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Small Specimen Test Technologies for measuring mechanical properties of reactor pressure vessel steels

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Small Specimen Test Technologies (SSTT) for measuring mechanical properties of RPV steels

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Joint ICTP/IAEA Workshop

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Outline

- Introduction – General concepts
- Miniature tensile specimens
- Instrumented indentation tests
- Reconstitution of Charpy specimens
- Impact tests on sub-size Charpy specimens
- Fracture toughness testing on sub-size specimens
    - transition region (Master Curve)
    - upper shelf regime (miniature C(T) specimens)
- Standardization of SSTT
- Small Punch Testing

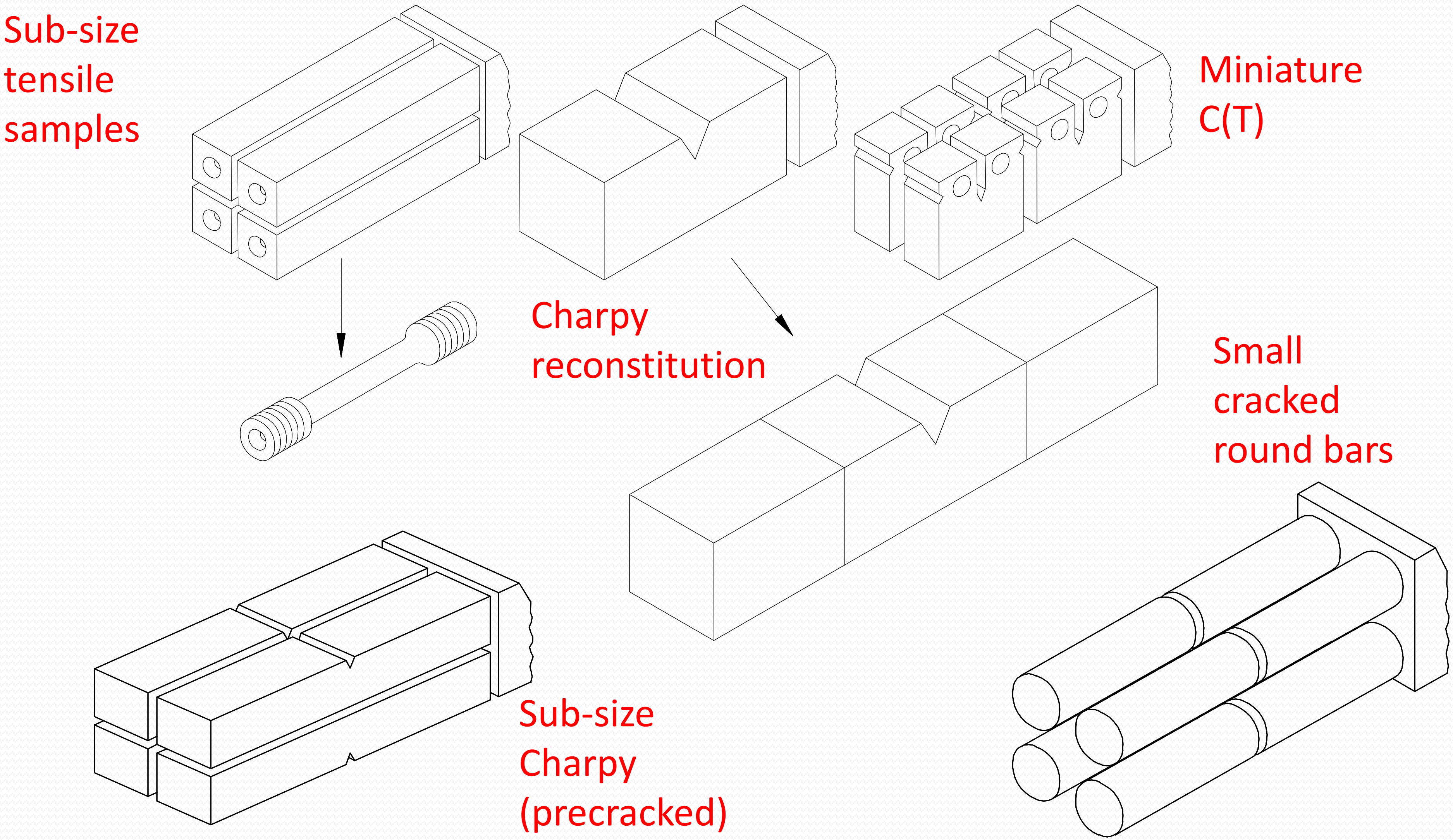
Introduction
Why small specimen testing?

- Evaluating mechanical properties is needed for integrity assessments and life predictions
- Materials are subject to degradation due to high temperatures, aggressive environment and/or neutron irradiation
- Evaluation of mechanical properties is by definition a destructive technique
- If specimen size is small enough, it can become “semi-destructive” (easy repair or even no repair is needed)

Introduction
Development of SSTT

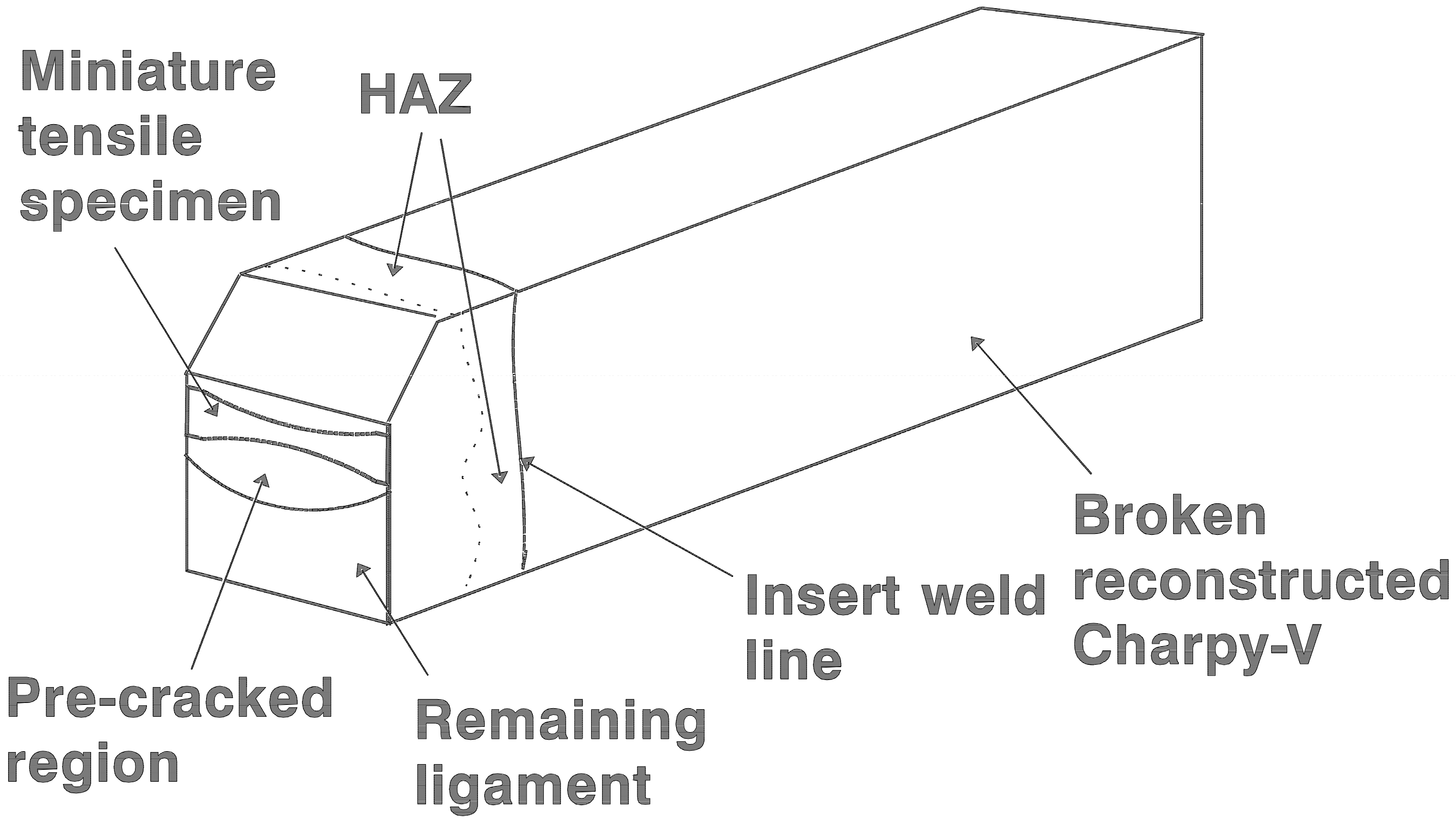
- Small Specimen Test Techniques have been developed, qualified and applied for the mechanical characterization of reactor pressure vessel steels (unirradiated and irradiated)
- Mechanical properties addressed:
  - tensile strength (miniature specimens, instrumented indentation)
  - impact toughness (reconstitution of Charpy specimens, KLST sub-size specimens)
  - fracture toughness (transition and upper shelf regimes, various sub-size specimen geometries)

Several options when only broken Charpy specimens are available

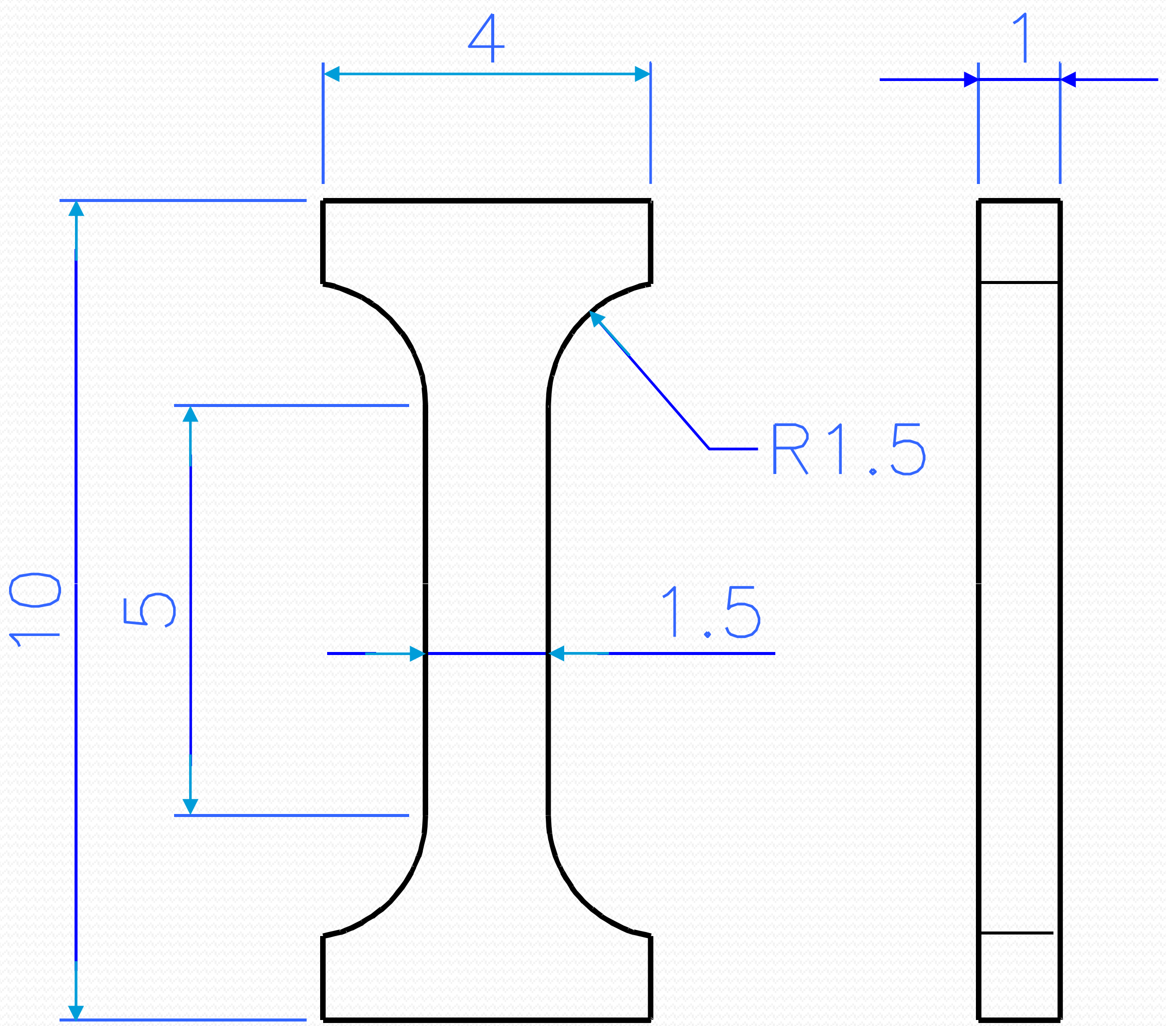


Miniature flat tensile specimens (1)

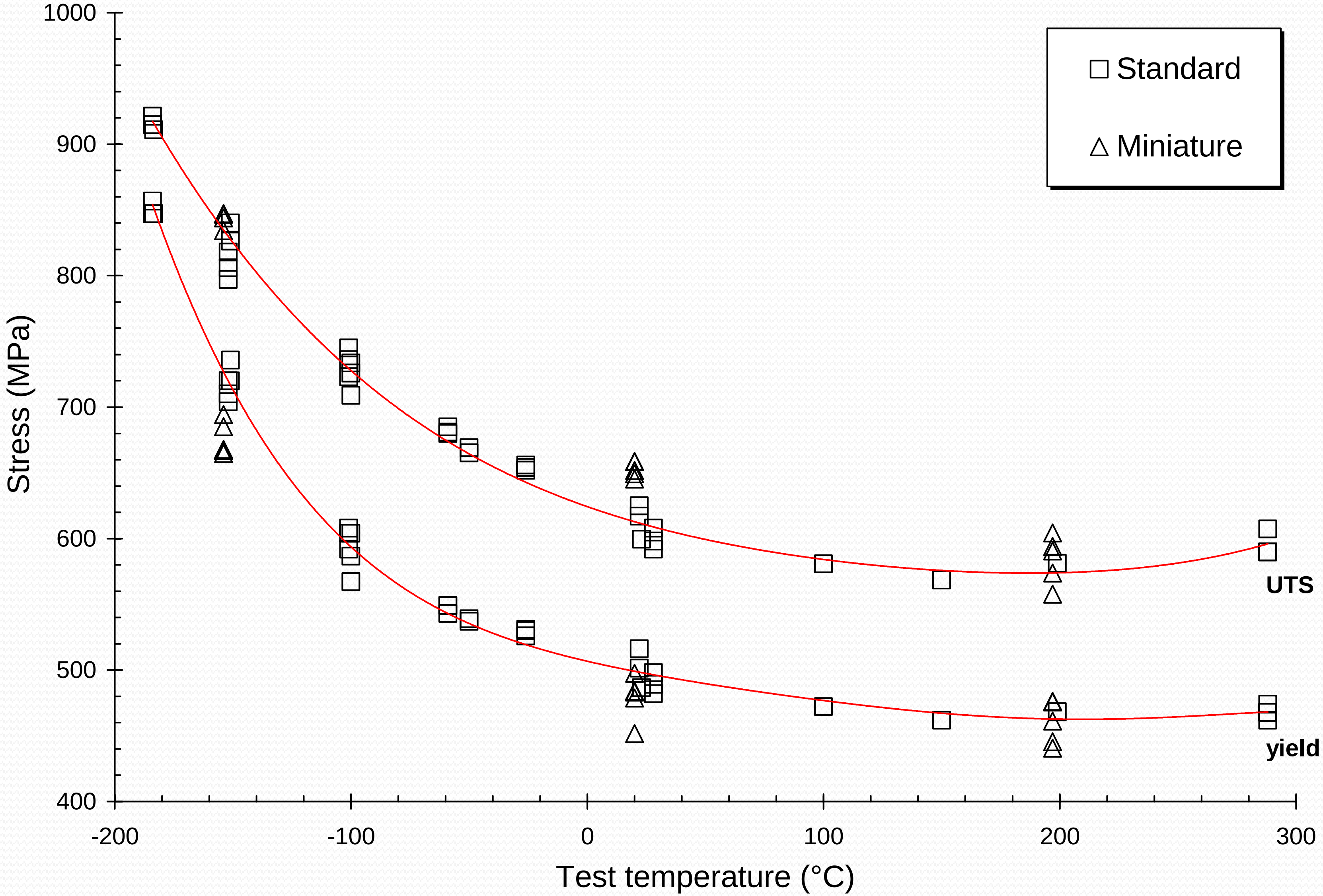
- The specific problem



Miniature flat tensile specimens (2)



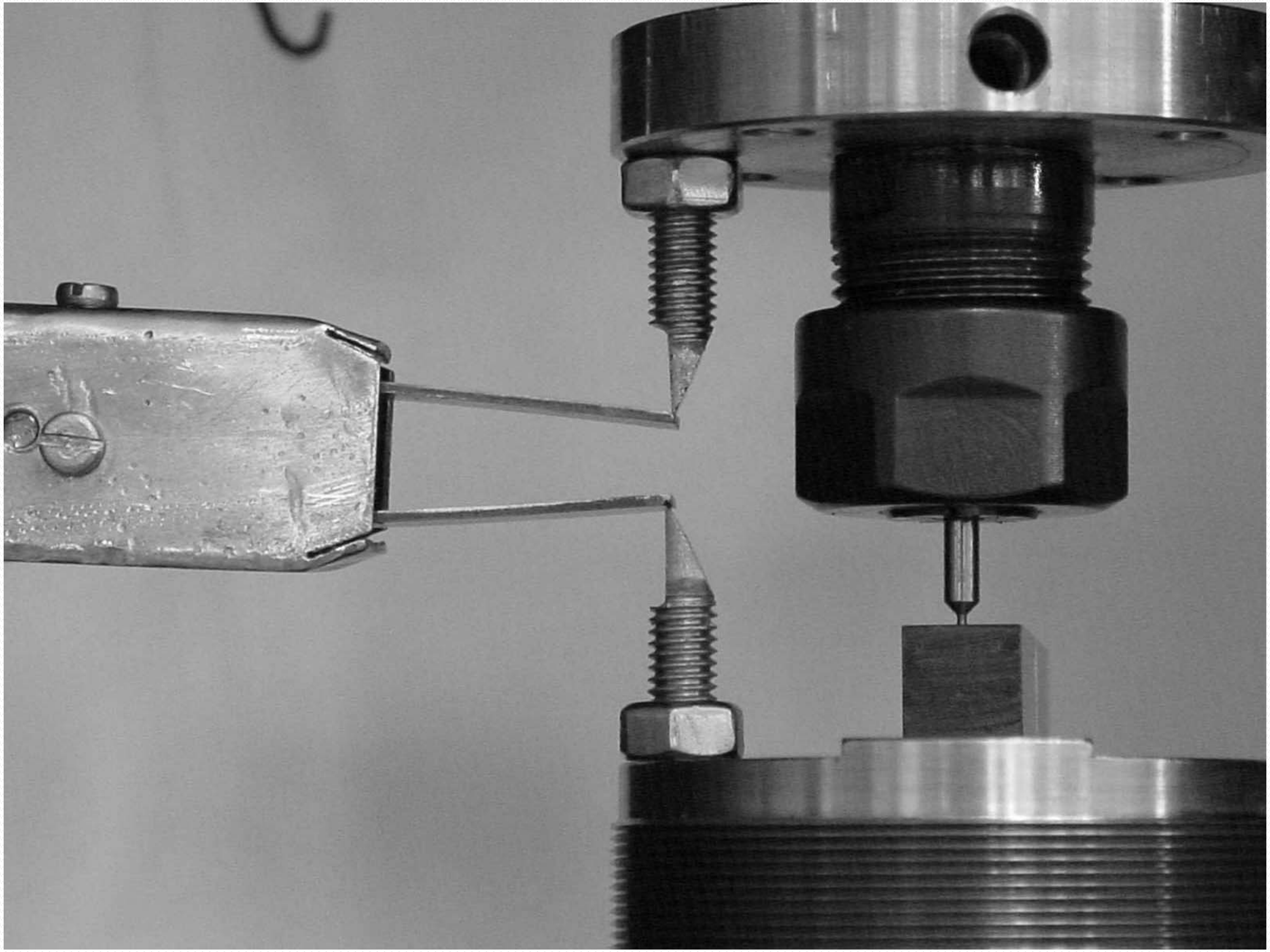
Miniature flat tensile specimens (3)



Miniature flat tensile specimens (4)
- Basic "facts" -

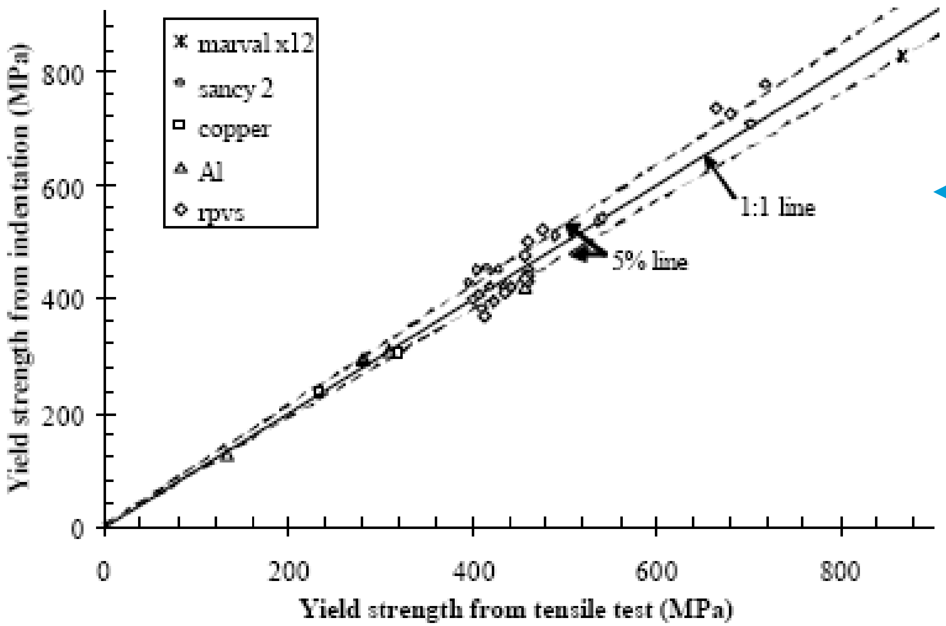
- Results from miniature specimens are in good agreement with standard sample data, within a few %
- The most critical aspects are:
  - Misalignments and extraneous displacements during gripping and mounting operations have to be carefully avoided (a special "specimen holder" was developed)
  - The significant influence of the test setup compliance has to be accounted for when determining the elastic portion of the test record (only the last part should be considered)
  - Since data scatter tends to increase for decreasing specimen size, a minimum number of 3 tests per temperature is recommended (preferably 5)

Instrumented indentation tests (1)



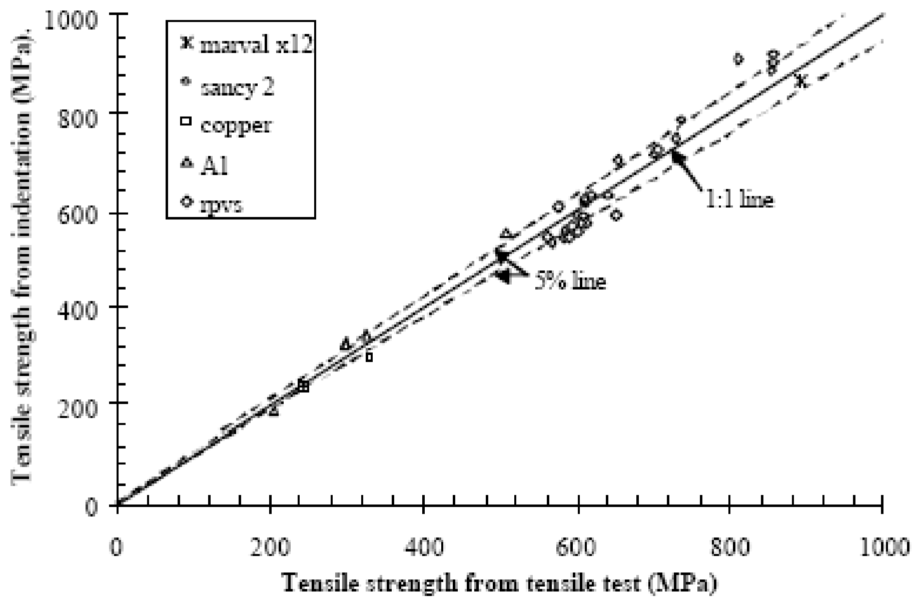
Instrumented indentation tests (2)

- Favourable comparison with tensile test results



Yield strength estimation

Tensile strength estimation



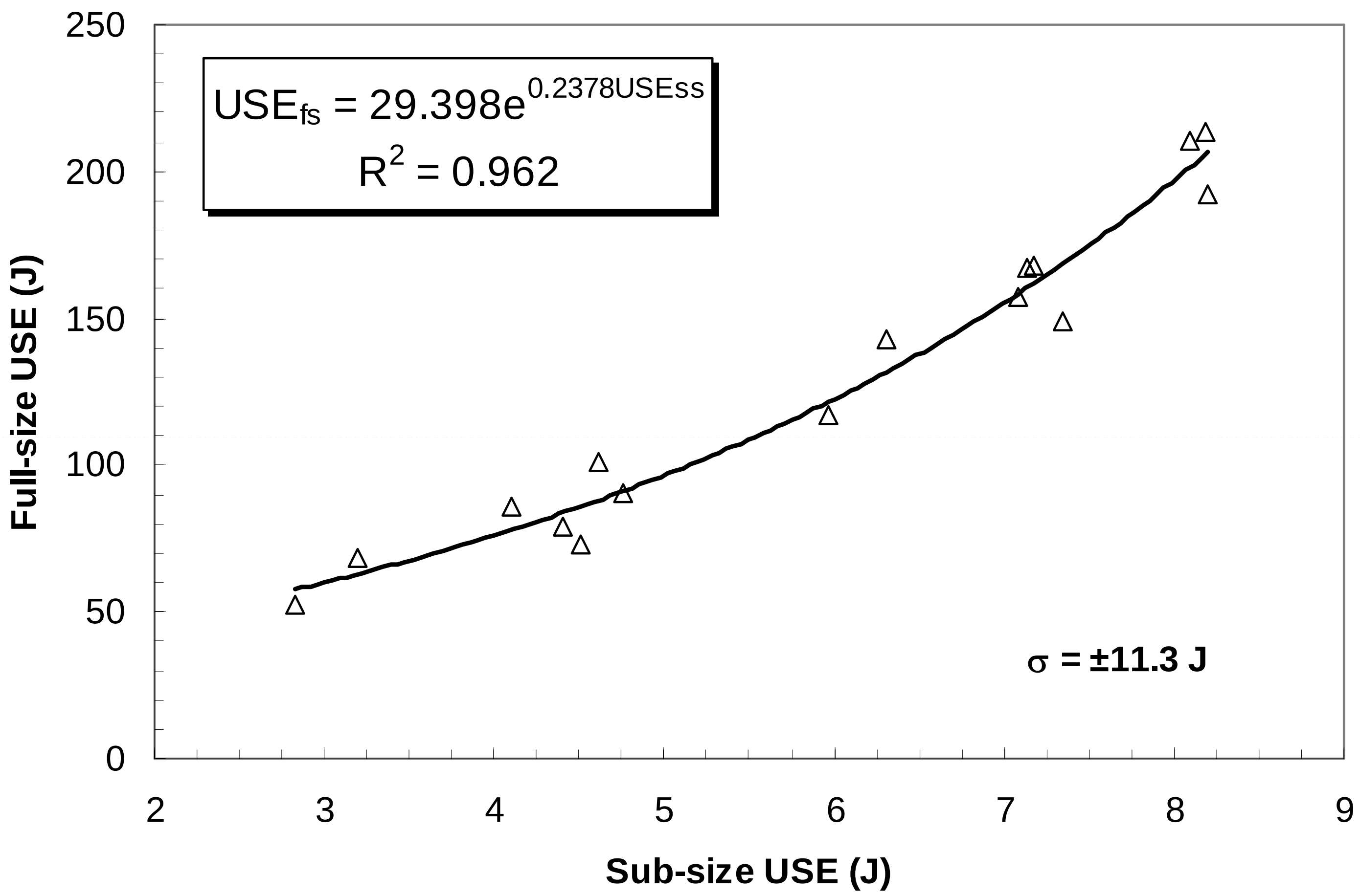
Reconstitution of Charpy specimens (1)

Reconstitution of Charpy specimens (2)
- Basic "facts" -

- If insert length is greater than 15 mm, no influence of reconstitution can be appreciated
- For inserts of 10-12 mm length, a decrease in Upper Shelf Energy (Charpy) and upper shelf toughness (PCCv) can be observed
- No influence of reconstitution in case of toughness tests in the transition regime (Master Curve analysis)
- The shortest inserts (10 mm) allow changing the sample orientation (e.g. from LT to TL)

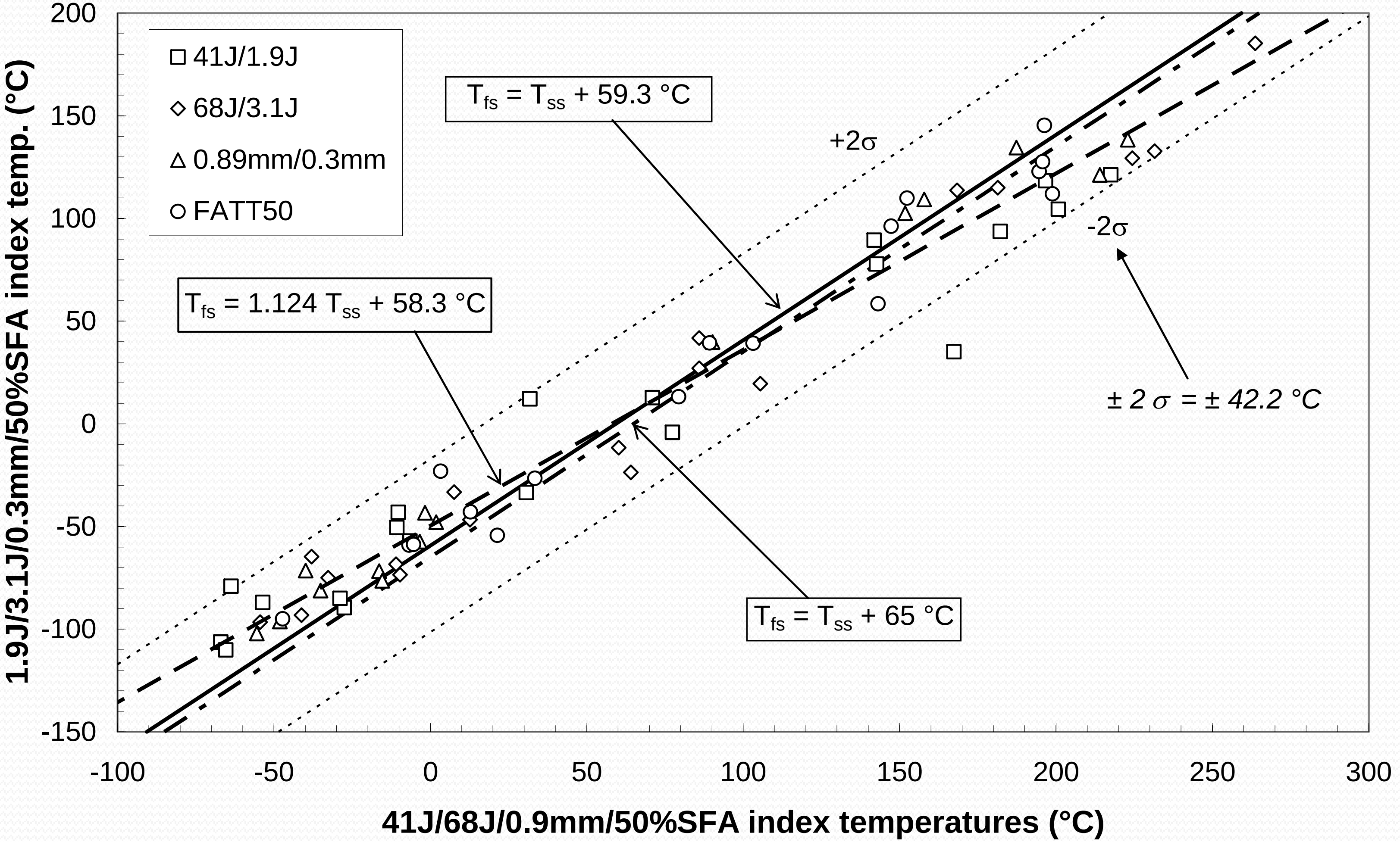
Impact tests on sub-size specimens KLST type (1)

- Estimation of USE values for full-size specimens



Impact tests on sub-size specimens KLST type (2)

- Estimation of transition temperatures

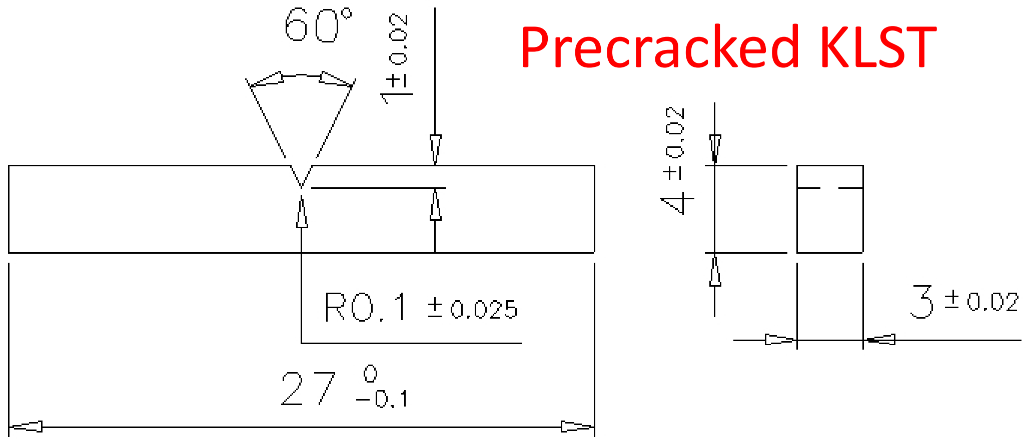


Fracture toughness testing
Various geometries investigated (1)

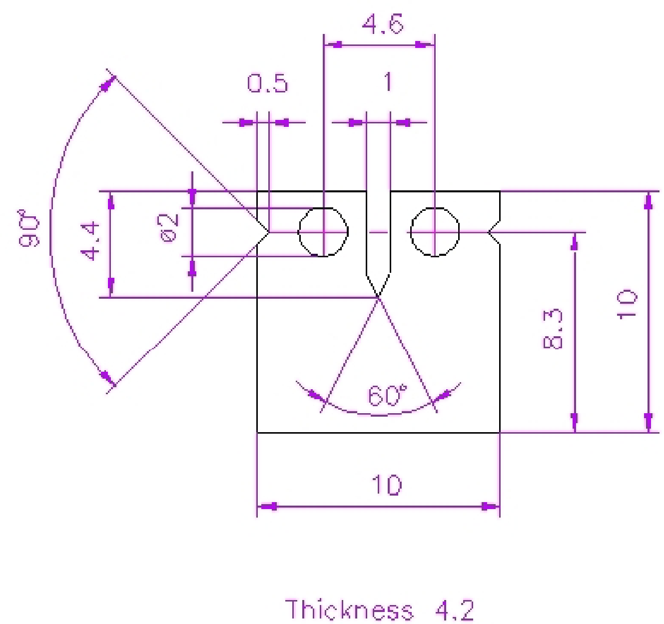
- Ductile-to-brittle transition regime (Master Curve analysis)
  - precracked sub-size Charpy specimens, P-KLST
  - sub-size cracked round bars, CRB
  - miniature Compact Tension specimens, MC(T)
- Fully ductile regime (J_{Ic} values, crack resistance curves)
  - precracked sub-size Charpy specimens, P-KLST
  - miniature Compact Tension specimens, MC(T)

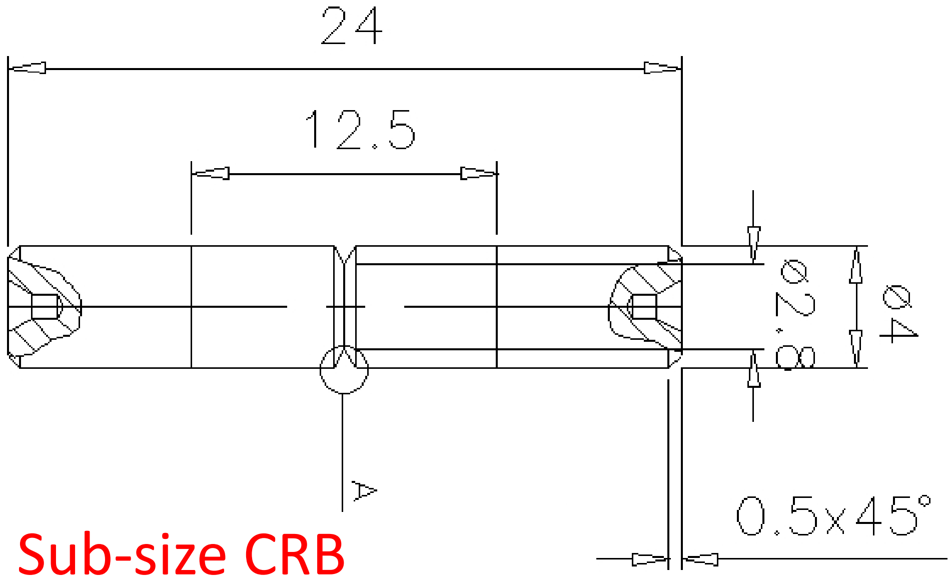
Fracture toughness testing
Various geometries investigated (2)

Precracked KLST



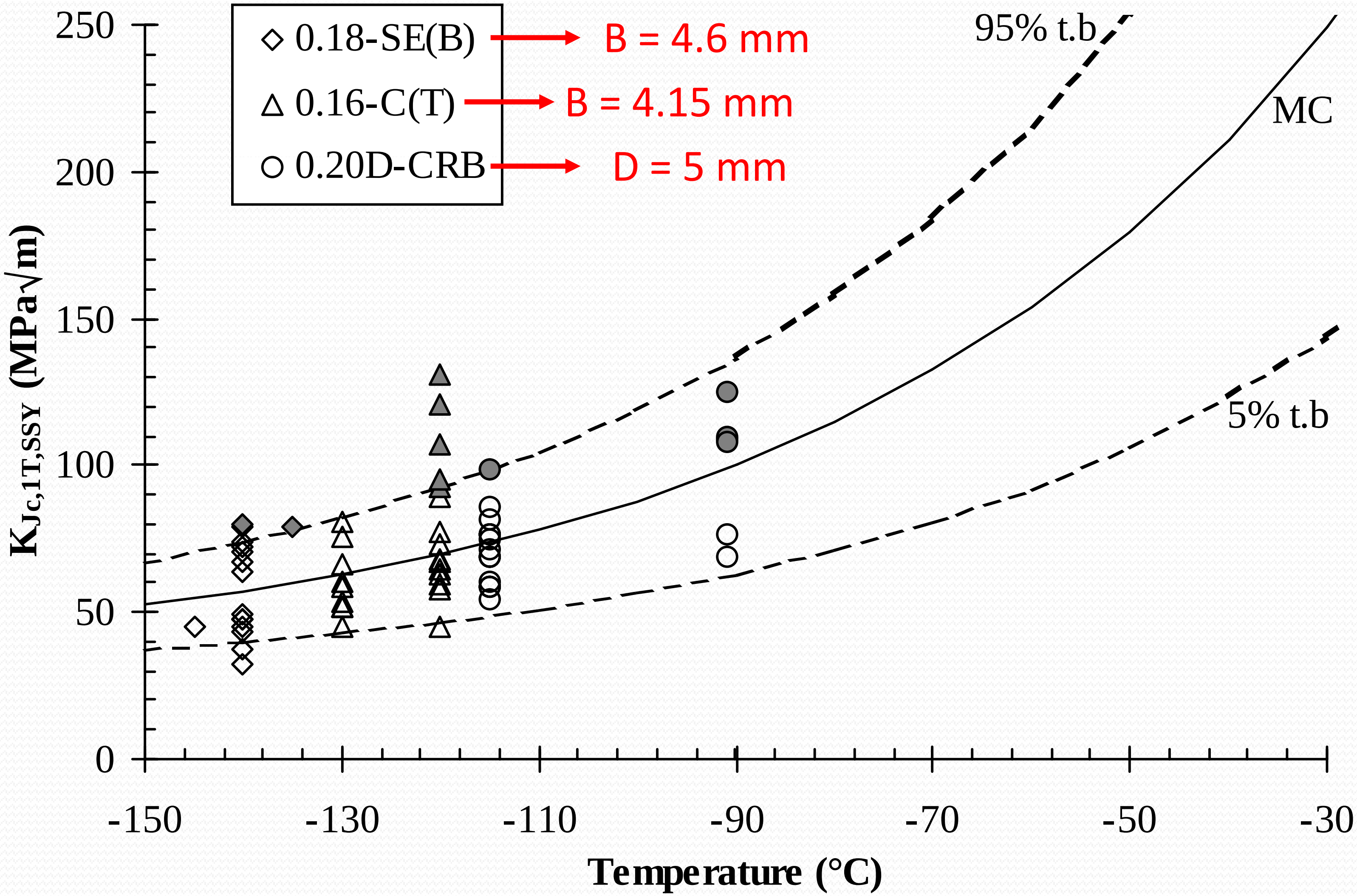
Mini C(T)





Sub-size CRB

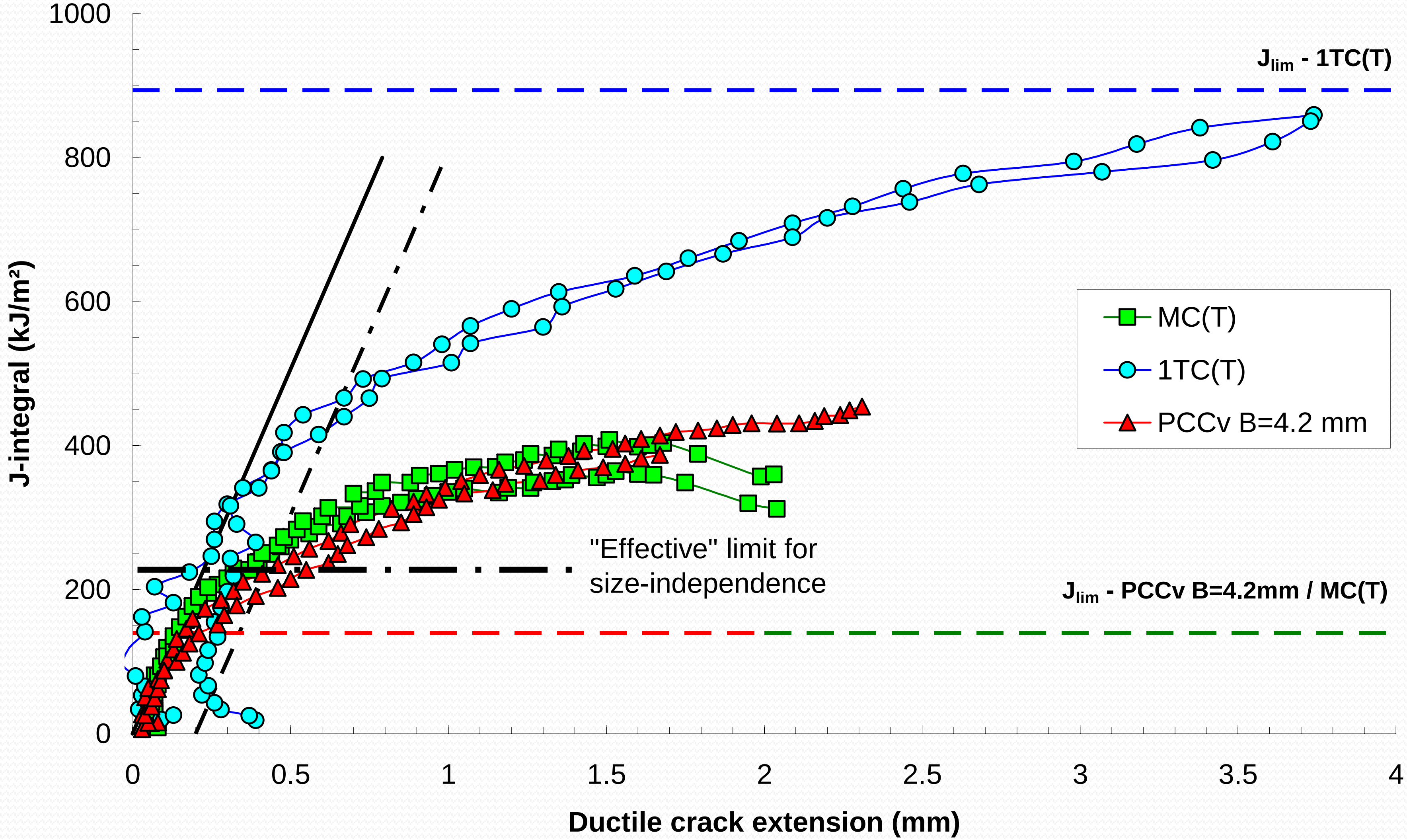
Fracture toughness testing (transition)
Master Curve analysis (1)



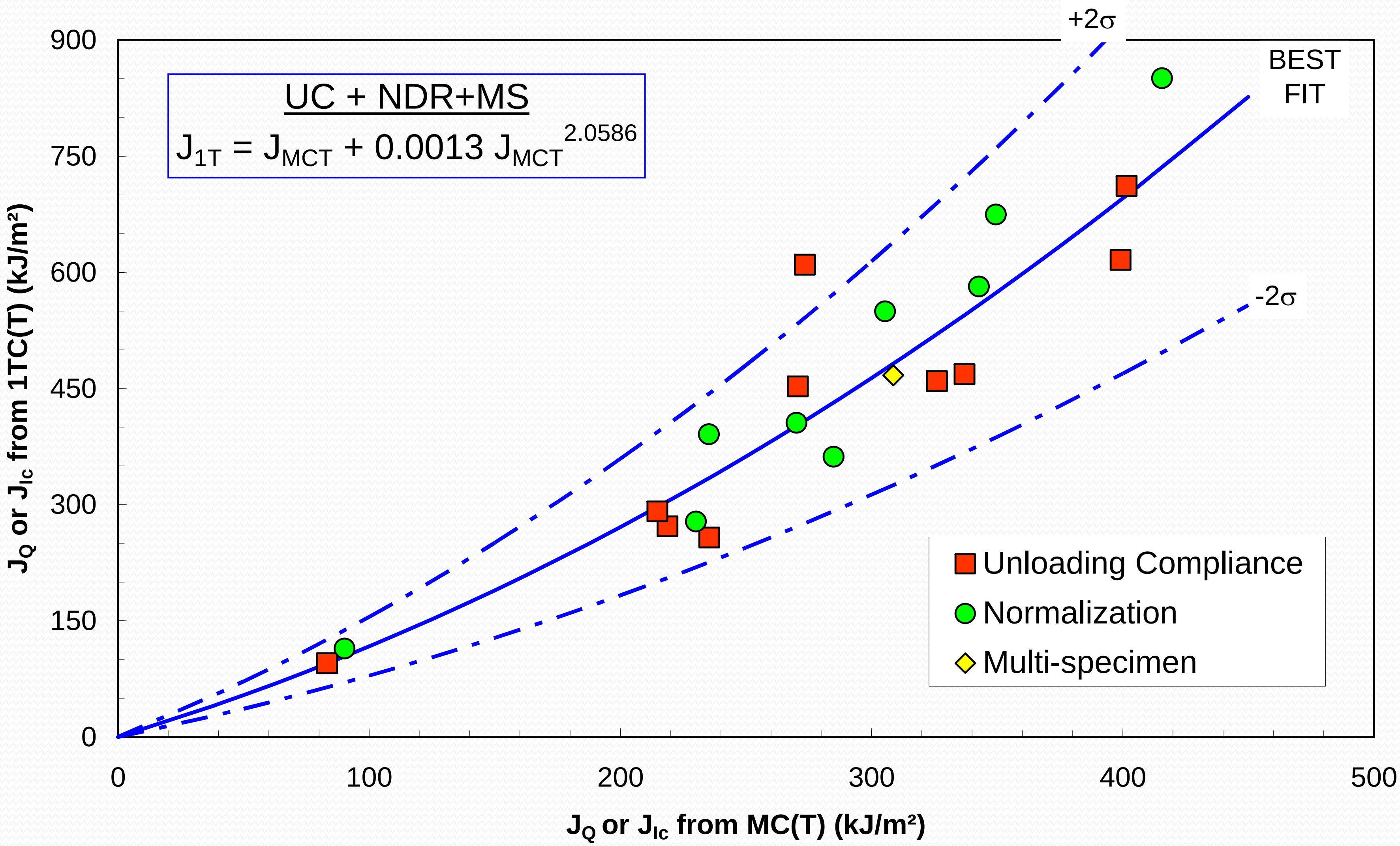
Fracture toughness testing (transition) Master Curve analysis (2) – Basic "facts"

- Irrespective of the specimen geometry chosen, reference temperatures measured from small specimens are in good agreement with those measured from larger samples (within statistical uncertainties)
- The main issue is the limited test temperature validity domain, determined by:
  - the lower limit of **applicability for** the Master Curve method (T_o – 50 °C)
  - the specimen measuring capacity (inversely proportional to the specimen ligament length)
- From this point of view, MC(T) are preferable to P-KLST (longer ligament ⇨ larger validity domain)
- The sub-size CRB results can be corrected for loss-of-constraint using a factor derived from FEM analyses

Fracture toughness testing
Upper Shelf (fully ductile) regime (1)



Fracture toughness testing
Upper Shelf (fully ductile) regime (2)



Fracture toughness testing
Upper shelf regime (3) – Basic "facts"

- Miniature specimens (of bend or C(T)-type) clearly underestimate the ductile fracture toughness measured from standard 1TC(T) samples
- An empirical correlation can be established which allows estimating the actual J_{Ic} with an uncertainty of 34% at the 95% confidence level
- The role of work hardening in lowering the tearing resistance of small samples has been confirmed
- The use of alternative fracture toughness parameters (CTOD, CTOA, Enrst's modified J-integral) seems to improve the agreement

Conclusions
Most critical aspects related to SSTT

- Significance of experimental data
- Transferability of measurements obtained from small specimens to actual components under investigation
- Analytical techniques, which can be:
  - equivalent to the "conventional" ones (e.g. Master Curve analysis)
  - specific to small specimen geometries, i.e. based on correlation approaches (e.g. KLST versus full-size Charpy specimens)
- Accuracy of test methods, accounting for the characteristics of the available instrumentation and the magnitude of the signals involved (force, displacement etc.)

Standardization of SSTT
Present Status & Perspectives

- Microstructural considerations dictate that only specimens with cross sectional dimensions sufficient to ensure a representative volume of material is tested should be used
- In order to satisfy this requirement, the size scale and mean separation distance of inhomogeneities that exist in the material must be known
- The cross sectional dimension of the miniature/subsize specimens should be at least 3-5 times greater than the largest inhomogeneity
- Therefore, the recommended SS size depends on the microstructure of the investigated material

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Worldwide Standardization Forums for mechanical tests

- ISO – International Standards Organisation
  - TC164 - Mechanical Tests
    - SC1 (*Uniaxial Tests*)
    - SC4/P (*Pendulum*)
    - SC4/F (*Fracture)*
    - SC5 (*Fatigue*)
  - Meets once a year (September/October)
- ASTM (American Society for Testing and Materials)
  - Technical Committee E08 (*Fracture and Fatigue*)
  - Technical Committee E28 (*Mechanical Tests*)
  - Meet twice a year (May and November)

Tensile Testing

- Both ASTM E8/E8M and ISO 6892:1998 do not explicitly limit the minimum size of the specimen
- Both include “subsize” specimens (an example: round specimen with 2.5 mm diameter)
- Any alternative miniature/subsize tensile specimen has to be validated and qualified against standard specimens
- If microstructural considerations do not come into play, SS should deliver equivalent results to larger samples

$\Rightarrow$ Standardization is not needed, but robust qualification (unirradiated condition) is required

Charpy Impact Testing

- Subsize Charpy specimens (KLST-type, 3 × 4 × 27 mm) are commonly used in the Fusion community for DBTT measurement and materials' qualification
- Neither ASTM E 23 nor ISO 148 include subsize specimens as such
- However:
  - ASTM E 2248 on miniaturised Charpy specimens has been issued in April 2009 (geometries: 5 × 5 × 27.5 mm and KLST)
  - ISO 14556:2000 (instrumented tests) includes KLST specimens (Annex D)

⇒ Standardization is already happening; correlations with standard specimens should be validated

Fracture Toughness Testing (linear elastic regime)

- In order to obtain valid fracture toughness measurements in case of fully brittle behaviour, large specimens are required
- Small specimens are generally not applicable to fracture toughness testing in the linear elastic regime
- Furthermore, lower shelf conditions have to be avoided throughout the operation of any structure or component

⇒ This fracture regime is not relevant for RPV integrity assessments

Fracture Toughness Testing (ductile-to-brittle transition)

- Fracture toughness properties in the ductile-to-brittle transition region are of primary importance for assessing the integrity of a structure or component
- ASTM E 1921 (Master Curve) does not restrict the minimum size of a specimen
- However, validity requirements related to specimen size have to be fulfilled for the results to be valid
- The most commonly SS used are the precracked KLST and the miniature C(T) (thickness 4-5 mm)
- Mini C(T) specimens have a larger validity domain than KLST, and should be given higher priority

⇒ Standardization is not needed; existing standards (basically E 1921) can and should be used

Fracture Toughness Testing (fully plastic regime)

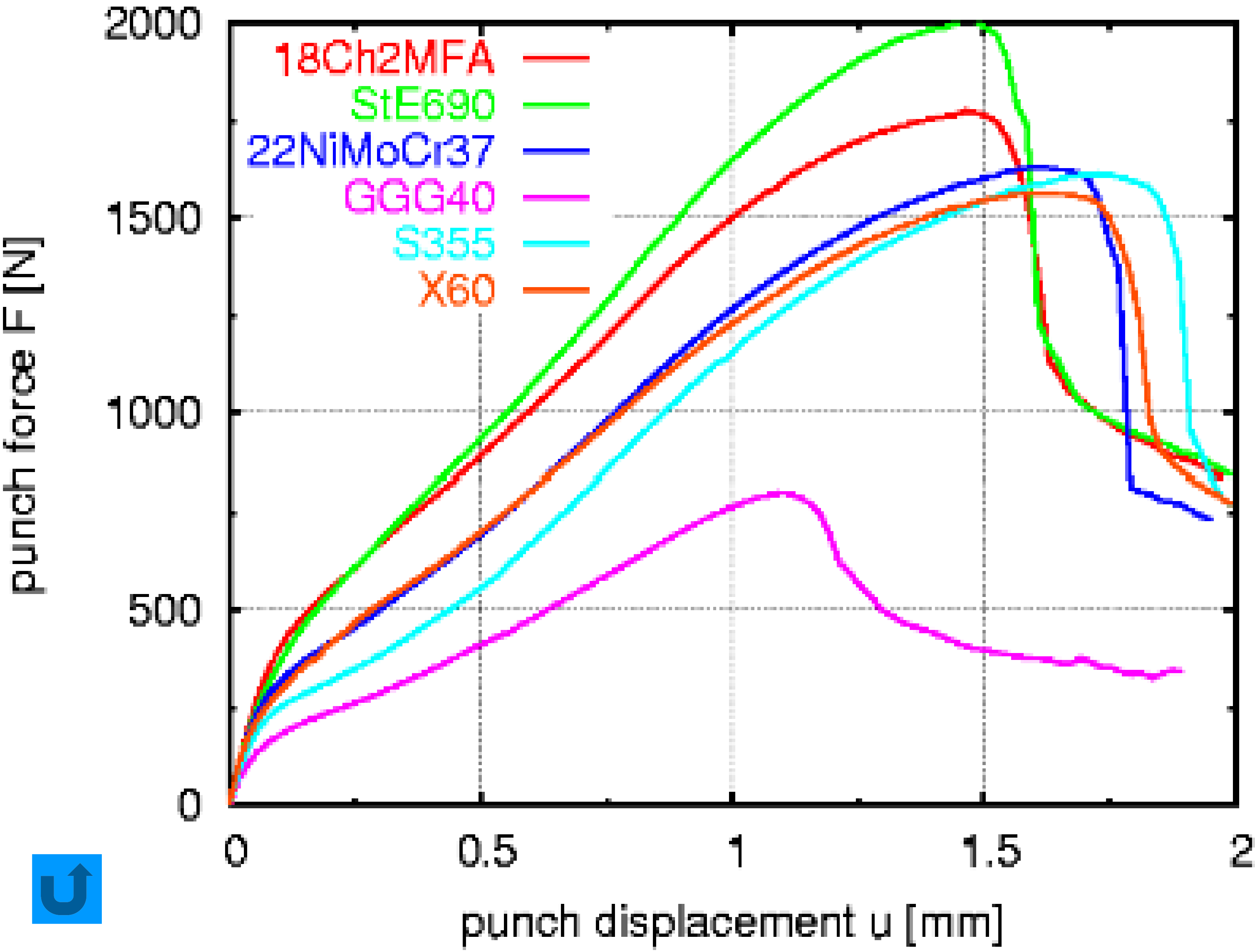
- Upper shelf fracture toughness properties consist in the initiation value and the crack resistance curve (R-curve)
- ASTM E 1820 and ISO 12135:2002 do not restrict the minimum size of the specimen
- However, validity requirements related to specimen size are imposed
- SS appear to underestimate the actual fracture toughness of the materials
- Correlations with larger specimens should be established and validated

⇒Standardization is not necessary, but correlations with larger specimens should be qualified

Small Punch Testing
(a really miniature specimen!)

- It's the smallest specimen ever (typically, TEM disc with 3 mm diameter and 0.25 thickness)
- Can be used for estimating:
  - tensile properties (using empirical correlations or FEM analyses)
  - DBTT values (using empirical correlations)
  - fracture toughness (using FEM analyses; reliability is doubtful)
  - creep properties
- Correlations are strongly material-dependent and need to be carefully validated
- Standards do not exist nor are in preparation (to my knowledge)

⇒ Standardization can be pursued, preferably in the ISO framework (Americans are not too keen on this)



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StE690
22NiMoCr37
GGG40
S355
X60
punch force F [N]
punch displacement u [mm]
0
500
1000
1500
2000
0
0.5
1
1.5
2