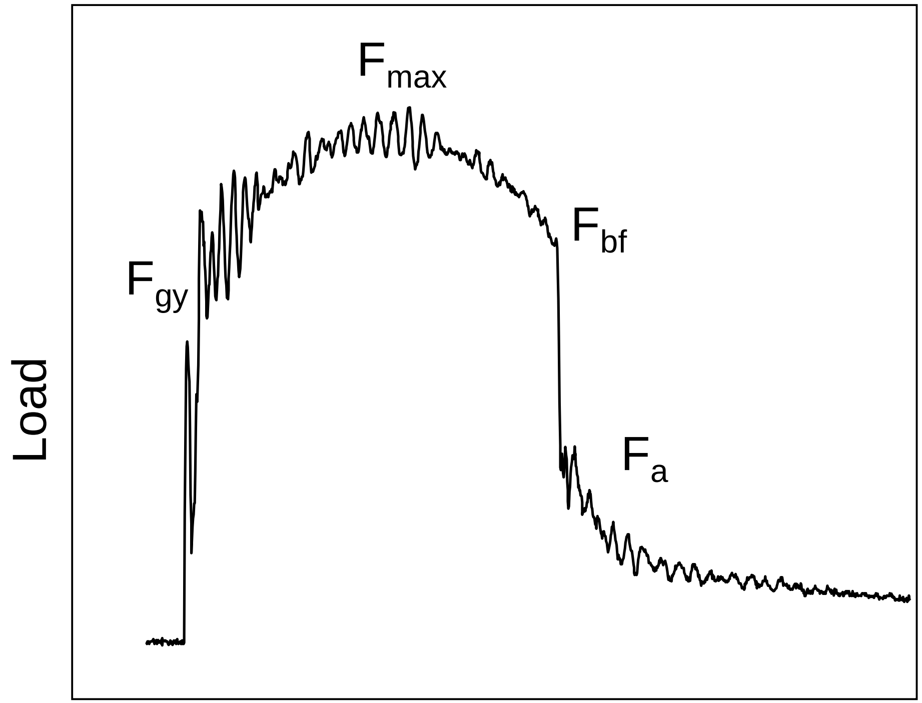
- Charpy test - Lateral expansion

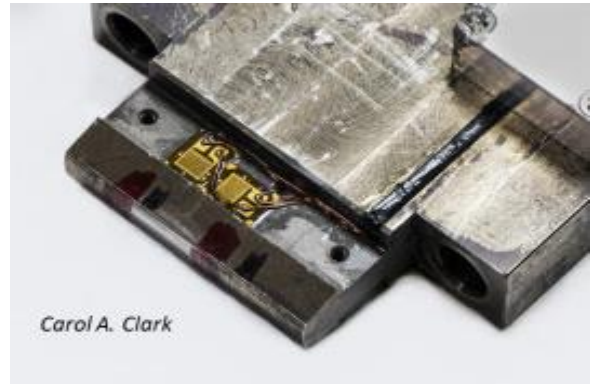




Instrumented Charpy test

❑ Characteristic loads





$$v(t) = v_0 - \frac{1}{m}\int_{t_0}^{t} F(t)dt$$

$$s(t) = \int_{t_0}^{t} v(t)dt$$

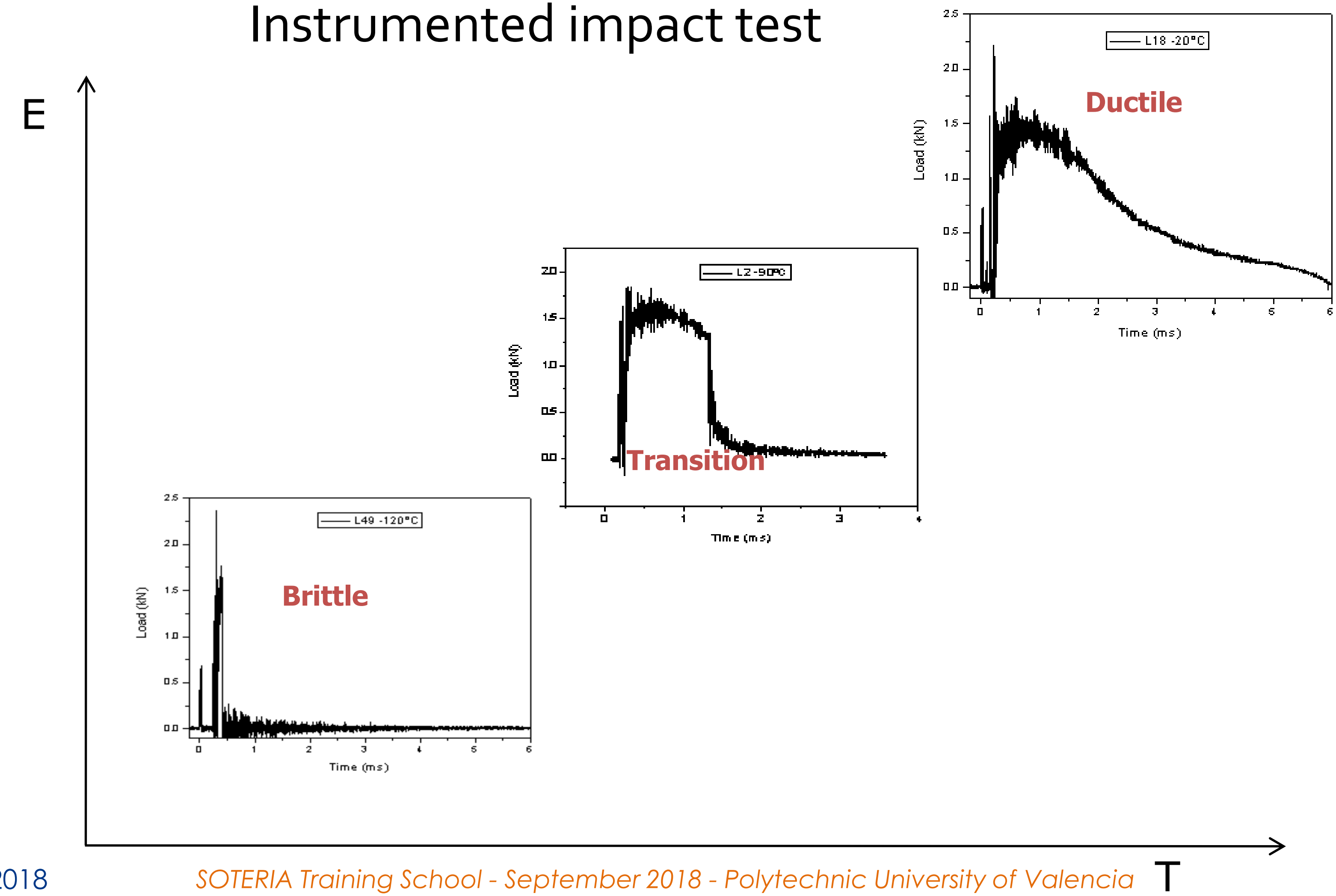
$$v_0 = \sqrt{2gh_0}$$

g = the local acceleration due to gravity, and
*h*0 = the falling height of the striker

ASTM E2298 – 15 Standard Test Method for Instrumented Impact Testing of Metallic Materials

Impact test

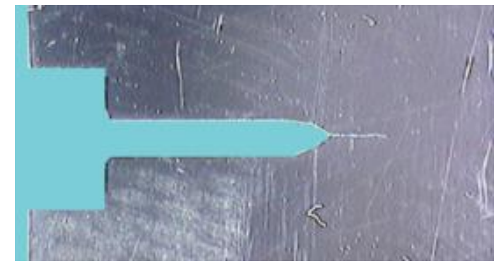
Instrumented impact test



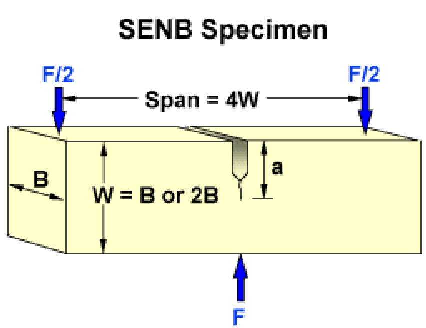
FRACTURE TOUGHNESS

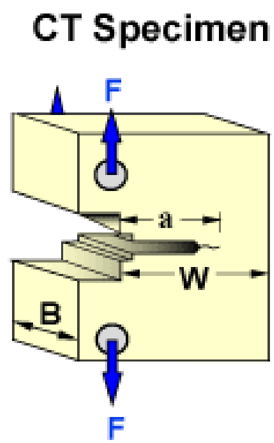
Fracture toughness test

- All fracture toughness test have several common features
  - Specimen geometries –Size to assure plain strain
  - Pre-crack by fatigue
  - Basic instrumentation – Load, displacement
  - Test is performed at constant displacement rate

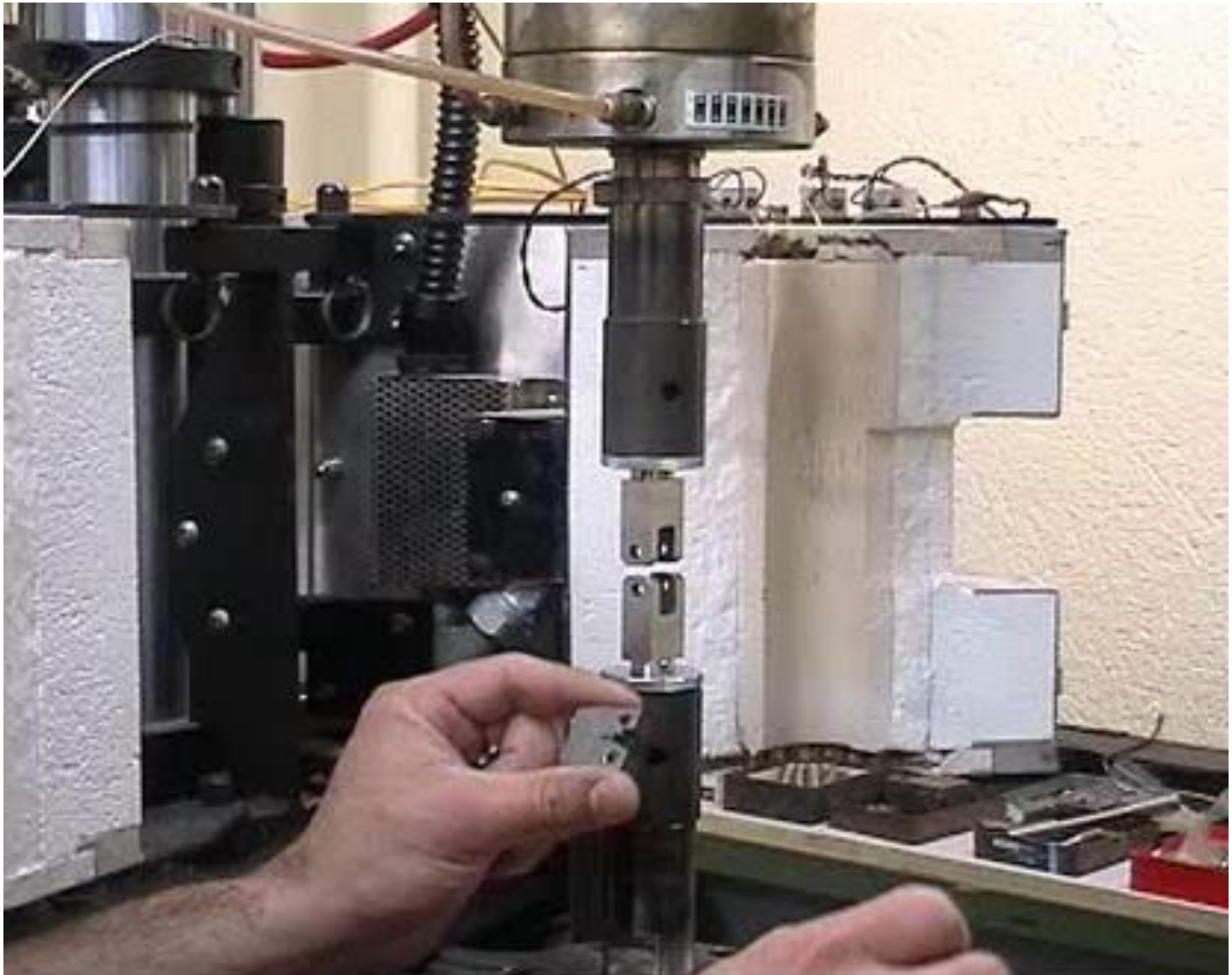


- The machine is the same as for tensile testing





Anderson 1995



Fracture toughness test

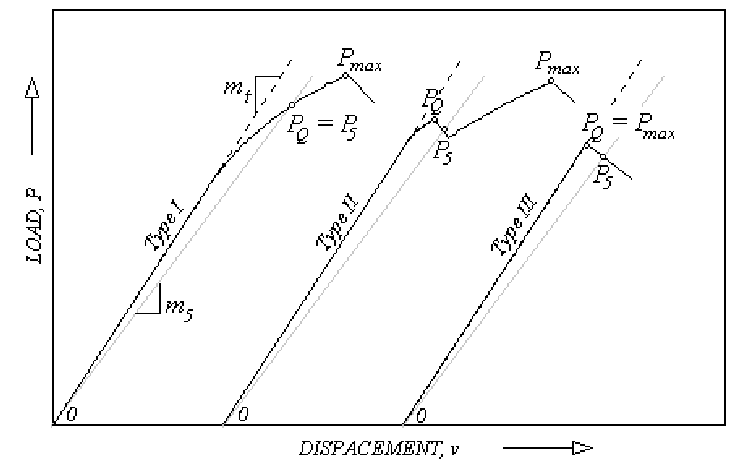
- Fracture toughness test types:
  - K tests:
    - K_{IC} determination
    - Lineal-elastic
    - Brittle fracture
  - J – CTOD tests
    - J_{IC}, δ_{IC} determination
    - Elasto-plastic
    - Ductile, transition

	ASTM standard
K_{IC}	E399-17 Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness KIc of Metallic Materials
K_{Ia}	E1221-12a Standard Test Method for Determining Plane-Strain Crack-Arrest Fracture Toughness, KIa, of Ferritic Steels
J-R Curve, J_{IC}, CTOD and K_{JIC}	E1820-17a Standard Test Method for Measurement of Fracture Toughness
Master Curve $K_{JC(1T)}$	E1921-18 Standard Test Method for Determination of Reference Temperature, To, for Ferritic Steels in the Transition Range

Fracture toughness tests

❑ K_{IC} test

- Plain strain is necessary condition for a valid K_{IC}, but also the specimen must also behave in linear elastic manner
- The pre-cracked specimen is loaded to failure at a constant displacement rate (mm/min). The resulting load – displacement curve can be type I, II, or III
- Definition of critical load PQ
  - $P_Q = P_5$ for Type I
  - P_Q is defined at pop-in for Type II
  - P_Q=Pmax for Type III



$$K_Q = \frac{P_Q}{B\sqrt{W}} f\left(a/W\right)$$

K_{IC}=K_Q only if Plain strain

$$0.45 \le a/W \le 0.55$$

$$B, a \ge 2.5\left(\frac{K_Q}{\sigma_{YS}}\right)^2$$

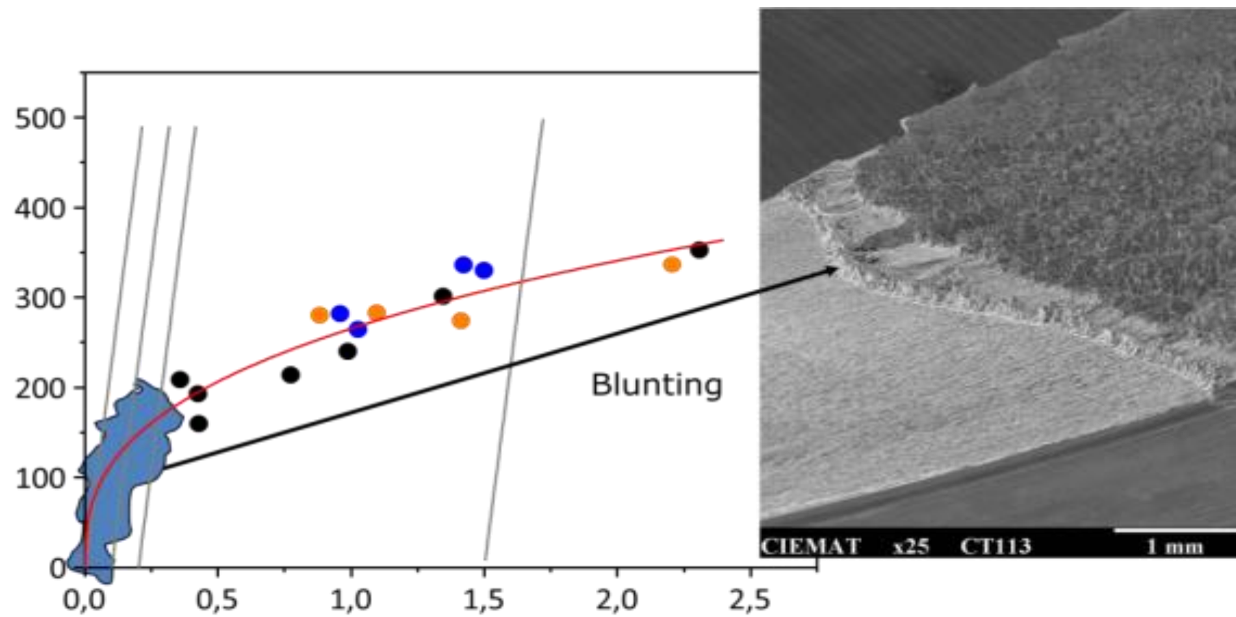
$$P_{max} \le 1.10 P_Q$$

Fracture toughness tests

- **J Tests**
- The pre-cracked specimen is loaded to failure at a constant displacement rate (mm/min)
- Crack growth determination
  - Multi-specimen
  - Single specimen

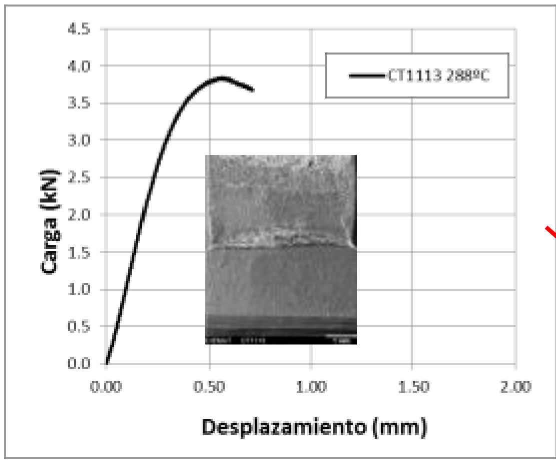
Crack growth determination

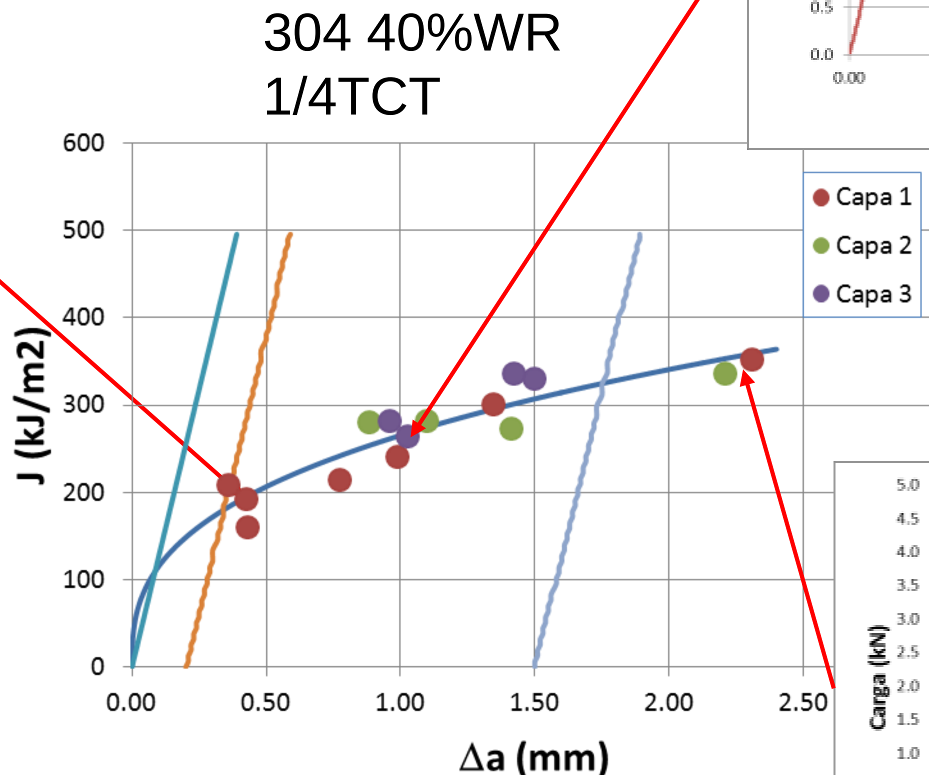
- Compliance
- Potential drop
- Normalization

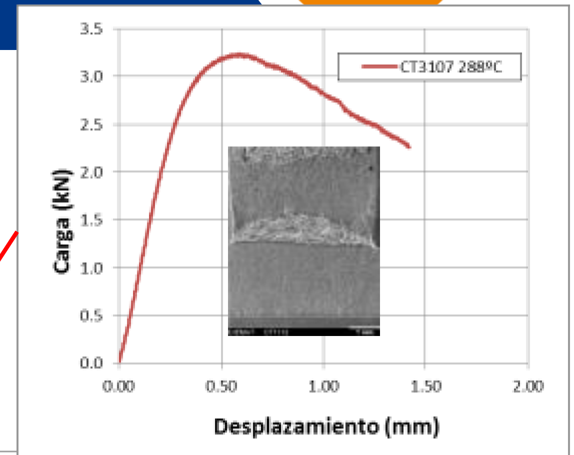


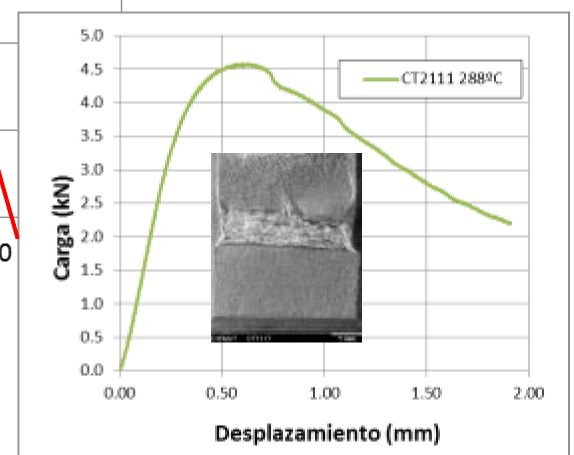
Fracture toughness tests

- Multi-specimen



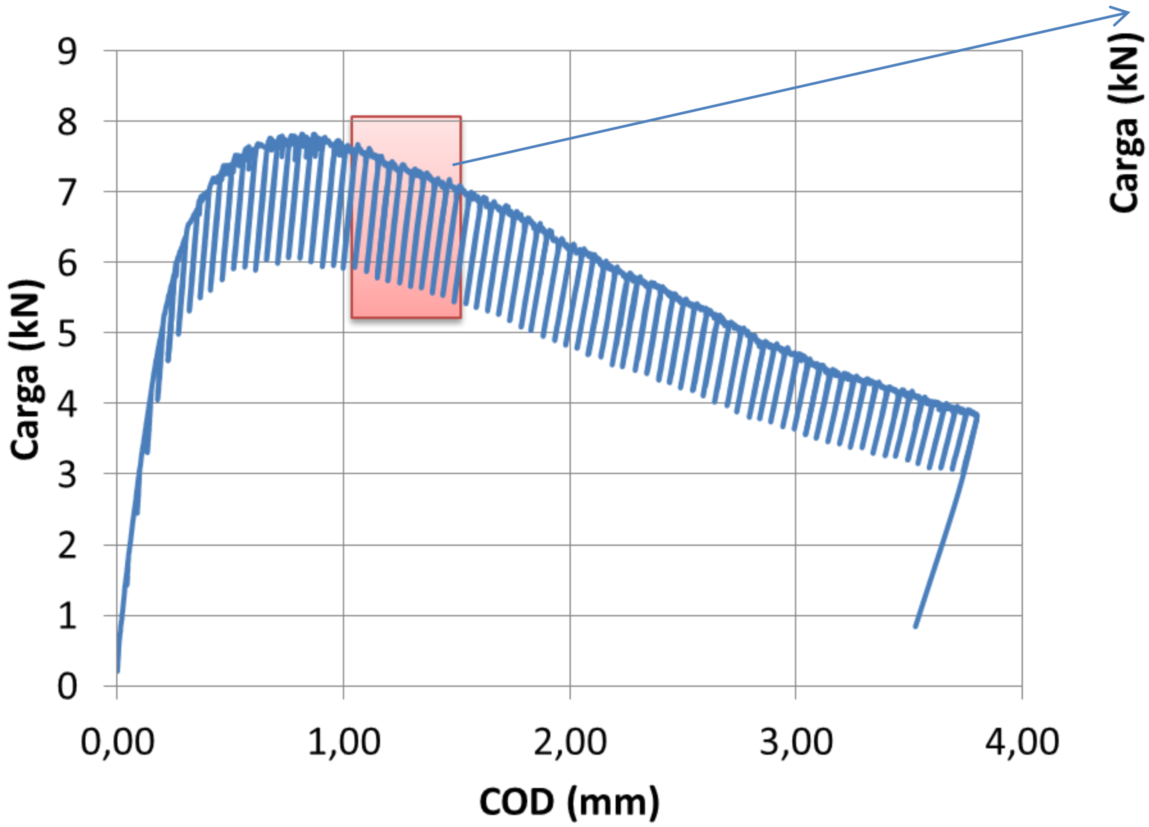


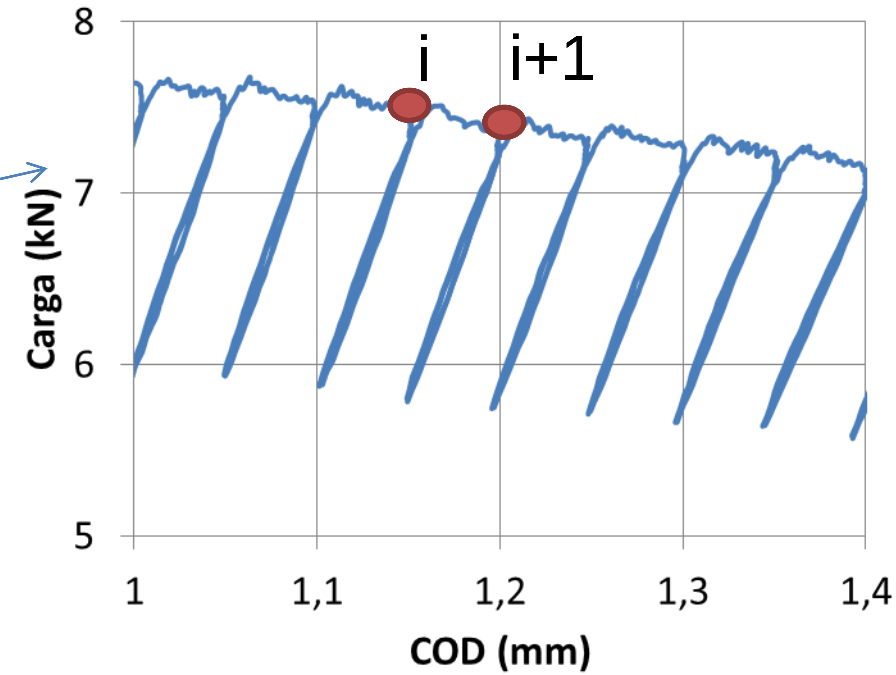




Fracture toughness tests

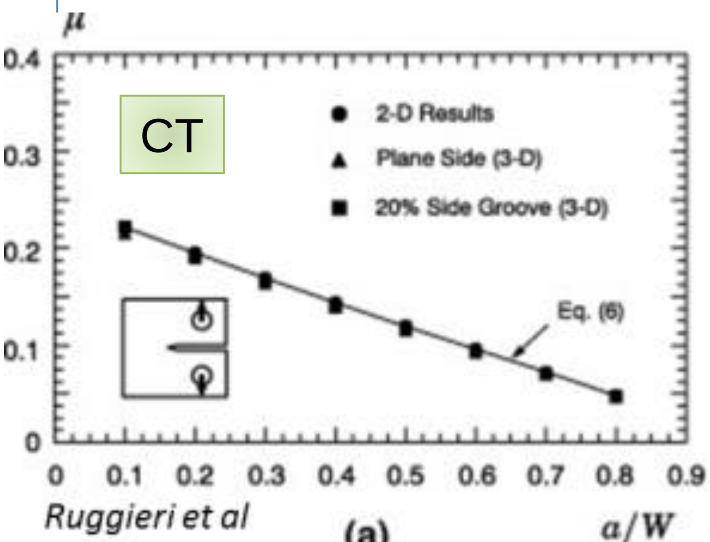
Specimen compliance

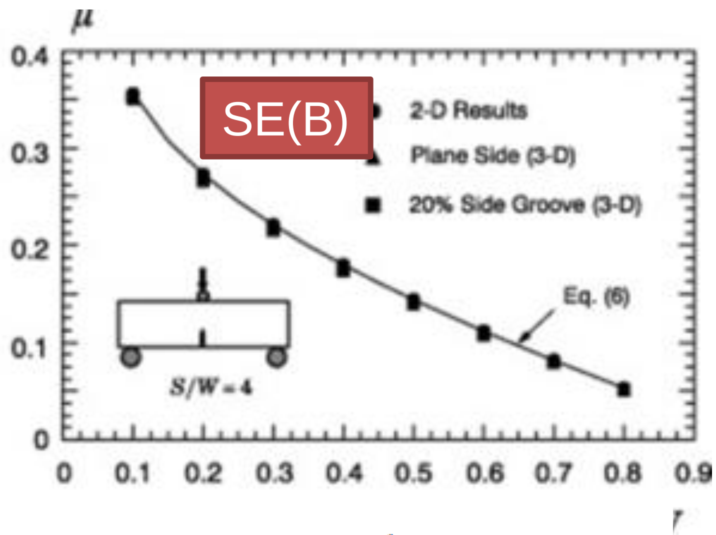


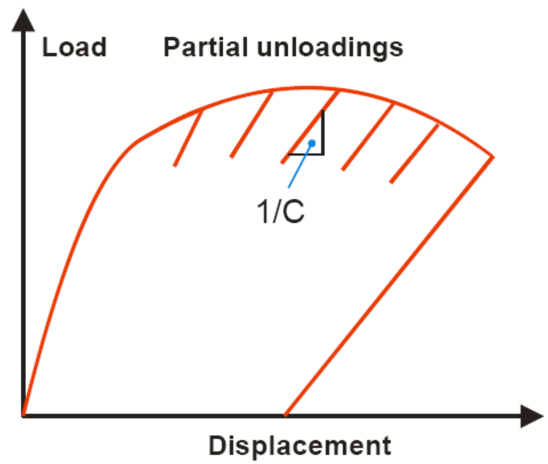


Fracture toughness tests

- Specimen compliance







$$u = \frac{1}{\left[B_e E C_{c(i)}\right]^{1/2} + 1}$$

$C_{c(i)}$ = specimen load-line crack opening elastic compliance ($\Delta v/\Delta P$) on an unloading/reloading sequence corrected for rotation

B_e = $B - (B - B_N)^2/B$.

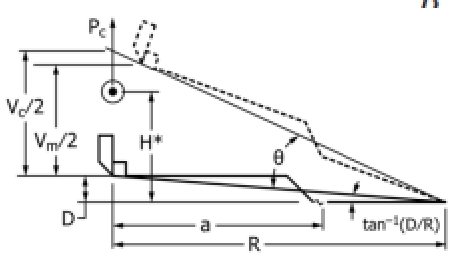
$$u = \frac{1}{\left[\dfrac{B_e W E C_i}{S/4}\right]^{1/2} + 1}$$

C_i = $(\Delta v_m/\Delta P)$ on an unloading/reloading sequence,

v_m = crack mouth opening displacement at notched edge,

B = $B - (B - B_N)^2/B$.

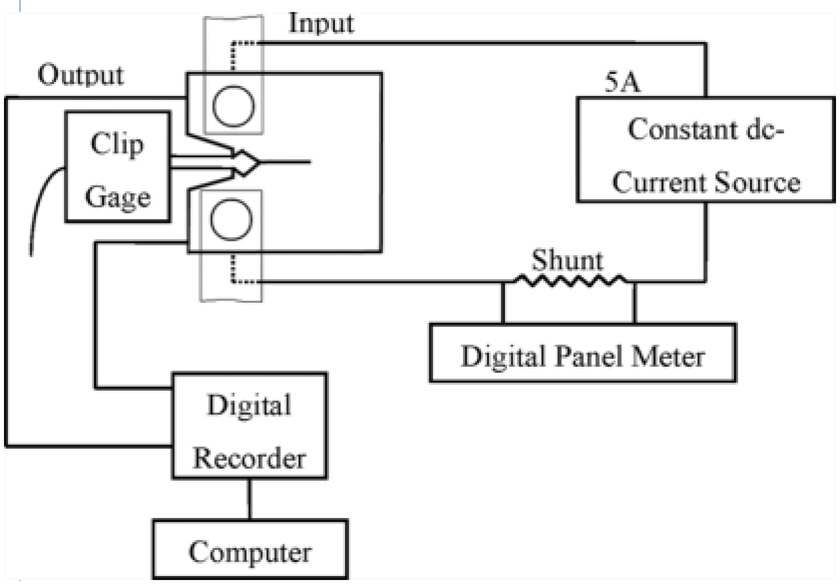
$$C_{c(i)} = \frac{C_i}{\left(\frac{H^*}{R_i}\sin\theta_i - \cos\theta_i\right)\left(\frac{D}{R_i}\sin\theta_i - \cos\theta_i\right)}$$

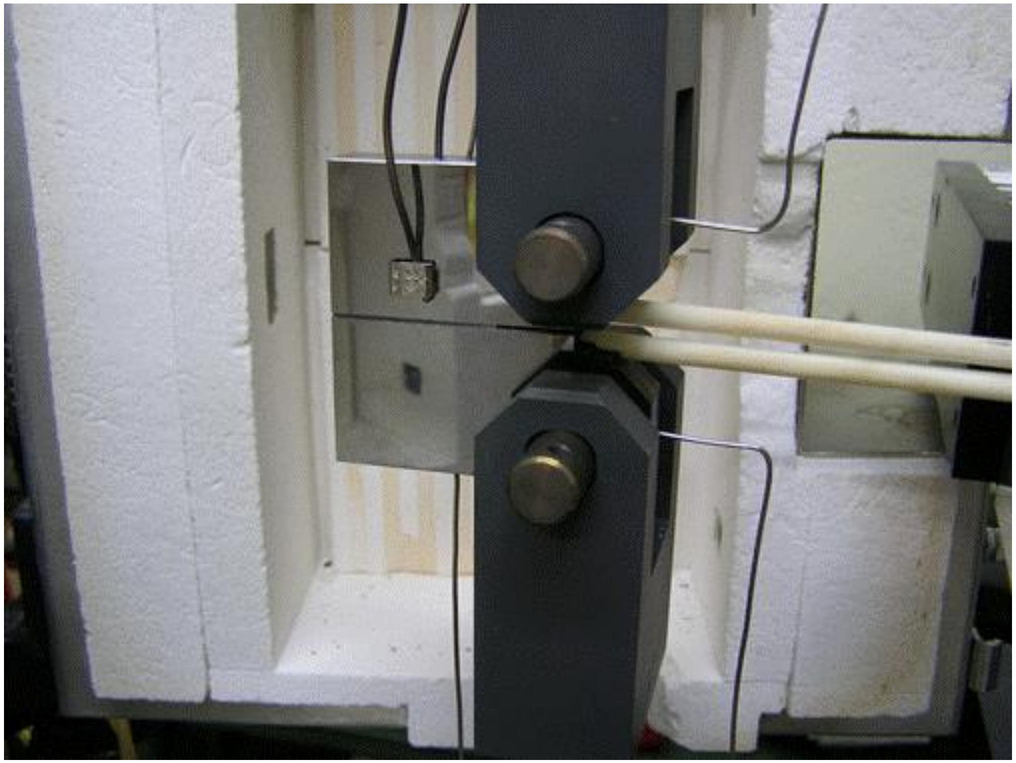


Fracture toughness tests

- Potential drop technique

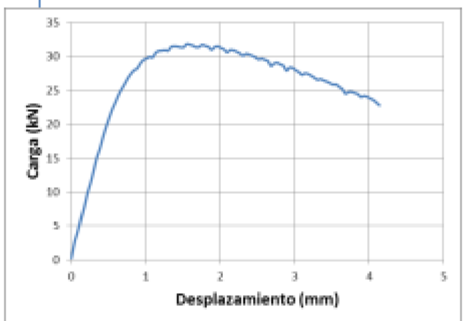
$$a = \frac{2W}{\pi}\cos^{-1}\frac{\cosh(\pi y/2W)}{\cosh\{(U/U_0)\cosh^{-1}[\cosh(\pi y/2W)/\cos(\pi a_0/2W)]\}}$$





Fracture toughness tests

❑ Normalization method



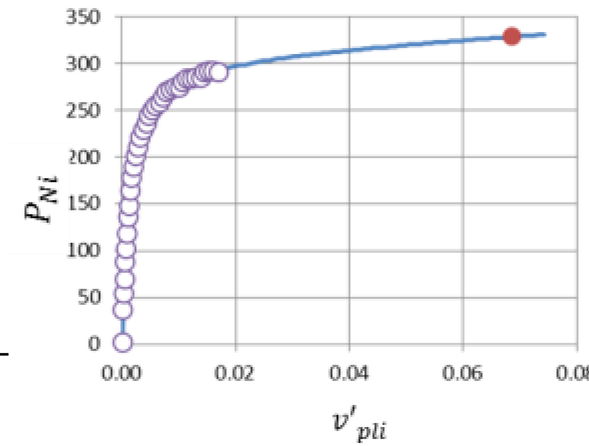
Step 1.- Normalizinz load and displacement up to maximun load P_{max} -> Last point – final crack length

$$P_{Ni} = \frac{P_i}{WB\left(\frac{W - a_{bi}}{W}\right)^{n_{pl}}}$$

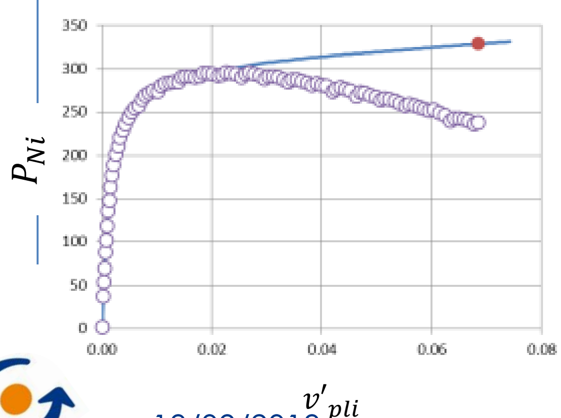
$$v'_{pli} = \frac{v_{pli}}{W} = \frac{v_i - P_i C_i}{W}$$

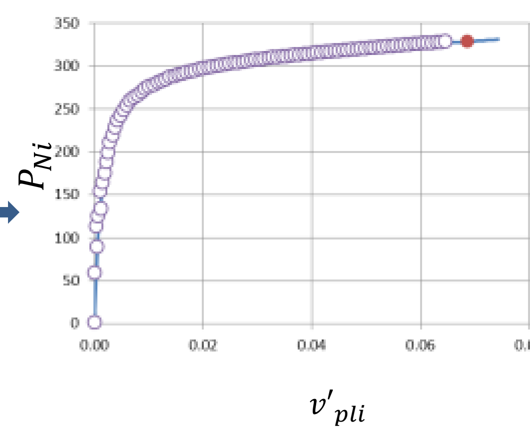
Step 2.- Data fitting

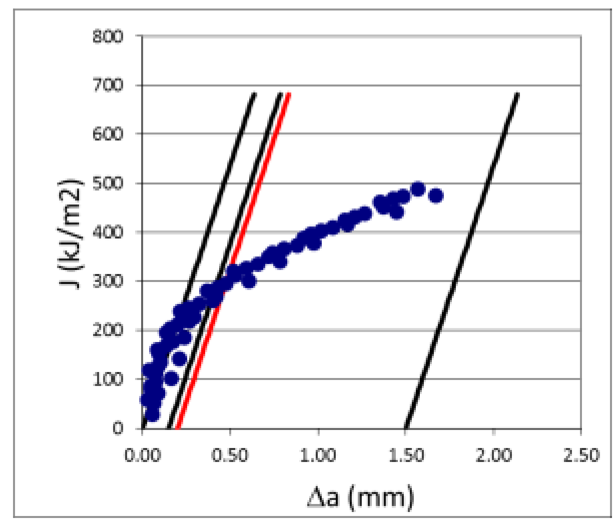
$$P_N = \frac{a + bv'_{pl} + {v'_{pl}}^2}{d + v'_{pl}}$$



Step 3.- Variantion of a_i to fit tests data with P_N function



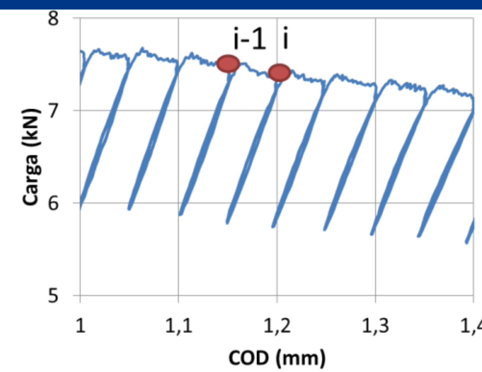




Fracture toughness tests

- J determination

$$J = J_e + J_{pl}$$



$$J_e = \frac{K_{(i)}{}^2 (1-\mu^2)}{E}$$

$$A_{pl(i)} = A_{pl(i-1)} + \frac{[P_{(i)} + P_{(i-1)}][v_{pl(i)} - v_{pl(i-1)}]}{2}$$

$$J_{pl(i)} = \left[J_{pl(i-1)} + \frac{\mu_{(i-1)}}{b_{(i-1)}} \frac{A_{pl(i)} - A_{pl(i-1)}}{B_N}\right]\left[1 - \gamma_{(i-1)} \frac{a_{(i)} - a_{(i-1)}}{b_{(i-1}}\right]$$

$v_{pl(i)}$ = plastic part of the load-line displacement, $v_i - P_{(i)}C_{LL(i)}$, and

$C_{LL(i)}$ = experimental compliance, $(\Delta v/\Delta P)_i$, corresponding to the current crack size, a_i.

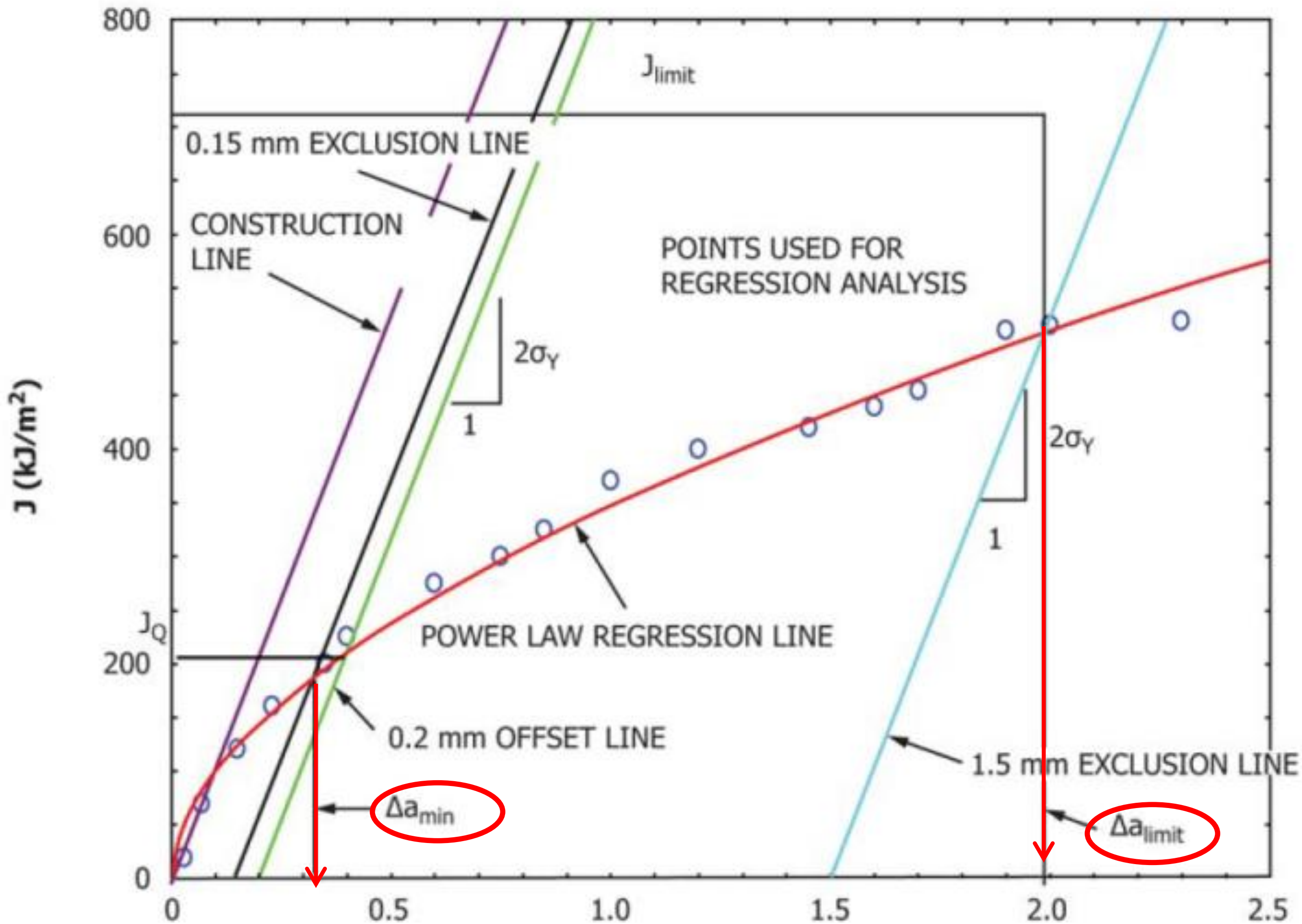
$$K_{(i)} = \frac{P_i}{\sqrt{BB_N W}} f(a/W)$$

$$\eta_{pl\,(i-1)} = 2.0 + 0.522\, b_{(i-1)}/W, \text{ and}$$
$$\gamma_{(i-1)} = 1.0 + 0.76\, b_{(i-1)}/W.$$

$$f(a/W) = \frac{\left[(2 + a/W)\left(0.886 + 4.64(a/W) - 13.32(a/W)^2 + 14.72(a/W)^3 - 5.6(a/W)^4\right)\right]}{(1 - a/W)^{3/2}}$$

$$C_{LL(i)} = \frac{1}{EB_e}\left(\frac{W+a_i}{W-a_i}\right)^2\left[2.1630 + 12.219\left(\frac{a_i}{W}\right) - 20.065\left(\frac{a_i}{W}\right)^2 - 0.9925\left(\frac{a_i}{W}\right)^3 + 20.609\left(\frac{a_i}{W}\right)^4 - 9.9314\left(\frac{a_i}{W}\right)^5\right]$$

Fracture toughness tests



Fracture toughness tests

E1820-17

$$B, bo > 10\left(\frac{J_{IC}}{\sigma_{YS}}\right)$$

E1820-01

$$B, bo > 25\left(\frac{J_{IC}}{\sigma_{YS}}\right)$$

E399-17

$$B, bo > 2.5\left(\frac{K_{IC}}{\sigma_{YS}}\right)^2$$

RPV material σ_{YS} ~ 500 Mpa

Validity

1TCT $B, b_0 = 50$ mm

$K_{IC(max)}$ = 50 MPa√m

$J_{IC(max)}$= 1250 kJ/m² (E1820-17)

500 kJ/m² (E1820-01)

SE(B) $B=10$ mm, $b_0 = 5$ mm

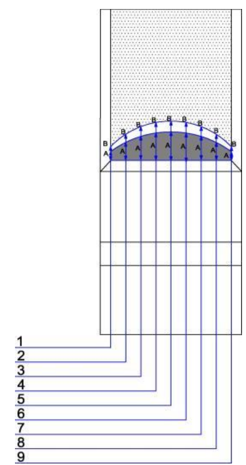
$K_{IC(max)}$ = 22Pa√m

$J_{IC(max)}$= 250 kJ/m² (E1820-17)

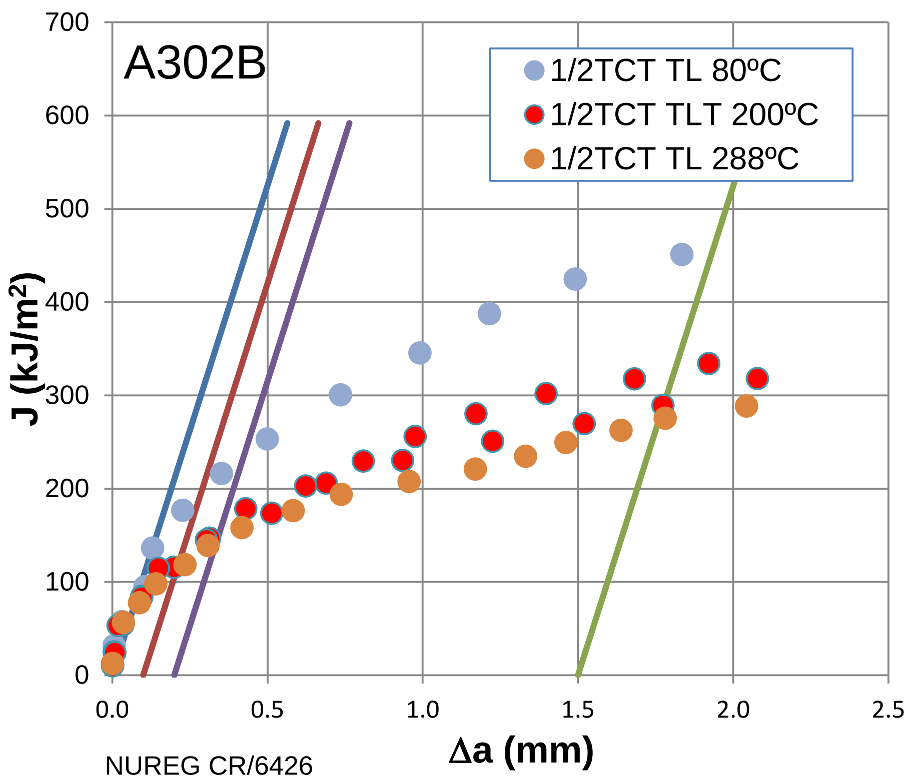
100 kJ/m² (E1820-01)

- Crack length

$$\Delta a_{max} = 0.25\, b_0$$



Fracture toughness tests



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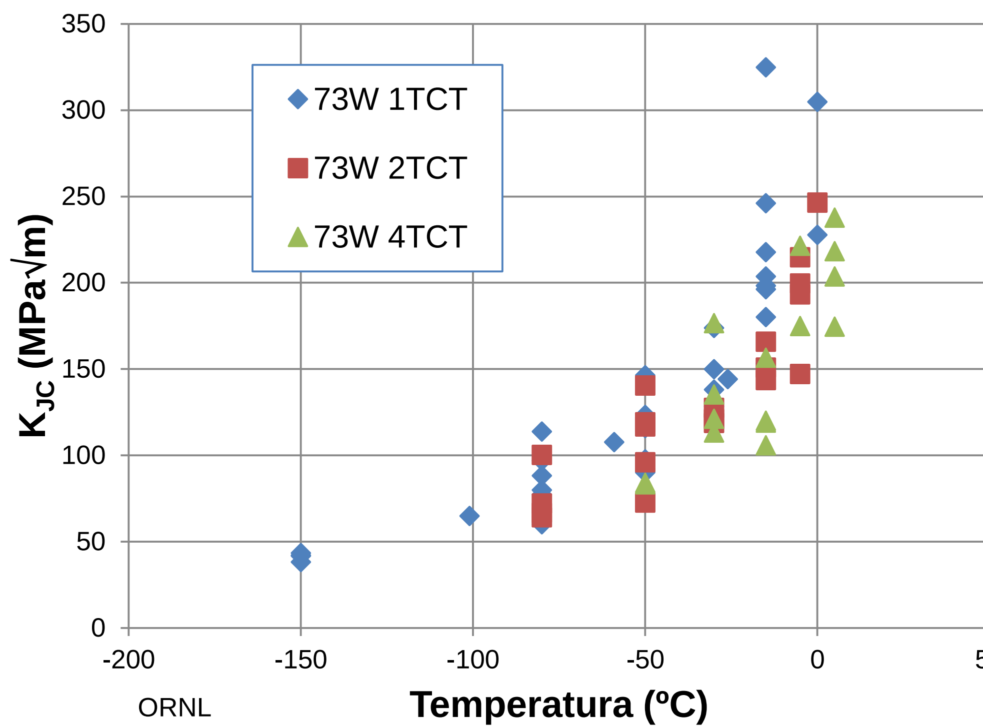
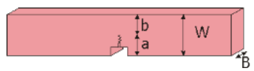


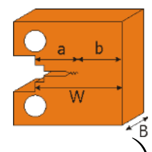
ORNL

Fracture toughness tests

T_0 determination- ASTM E1921 Fracture toughness tests of pre-cracked specimens in the transition range.



$$K_e = \left(\frac{PS}{W^{3/2}B}\right) f\left(a_0/W\right)$$

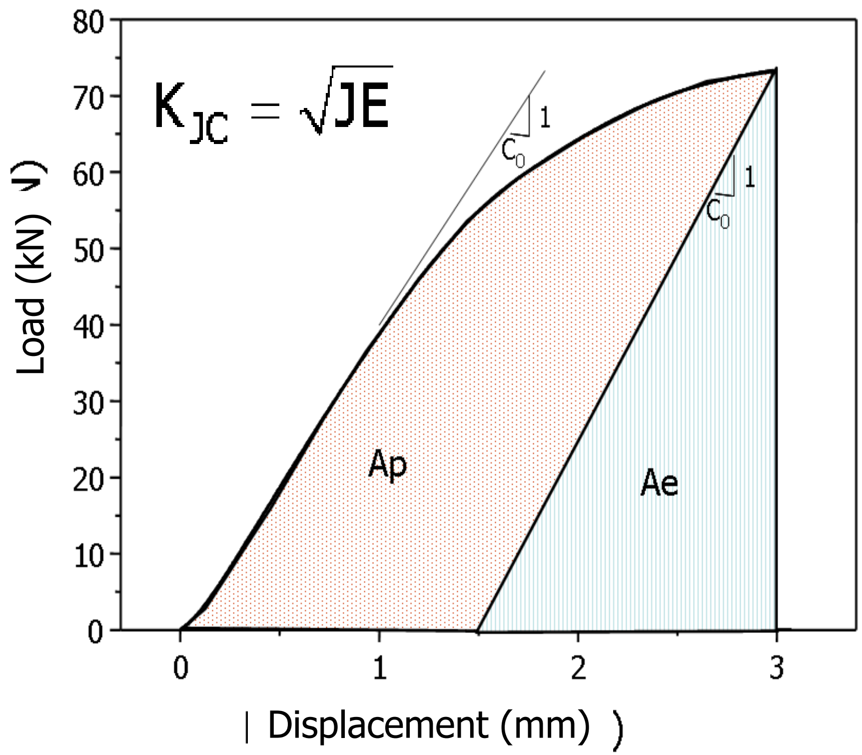


$$K_e = \left(\frac{P}{\sqrt{WBB_N}}\right) f\left(a_0/W\right)$$

$$J_e = \frac{\left(1-\mu^2\right)K_e^2}{E}$$

$$J_P = \frac{\eta A_p}{B_N b_0}$$

$$J_C = J_e + J_p$$



$$K_{JC} = \sqrt{J_C \frac{E}{1-\mu^2}}$$

$$K_{JC(limit)} = \sqrt{\frac{E b_0 \sigma_{YS}}{30\left(1-\mu^2\right)}}$$

$$K_{JC(1T)} = 20 + \left(K_{JC1} - 20\right)\left(\frac{B_1}{25.4}\right)^{1/4}$$

Fracture toughness Master Curve

One temperature testing

$$K_0 = \left[\frac{\sum_{i=1}^{n}\left(K_{JC(i)} - 20\right)^4}{r}\right]^{1/4} + 20$$

$$K_{JC(med)} = (Ln2)^{1/4}(K_0 - 20) + 20$$

$$T_0 = T_{ensayo} - \left(\frac{1}{0.019}\right)\ln\left(\frac{K_{JC(med)} - 30}{70}\right)$$

Multi-temperature testing

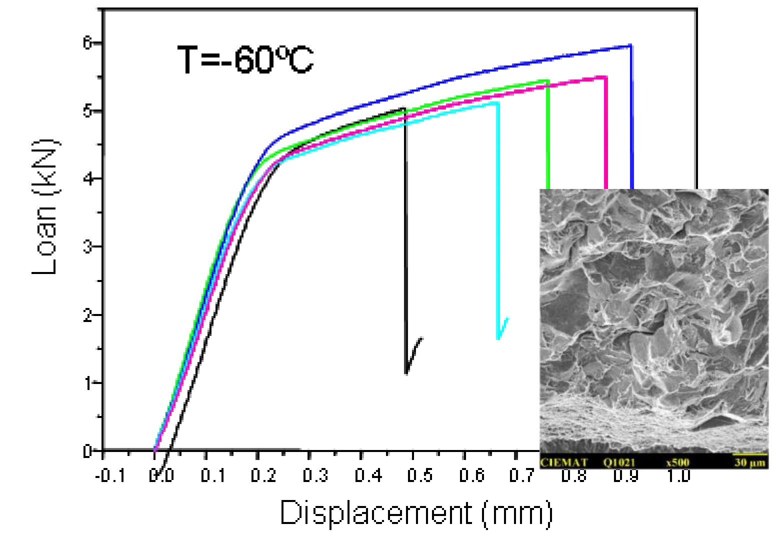
$$\sum_{i=1}^{N}\delta_i \frac{\exp(0.019(T_i - T_0))}{11 + 77\exp(0.019(T_i - T_0))} - \sum_{i=1}^{N}\frac{\left(K_{JC(i)} - 20\right)^4 \exp(0.019(T_i - T_0))}{\left[11 + 77\exp(0.019(T_i - T_0))\right]^5} = 0$$

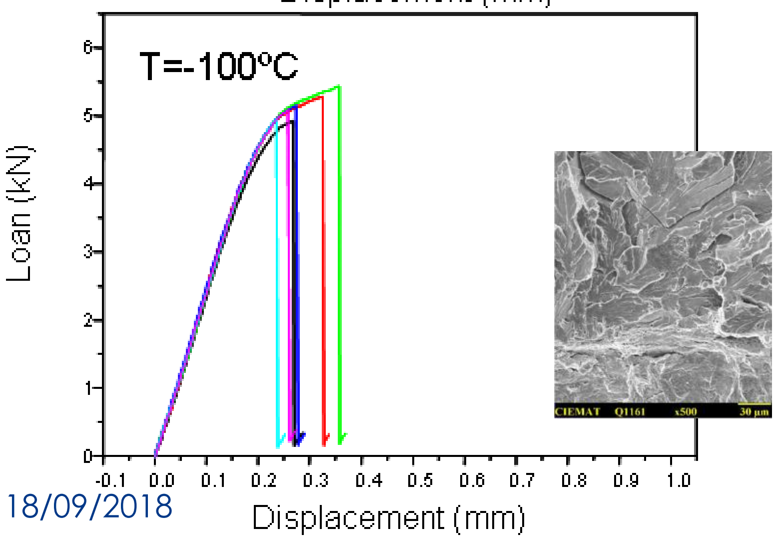
δ = 1 valid y =0 invalid

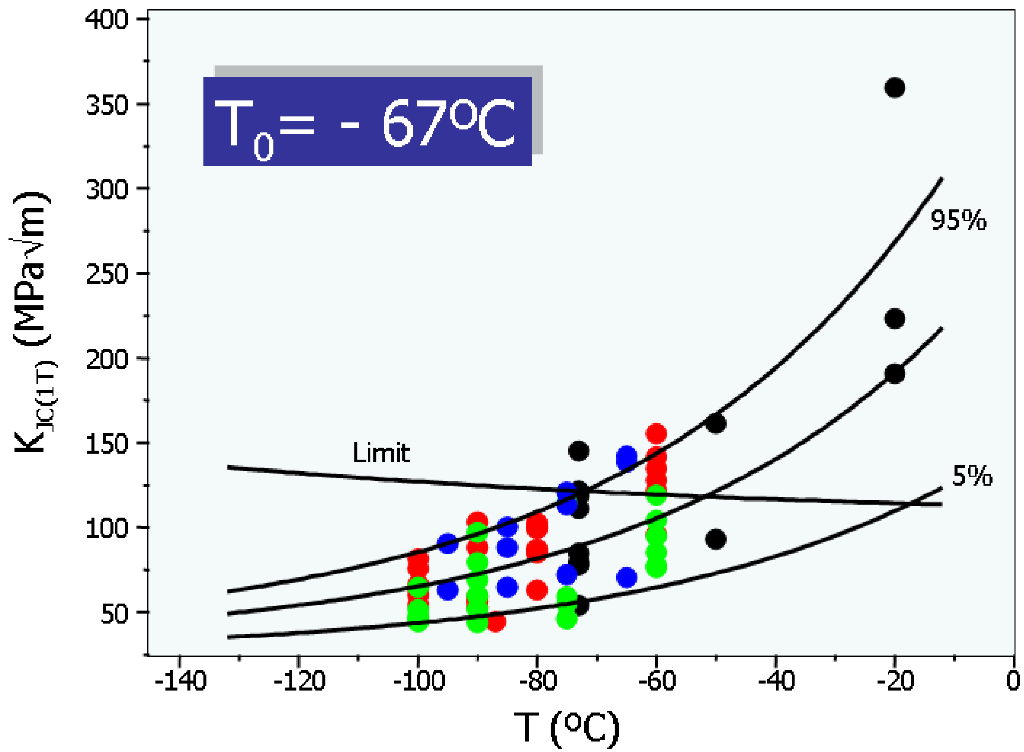
Fracture toughness Master Curve

- Determination of T_0 for JRQ material with pre-cracked charpy specimens (CIEMAT data)

$$K_{JC(med)} = 30+70\ \exp(0.019(T-T_0))$$







Sumary

- The mechanical property needed to assess the integrity of the RPV is the fracture toughness
- Fracture toughness valid data followings “old” standard imply the tests of large specimens
  - Impractical for surveillance programs
  - Fracture toughness is obtained via charpy tests
- Tensile tests are performed to have reference data but are not required by code
- New approaches allows to obtain valid fracture toughness data by testing small specimens

You can have the best equipment but always you need the best technicians