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Tensile Mechanical Properties and Testing: Fundamentals, Systemic Influences, and Strain Hardening Analysis

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Senior Researcher CNR-ICMATE

ICMATE
Istituto di Chimica della Materia Condensata e di Tecnologie per l'Energia

The National Research Council of Italy (CNR)

The National Research Council of Italy is the largest public institution in Italy. Founded in 1923, it employs approximately 8500 people, 5500 of which work in research and research support (52% men – 48% women).



It is organized in seven Departments:

- *Physics Sciences and Materials Technologies*
- *Chemical Sciences and Materials Technologies*
- *Biological Science*
- *Engineering – ICT*
- *Human and Social Sciences and Cultural Heritage*
- *Bio-Agri-food Sciences*
- *Earth System Sciences and Environmental Technologies*

The National Research Council of Italy (CNR)

The **Institute of Condensed Matter Chemistry and Technologies for Energy** (**ICMATE**) is one of the 88 institutes under the umbrella of CNR.

CNR-ICMATE is part of the Department of Chemical Sciences and Materials Technologies (DSCTM), with about 74 researchers/technologists and 21 technicians/administrative staff.

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Unit of Milan

Electrochemistry and Nano-materials

Optical Diagnostics in Reactive Systems

Characterization and properties of innovative metallic materials for industrial applications

CNR-ICMATE



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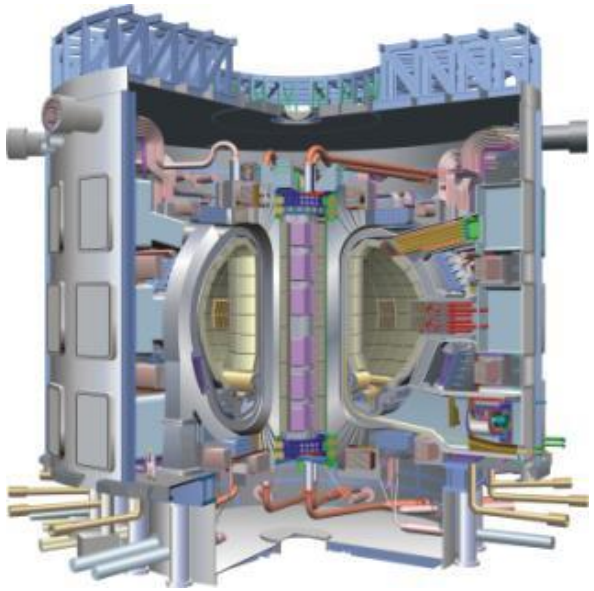
Electrochemistry and Nano-materials

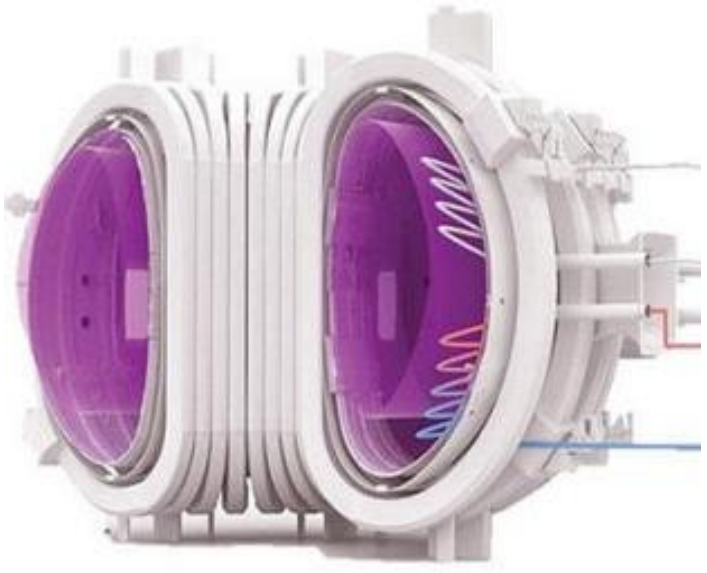
Optical Diagnostics in Reactive Systems

Characterization and properties of innovative metallic materials for industrial applications

ICMATE Activities

EUROfusion is the consortium cohordinating the European efforts towards nuclear fusion. It supports major projects like **ITER** and **DEMO**, which should be the first industrial reactor to provide electricity.





EUROfusion

Austrian Academy of Sciences AUSTRIA
Ecole Royale Militaire Laboratory for Plasma Physics BELGIUM
Ru er Bošković Institute CROATIA
Institute of Plasma Physics Academy of Sciences of the Czech Republic CZECH REPUBLIC
Technical University of Denmark DENMARK
University of Tartu ESTONIA
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Max-Planck-Institut für Plasmaphysik GERMANY
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Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile ITALY
LATVIA
Institute of Plasma Physics and Laser Microfusion POLAND
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Institute for Atomic Physics ROMANIA
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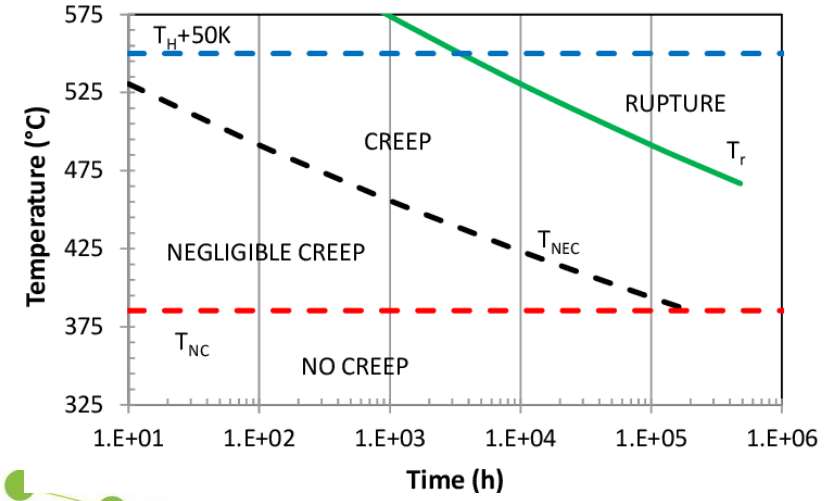
ICMATE is involved in two Work Packages, WPMAT-EDDI (Materials Projects – Engineering Data and Design Integration) and WPPFC (Plasma Facing Components).

ICMATE Istituto di Chimica della Materia Condensata e di Tecnologie per l'Energia

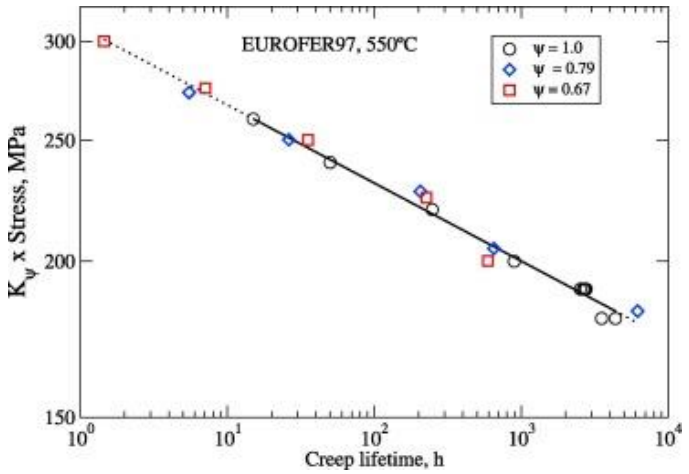
ICMATE Activities

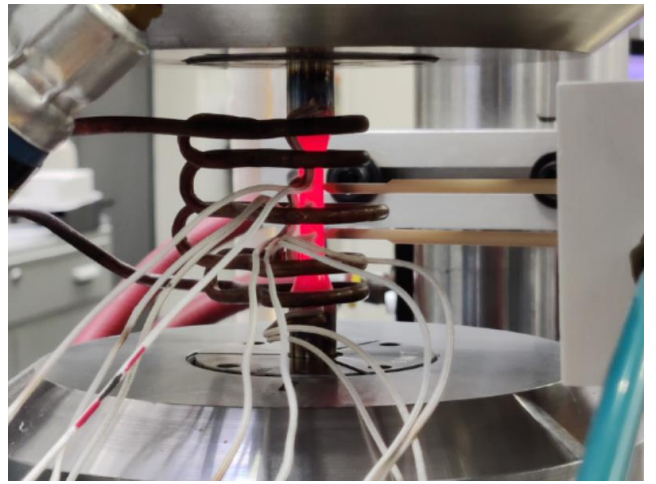
RAFM (reduced activation ferritic martensitic) steels, such as **Eurofer 97**, are candidate materials for nuclear fusion reactors since their chemical composition (W instead of Mo, Ta and V instead of Nb, low Ni content) makes them less susceptible to damage from neutron irradiation with respect to common FM steels. **ICMATE** works on the mechanical characterization under **creep** and **creep/fatigue** conditions of these steels.

Creep testing to find the negligible creep conditions for the steel Eurofer 97



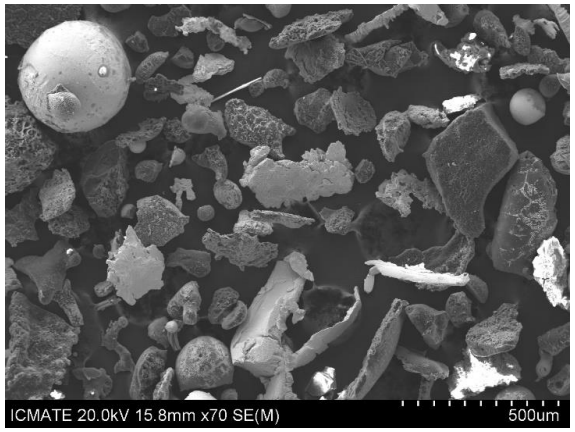
Creep testing of pre-fatigued samples to provide rules for design under complex load conditions



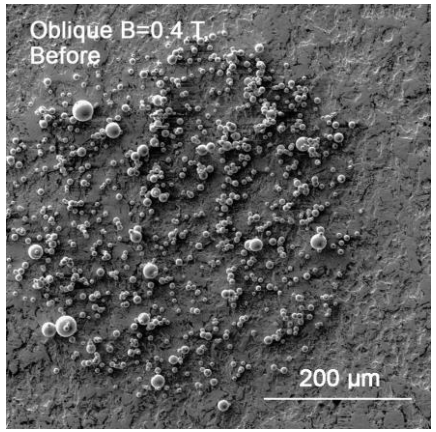


ICMATE Activities

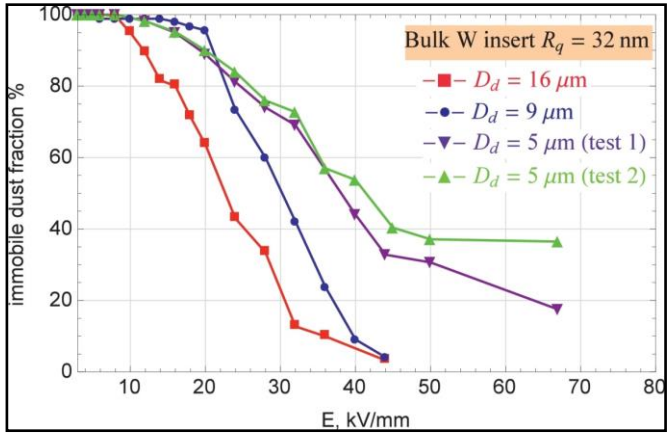
The presence of metallic dust within fusion reactors can cause safety and efficiency issues.
ICMATE's efforts have focused on the experimental characterization of four key pillars



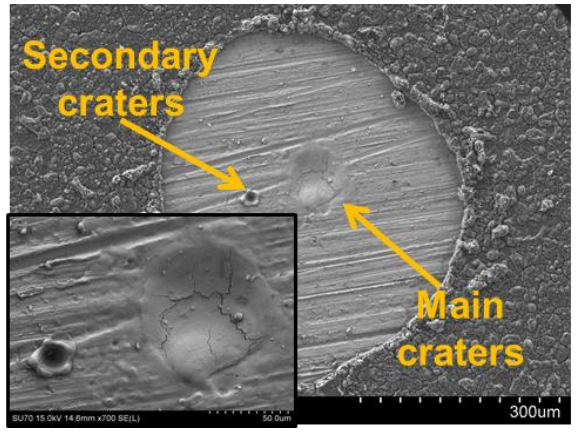
Actual dust characterization



Dust mobility



Measurement of adhesion forces

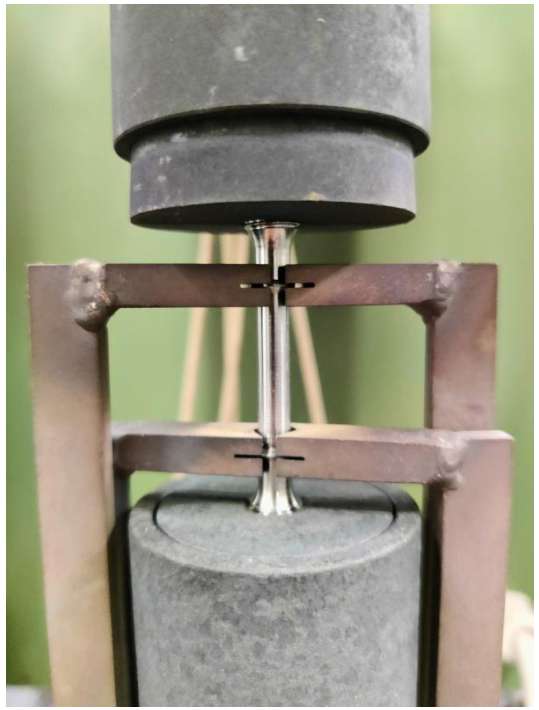


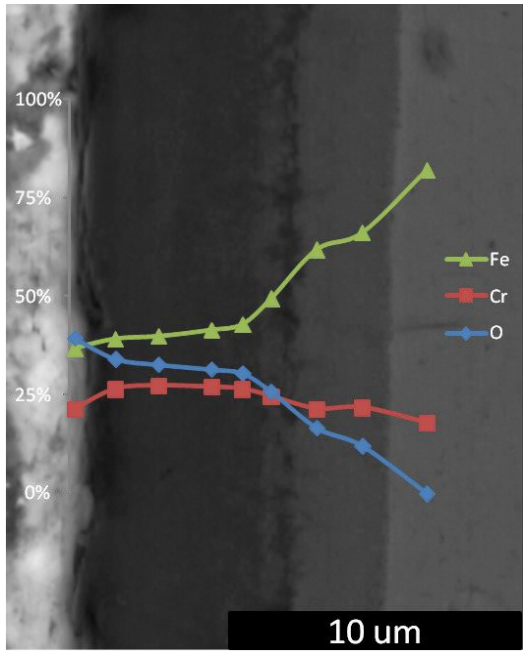
Analysis of PFCs damage

ICMATE Activities

Liquid lead compatibility is a major issue for the development of materials for the IV generation reactors. ICMATE works on the mechanical characterization of newly developed **AFA steels** and on corrosion testing of candidate materials, in the framework of the CONNECT-NM consortium.







Coordination of the European Research Community on Nuclear Materials for Energy Innovation

ICMATE Activities



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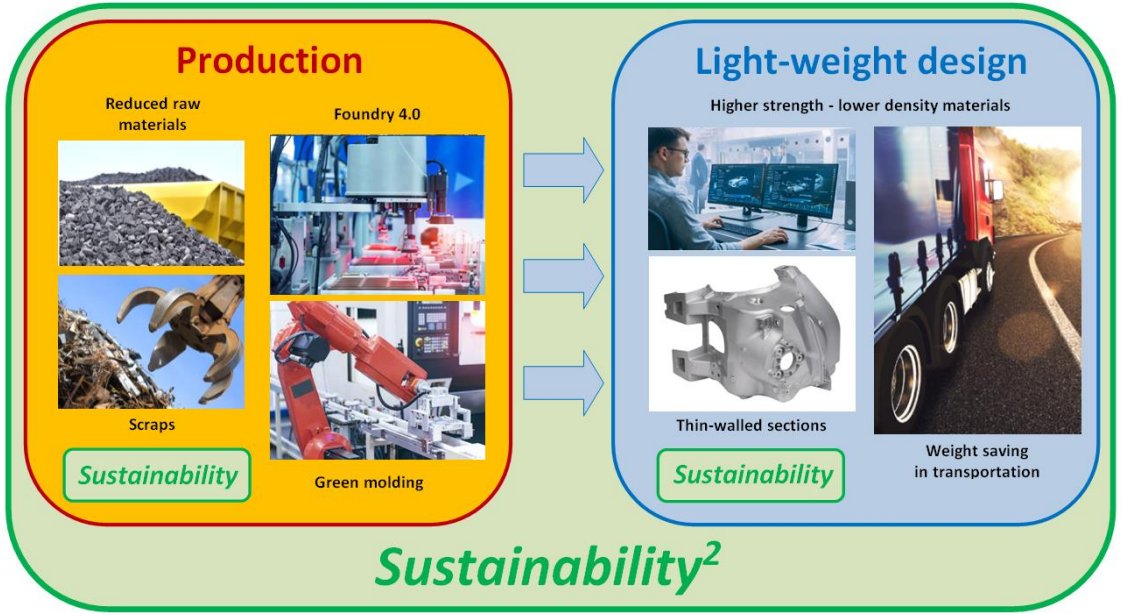
Funded by the European Union

Aalto University
School of Engineering

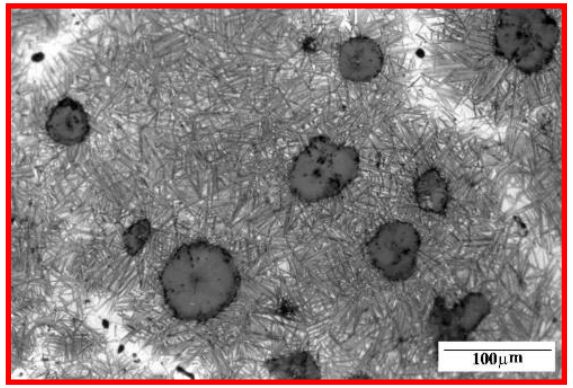
AGH

FACULTY OF FOUNDRY ENGINEERING
AGH UNIVERSITY OF KRAKOW

Consiglio Nazionale delle Ricerche







ICMATE Activities

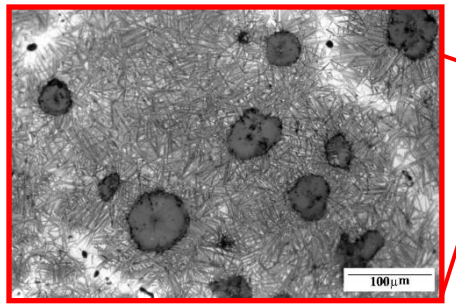
ADIs are candidates in many engineering applications because of their cost efficiency and their high strength-to-weight ratio

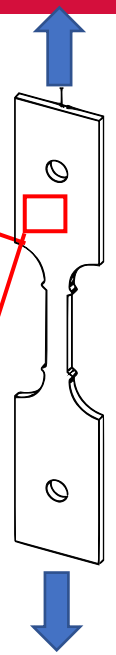




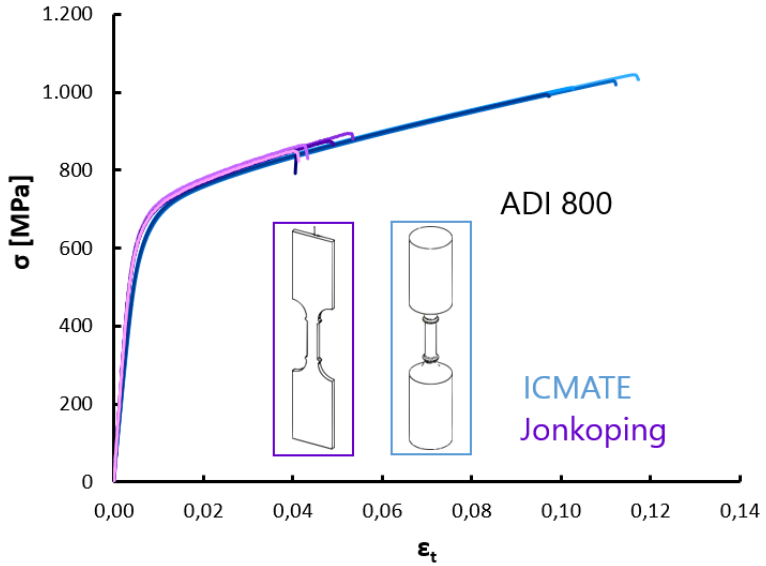


Effects of tensile stress on the ausferrite transformations

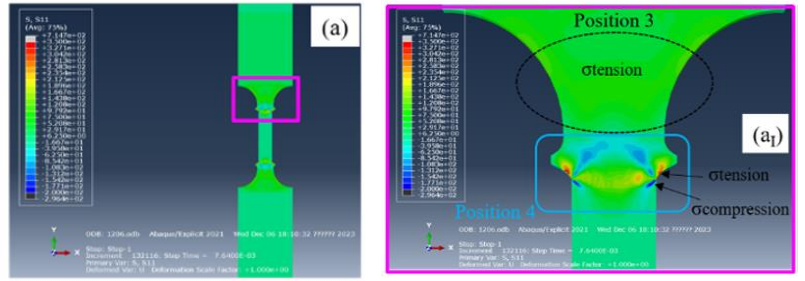




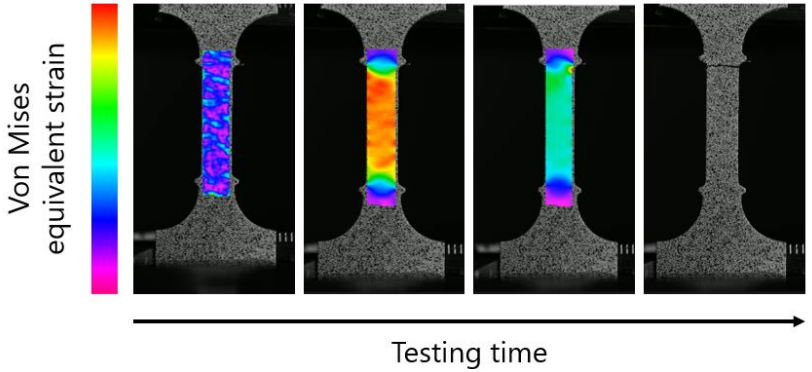
AUSFERRITE
High C Content Austenite
(metastable) γ_{HC} + acicular ferrite α

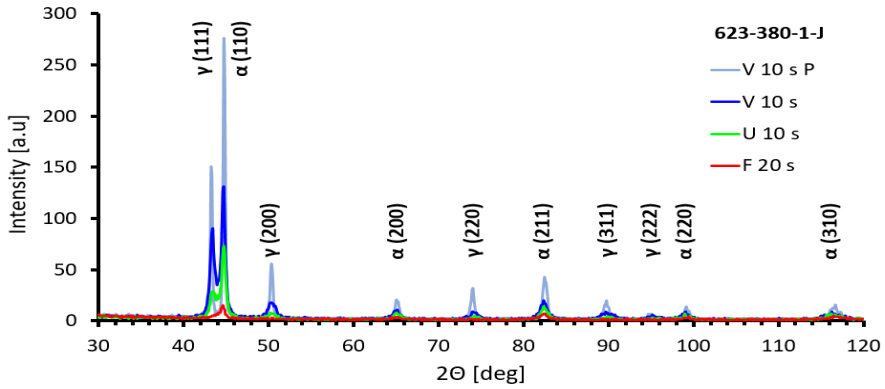


Finite Elements Modeling (FEM)
Lun Fu



Digital Image Correlation (DIC)





Contents

- Tensile Testing
- Sample Size and Shape
- Engineering stress-strain
- Testing Procedure
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- Influence of Test Rate
- Strain Control and Stroke Control
- Influence of Tensile Test Equipment
- Influence of Tensile Pulling System

Tensile Testing

Quasi-static tensile test consists of pulling a specimen with a certain elongation rate until rupture occurs, to determine the tensile mechanical properties:

- Young's modulus E (GPa)
- Yield stress YS (MPa)
- Tensile strength Rm (MPa)
- Elongation to fracture (%)
- Reduction of area Z (%)

International standards (in CNR-ICMATE, ASTM E8/E8-24, "Standard Test Methods for Tension Testing of Metallic Materials") prescribe the conditions under which tests have to be carried out:

- Sample Size and Shape
- Tensile Test Procedure
- Influence of Elongation Rate
- Influence of Tensile Test Equipment

Equivalent standards:

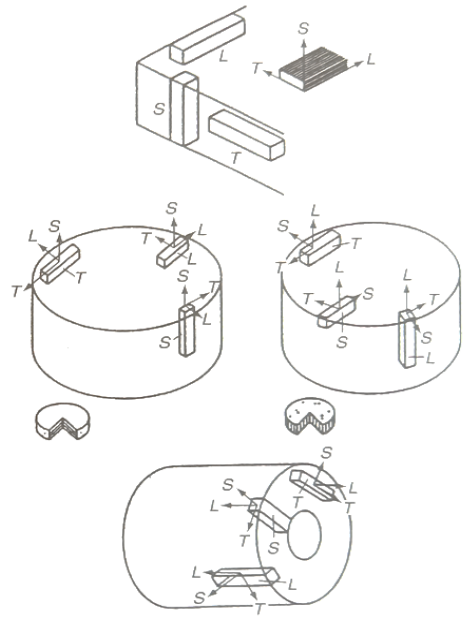
International Organization for Standardization (ISO), ISO 6892-1, "Metallic materials — Tensile testing — Part 1: Method of test at room temperature", 2019;

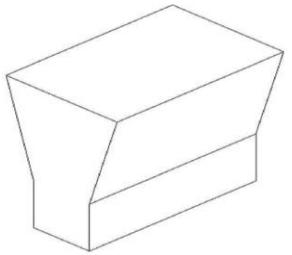
UNI EN 10002-1:2004;

D-19 - Deutsches Institut fur Normung E.V. (DIN) Euronorm (EN), DIN 50125.

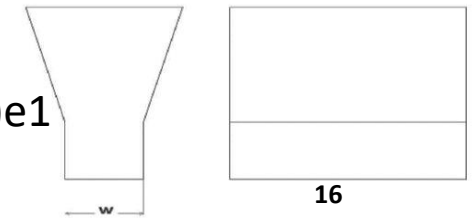
Tensile Sample Preparation

- The test specimens must be **taken and prepared** complying with the requirements of the standards relating to the different materials and the sections of the pieces that will be tested.
- The material to be examined and the **preparation of the tensile specimen** must be carried out in such a way as not to alter the characteristics of the material:
  - the machined tensile specimens must **not show traces of tools or scratches** as, due to the notch effect, they would lower the values of the mechanical characteristics.
  - **cutting, shearing or punching** during sample preparation may strain-harden the surface or the edges of the tensile specimen; so, standards require subsequent machining or other methods to **remove surface or edge damage** created during sample preparation, like milling or grinding.



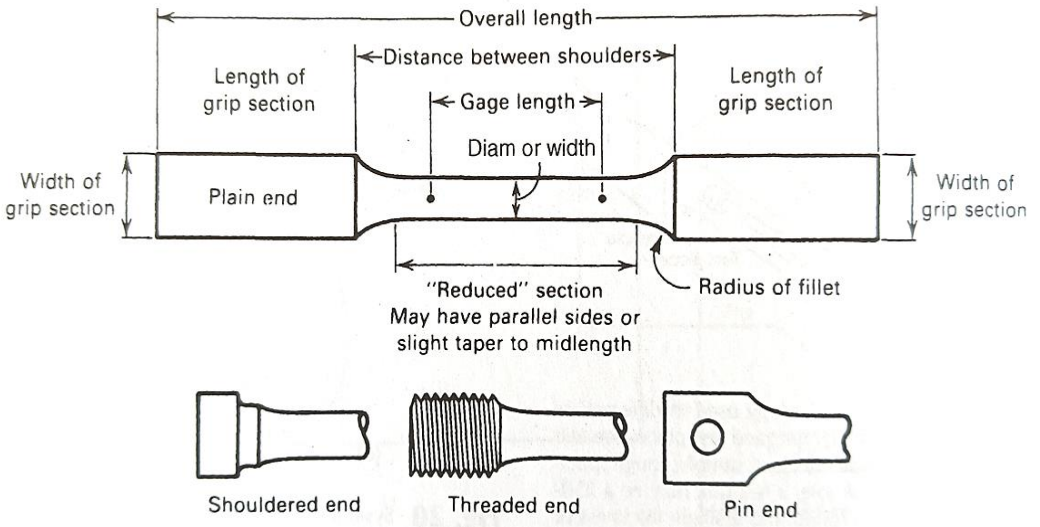


Y-block casting complying with ASTM A 536-84(2019)e1



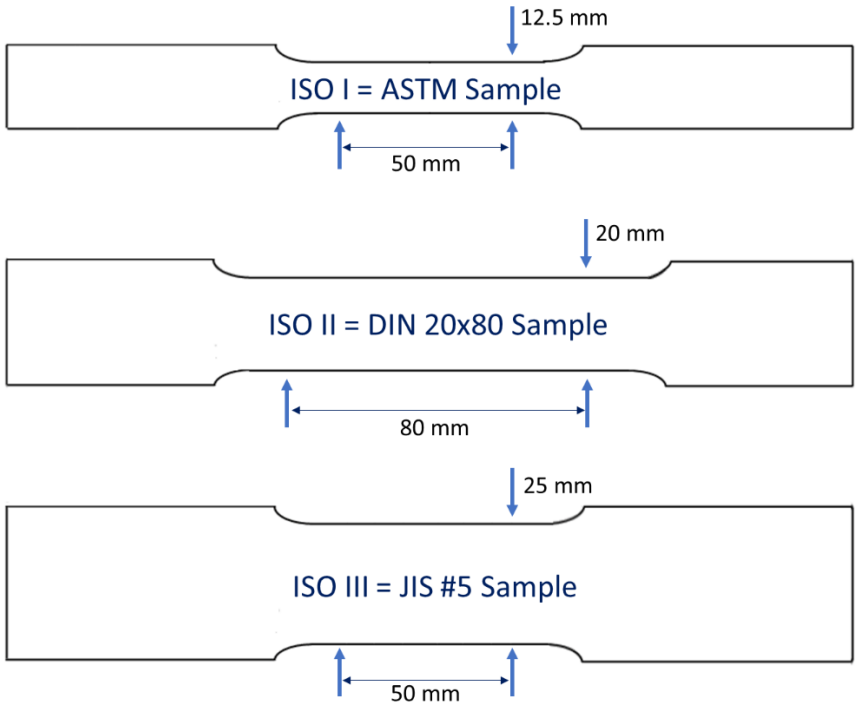
Sample Size and Shape

- The tensile specimens are provided with two ends that are used for clamping to the testing rig, called **specimen heads**, so the useful length of the specimen called **gauge** on which the deformation measurements are carried out, is less than its total length.
- The **specimen heads** can be *squared*, *threaded* or *pin end*; the specimen shape (called *double T* or *dog bone*) and the dimensions of the specimens are standardized for each type of material.
- The **geometry** of the specimen is designed in such a way that there is the rupture in the gauge of the tensile specimen because of greater stress, since near the jaws there is no uniaxial force.



Sample Size and Shape

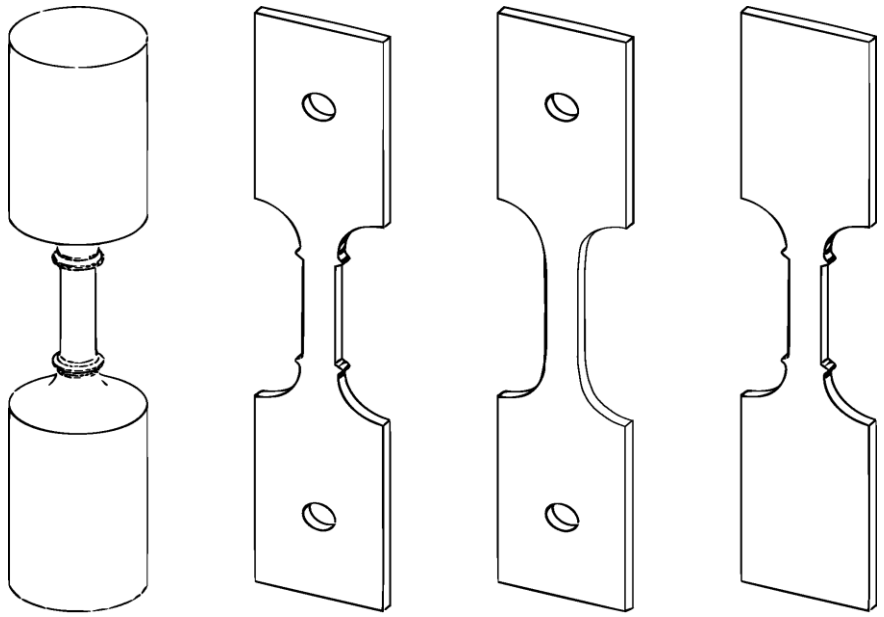
- Significant differences exist in the width and gauge length of the tensile specimens in **different standards.**
- The ASTM and DIN bars have a 4:1 ratio of gauge length to width, where the JIS bar has a 2:1 ratio.
- Even though each of the bars specify a different sample width (and therefore different cross-section), the **load is normalized** by this value, which negates differences from sample shape.
- **Strength** is defined as the load divided by the cross-sectional area.
- **Yield strength and tensile strength** are not a function of the shape of the tensile specimen.
- So, tensile flow curve is (or should be) **independent** on the specimen geometry.



Sample Shape

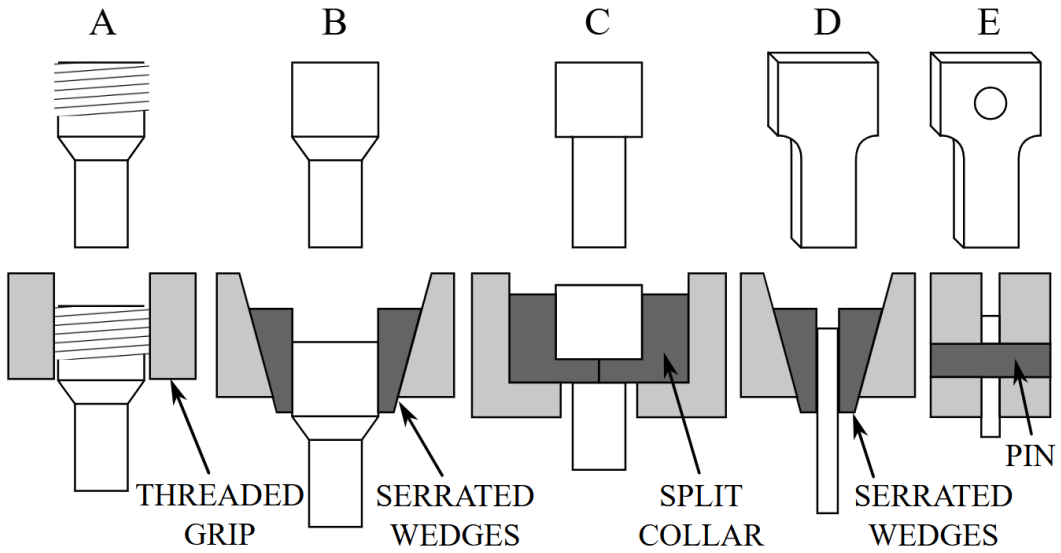
- As the flow curve is expected to vary only with the material, **differently shaped specimens should not** lead to different tensile flow curves.
- Indeed, also the **gripping system** is a relevant part of the "geometry" of the pulling system and may affect the experimental flow curve.
- To limit as much as possible the errors because of the geometry effects on the tensile flow curve, great efforts have been made in the past to **regulate and standardize the shape of the specimens**.

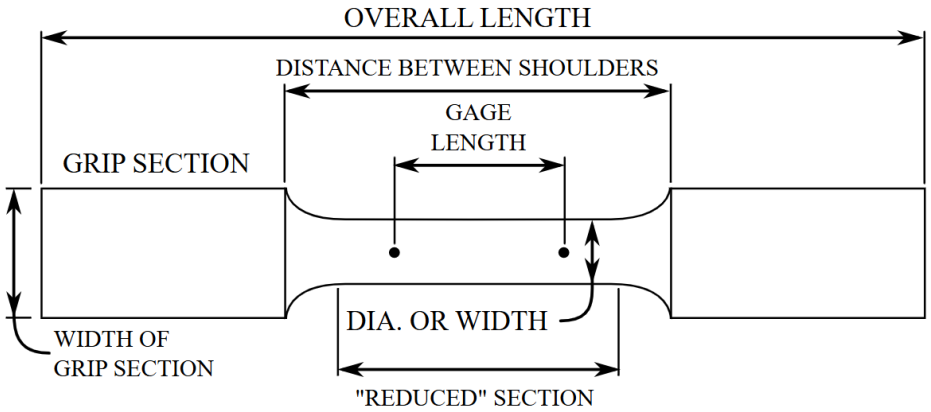
Flat specimen for thin sections



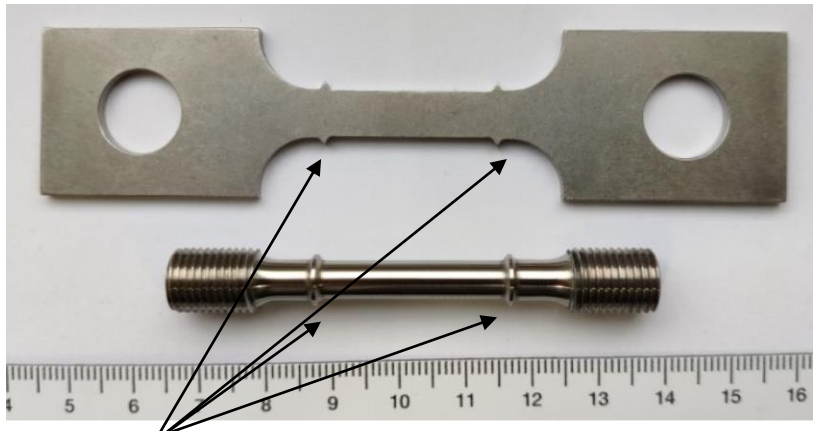
Round specimen | Flat specimen with ridges and pin end | Flat specimen with pin end | Flat specimen with serrated wedges

Gripping System





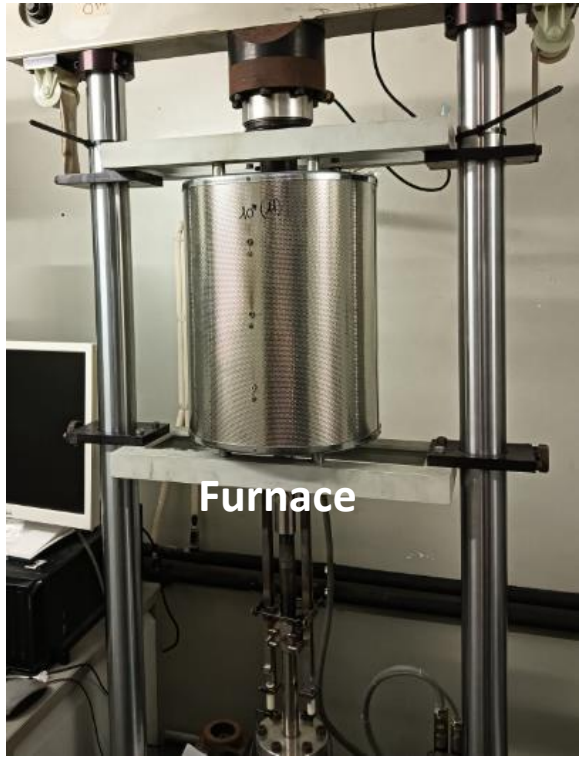
A. Threaded shoulder for use with a thread
B. Round shoulder for use with serrated grips
C. Butt end shoulder for use with a split collar
D. Flat shoulder for used with serrated grips
E. Flat shoulder with a through hole for a pinned grip

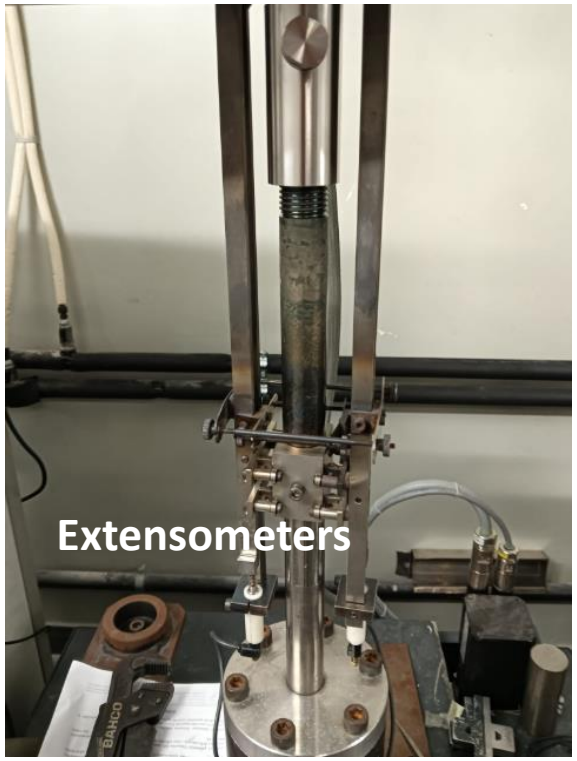


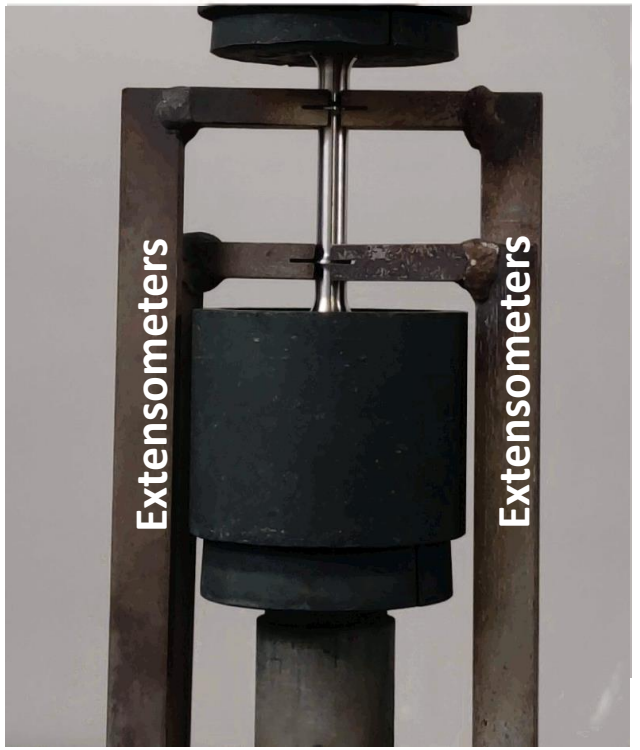
Ridges for clamping extensometers to be used in furnace
Ridges allow that deformation is recorder up to rupture

Gripping System

Electromechanical testing rig for room and high temperature testing



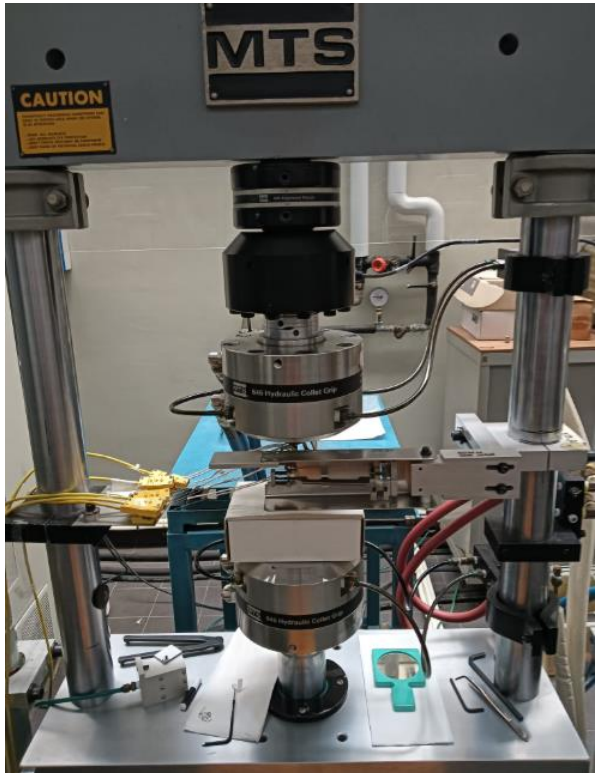






Gripping System

Hydraulic testing rig with hydraulic grips (for round shoulder specimens) Fatigue testing





Electromechanical testing rig with jaws for flat tensile specimens

Testing procedure

- The specimen is fixed between a grip system in a vertical position.
- The **crosshead** grip begins to move at a constant speed: **stroke control**.
- With extensometers at the gauge and close loop control the grip moves to have a constant elongation rate of the gauge length: **strain control**.
- In both cases, a state of stress begins to arise in the material and an increasing force is generated, opposite to the direction of the **machine crosshead**.
- The machine is stopped when the specimen breaks or when the crosshead has moved to a predetermined distance or to the limit.
- The machine has a **load cell** that measures the force applied to the specimen instant by instant, to which a strain gauge is also applied, which measures the elongation.
- Thanks to the strain gauge and the load cell, stress and deformation values are obtained at constant time intervals (**stress-strain flow curve)**.



Engineering stress-strain curve

The engineering stress *S* (MPa) is simply the ratio between the load and the initial cross sectional area of the specimen:

$$S = F/A_o$$

with F (N) is the applied load;

A_o (m^2) is the initial area of the specimen resistant section.

The engineering strain *e* is given by:

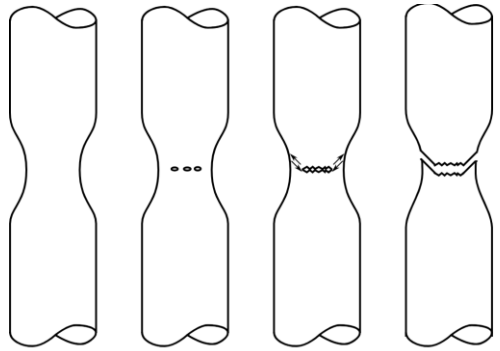
$$e = \Delta L/L_o = (L - L_o)/L_o$$

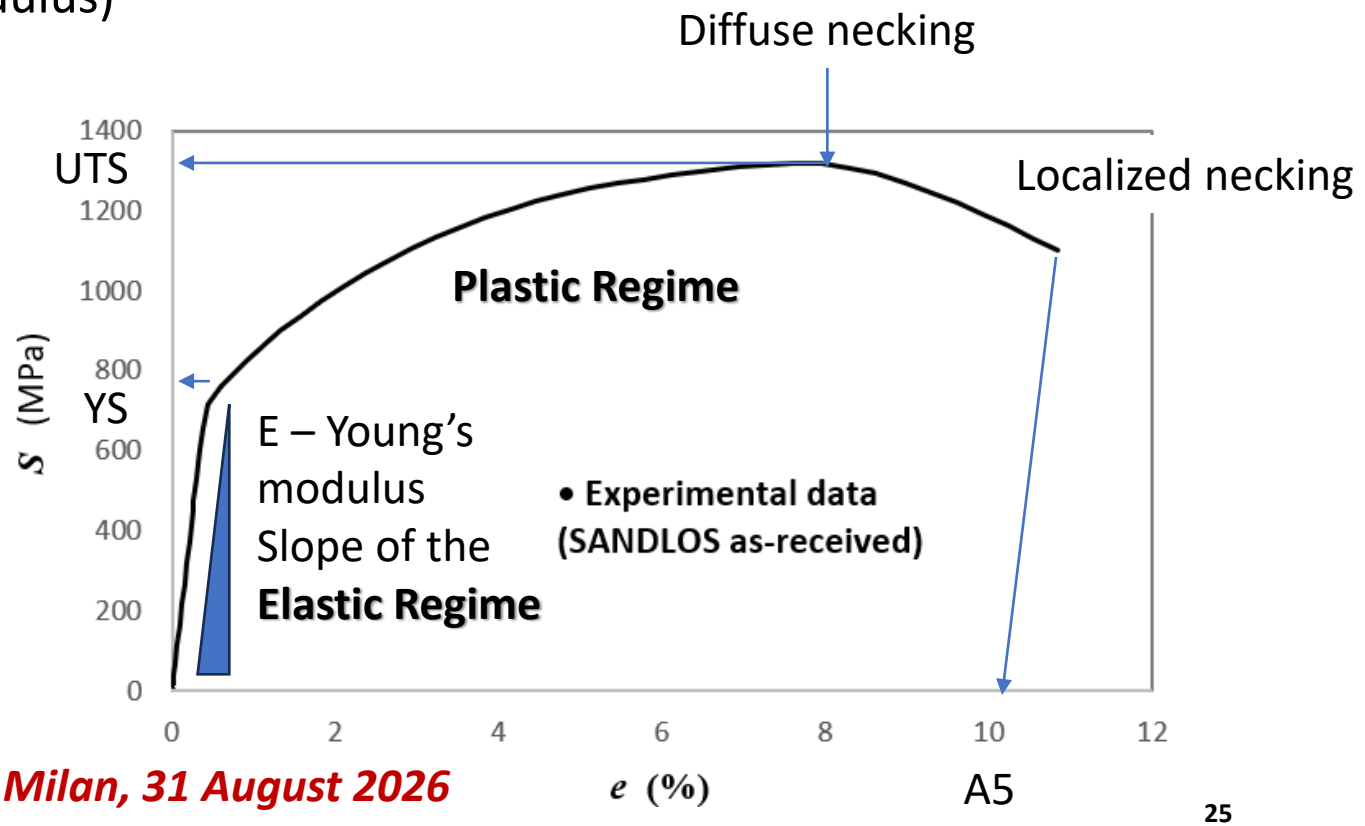
where L (m) is the evolving length of the gauge specimen obtained by elongating the specimen;

L_o (m) is the initial gauge length of the specimen.

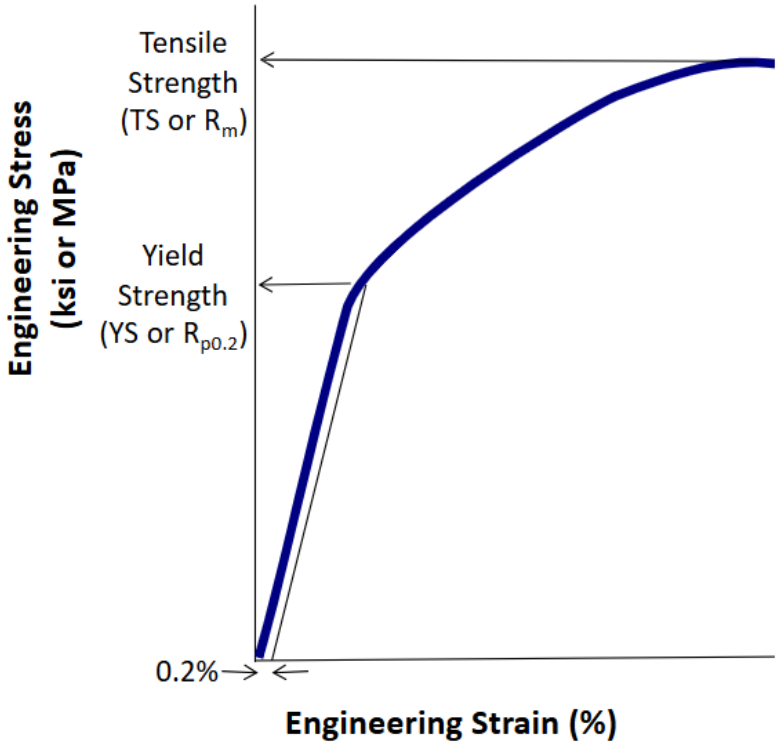
Engineering stress-strain curve

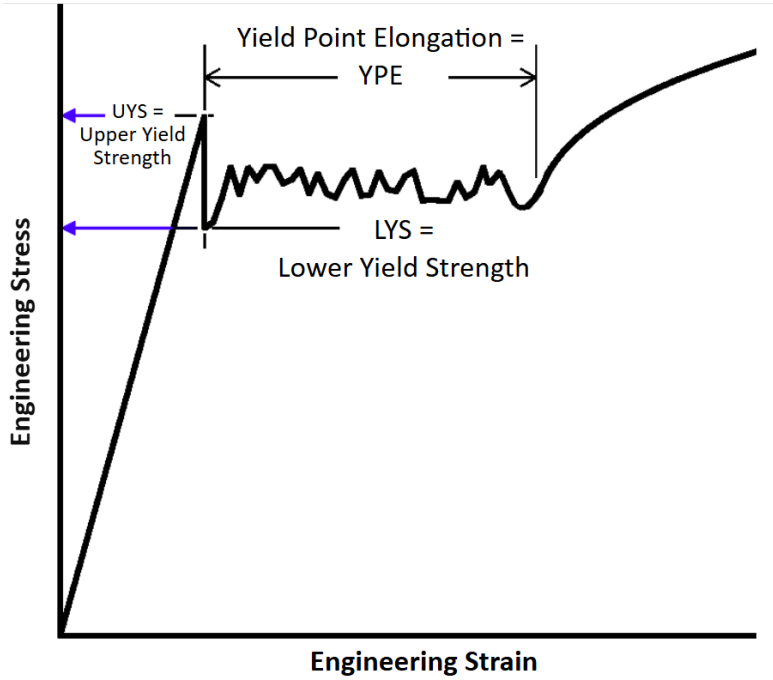
- From the engineering stress-strain curve, parameters important for application are gathered:
  - Elastic Modulus (E - Young's Modulus)
  - Yield Strength (YS)
  - Ultimate Tensile Strength (UTS)
  - Total Elongation (A5)
    (by measuring broken parts)





Engineering stress-strain curve



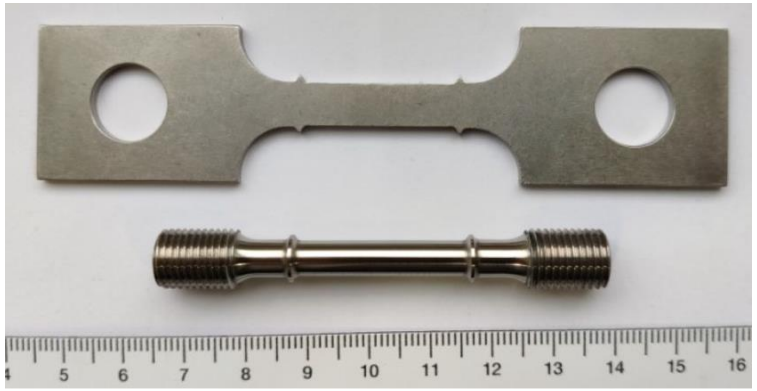


Engineering stress-strain curve

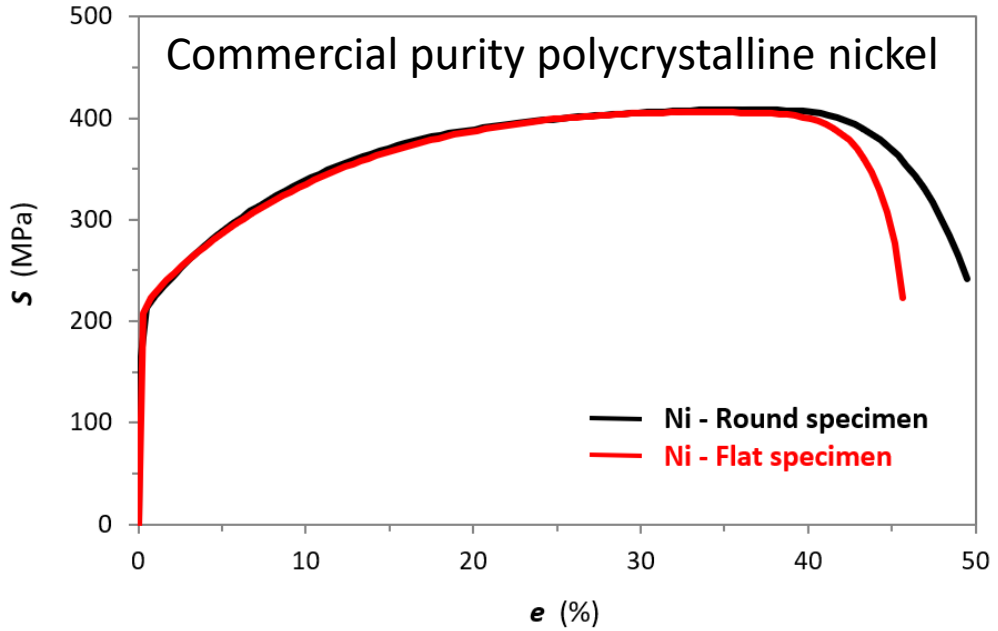
The shape of the specimen is regulated and standardized, so no shape effect on the flow curves should be present.

Flat specimen with pin-hole grip

Round specimen with threaded grip



Both geometries complying with ASTM E8/E8-24



S = engineering stress (MPa)
e = engineering strain (%)

True stress σ – True strain ε

To obtain the true value of the mechanical stress, it is necessary to take into account the **variation of the cross sectional area** with elongation (A(*e*)) that reduces during straining because of the tensile loading:

$$\sigma = F/A(e)$$

In the elastic range, the stress practically corresponds to the stress (for many other metallic alloys, the Poisson effect can be neglected), while in the plastic range the area A(*e*) is significantly reduced with the load, and the phenomenon of plastic constriction occurs.

The tensile correction factor corresponds to the inverse of the narrowing coefficient:

$$\sigma = S \cdot (A_o/A(e)) = S \cdot (1 + e)$$

Also, strain must be corrected with the effects of variation of the area, resulting into the true strain ε:

$$\varepsilon = \ln(L/L_o) = \ln(1 + e)$$

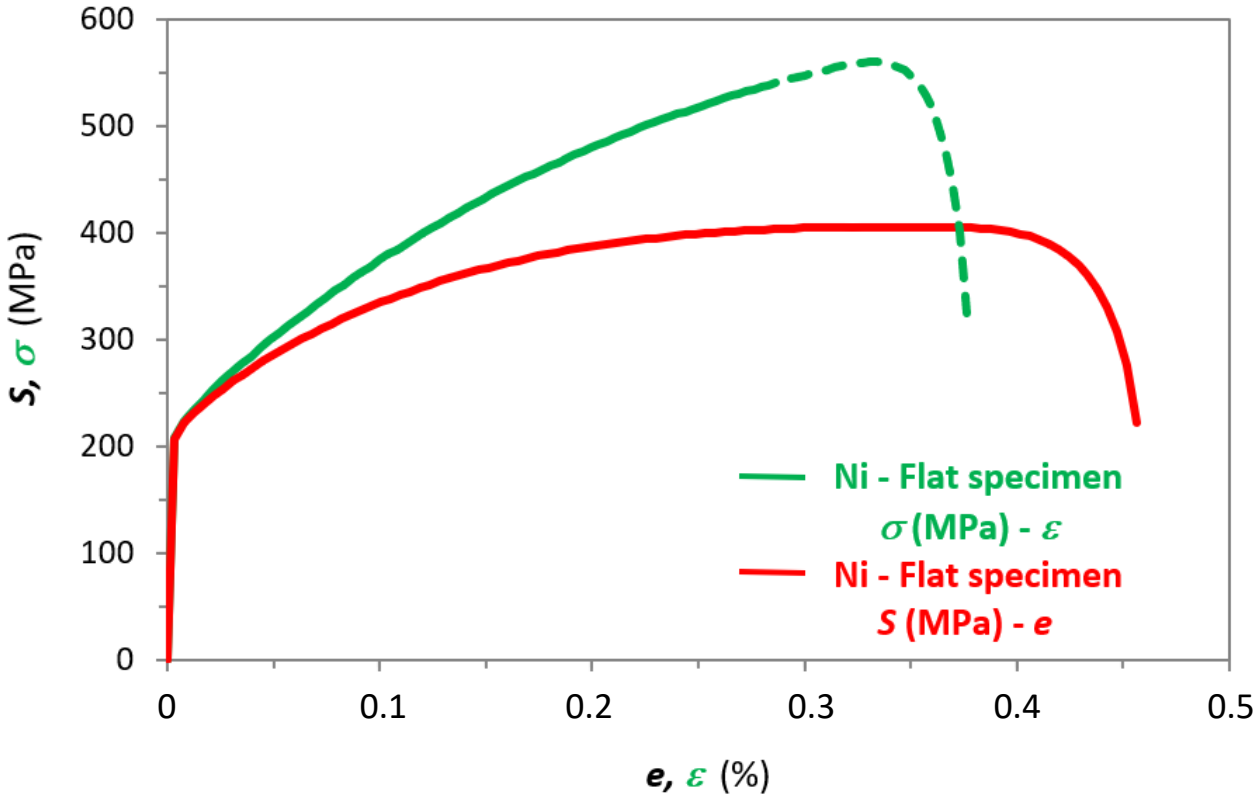
Comparison: engineering and true stress- strain

Engineering stress S (MPa) = F/A_o

Engineering strain e (%) = $(L - L_o)/L_o$

True stress $\sigma = S \cdot (1 + e)$

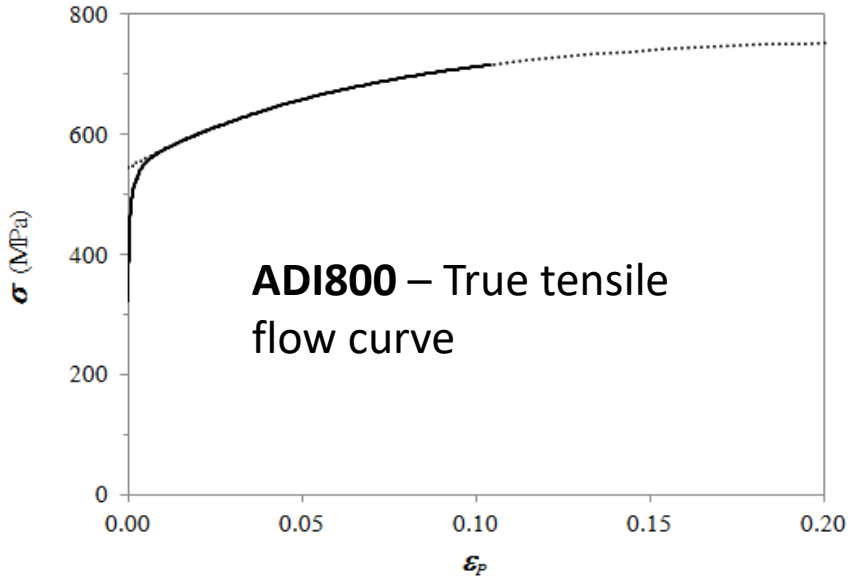
True strain $\varepsilon = \ln(1 + e)$



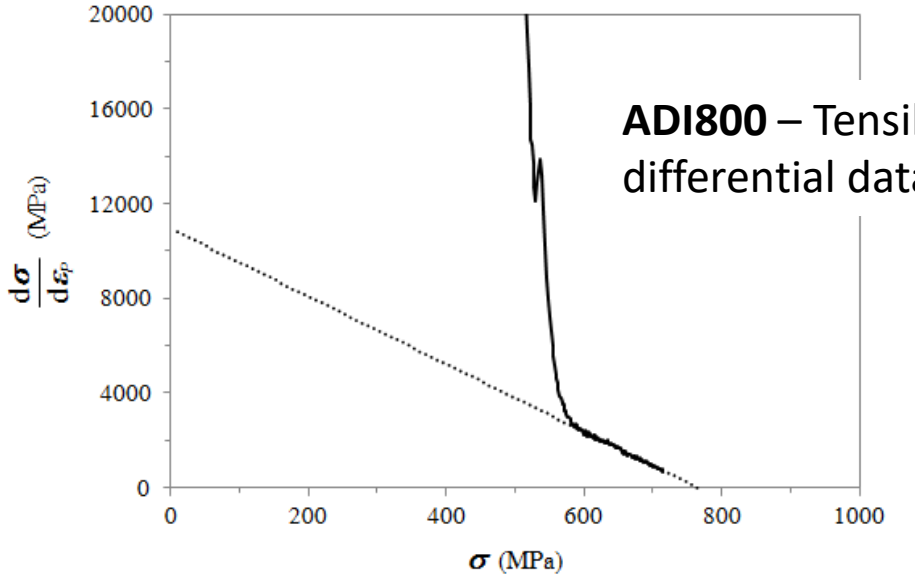
True curve $\sigma - \varepsilon$: strain hardening analysis

Strain hardening is the variation of the material strength with straining.

Technically, the strain hardening analysis is the investigation on the strain hardening rate ($d\sigma/d\varepsilon_P$) versus the stress (σ).



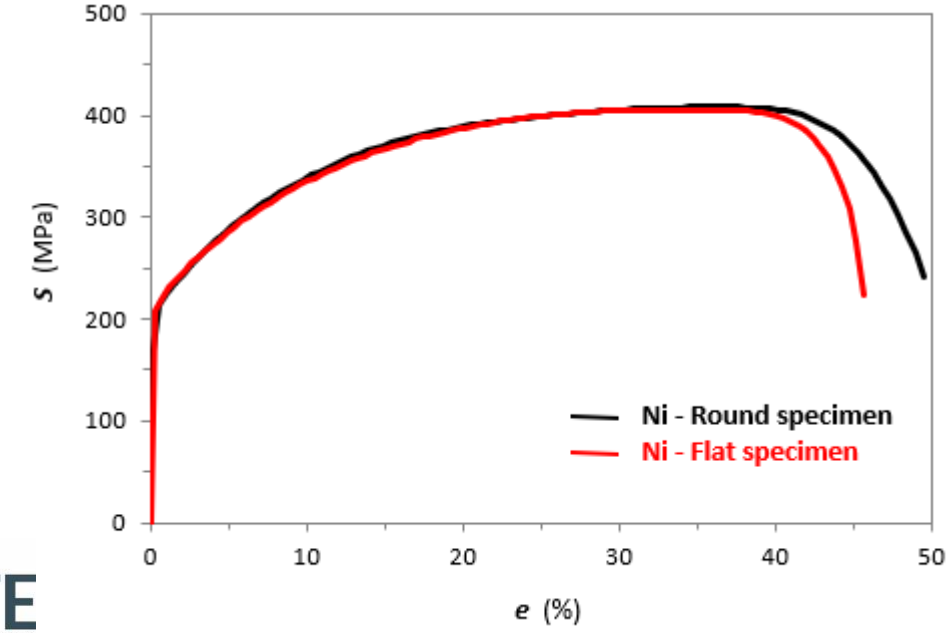
ADI800 – True tensile flow curve

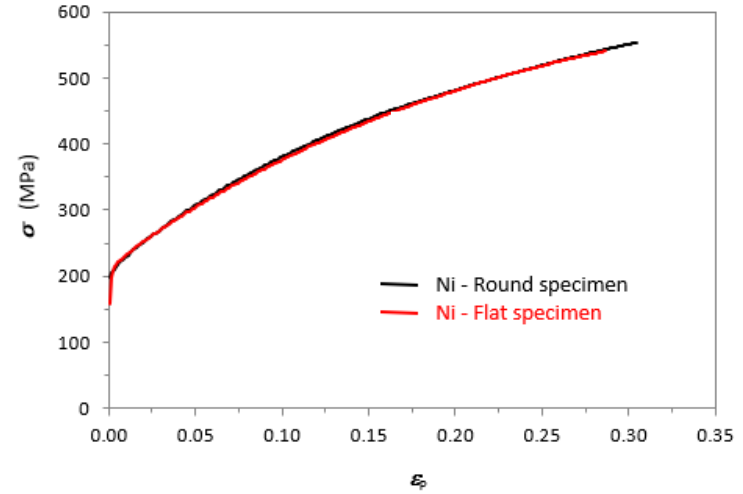


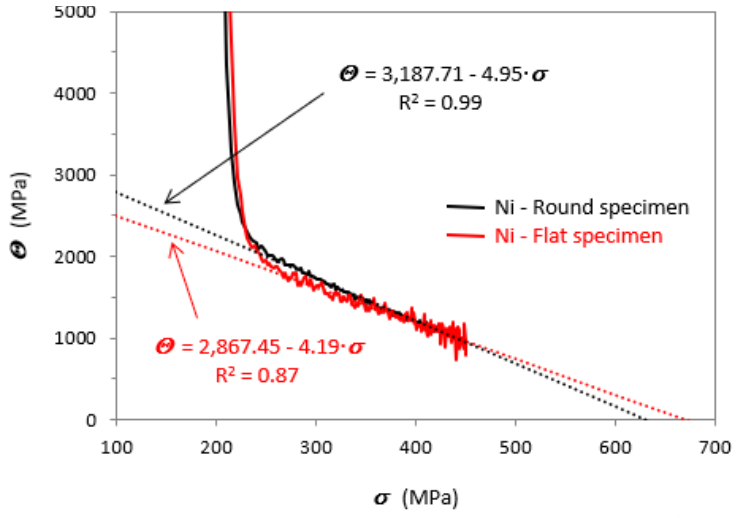
ADI800 – Tensile differential data

True curve $\sigma - \varepsilon$: strain hardening analysis

Strain hardening is **very sensitive to any change** in the material microstructure (chemical composition and phase transformation), but also tensile system (testing rig, specimen geometry, gripping system etc.)







Influence of Tensile Test Rate

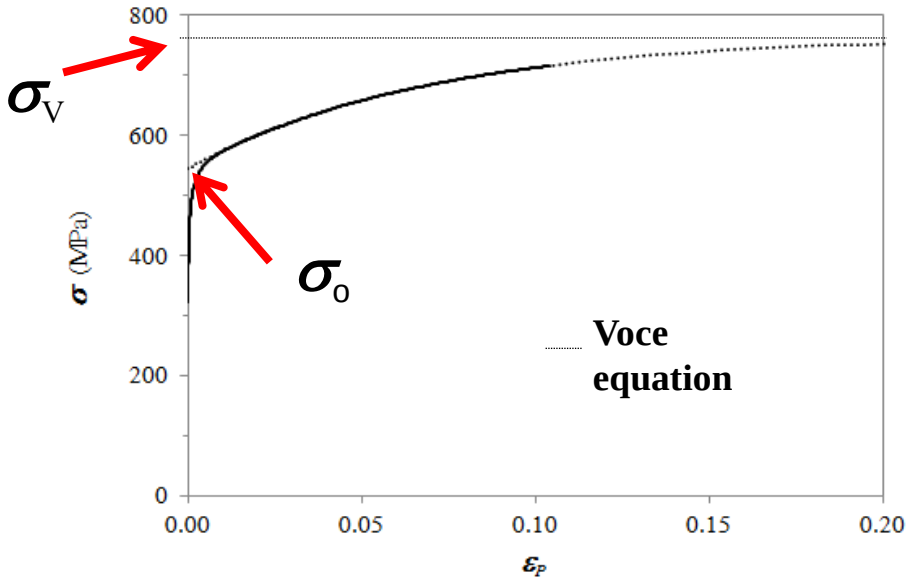
- Conventional tensile testing is done at strain rates slow enough to be called **"quasi-static"** (typically, 10^{-4} 1/s)
- These rates are several orders of magnitude slower than the deformation rates during metal forming or stamping, which itself is several orders of magnitude slower than what is experienced during a crash event.
- **Stress-strain curves change with test speed (different strain rates)**, typically getting stronger as the speed increases.
- The magnitude of these changes varies with metallic alloys.
- An example of this dependence can be highlighted with the **use of strain hardening analysis**, which can go deeper in rationalization metallic plastic behaviour (as the strain rate dependence).

True curve $\sigma - \varepsilon$: strain hardening analysis

Voce equation

$$\sigma = \sigma_V + (\sigma_0 - \sigma_V) \cdot \exp(- \varepsilon/\varepsilon_C)$$

σ_V = saturation stress;
ε_C = characteristic strain;
σ_0 = back-extrapolated stress to $\varepsilon = 0$.

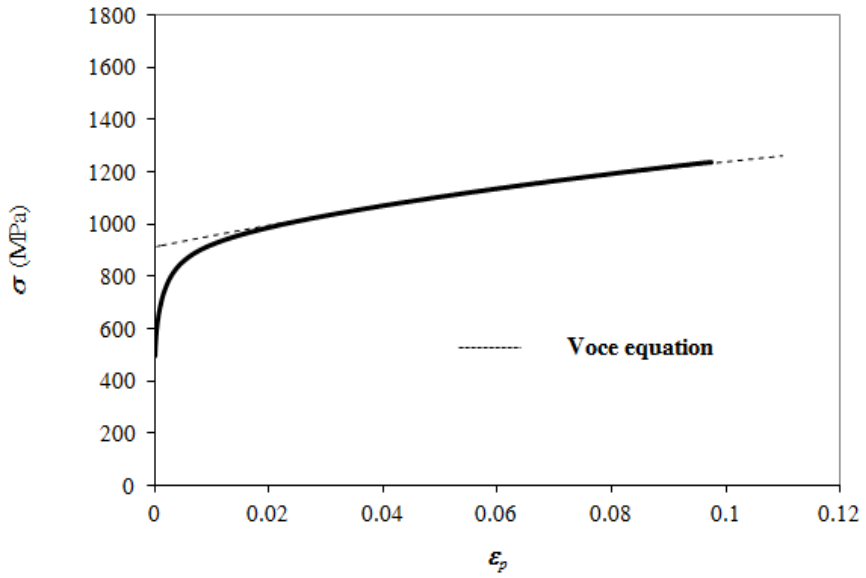


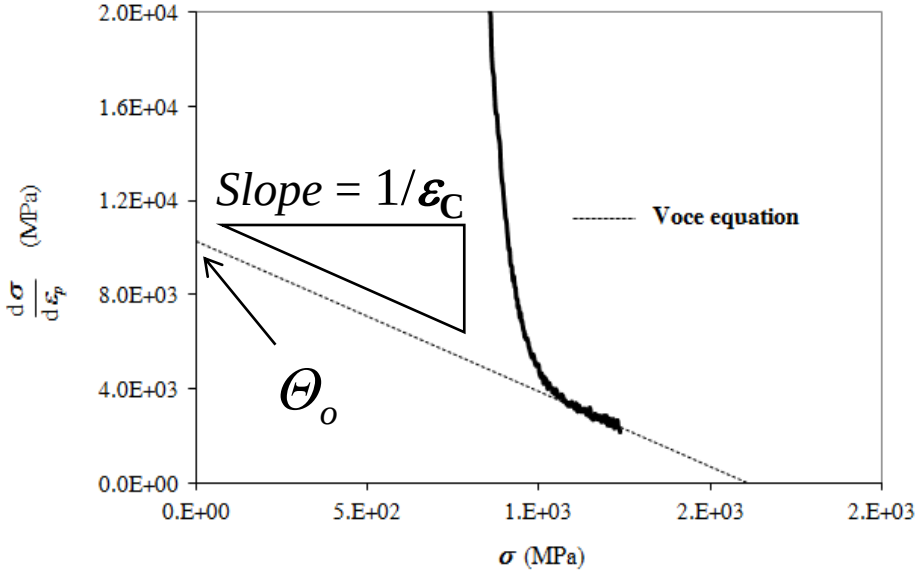
Strain hardening analysis

If strain hardening analysis of tensile flow curves is carried out, the Voce equation parameters ε_C and $\sigma_V = \Theta_o \cdot \varepsilon_C$ can be found by using the differential form of Voce equation:

$$\frac{d\sigma}{d\varepsilon_P} = \Theta_o - \frac{1}{\varepsilon_C} \cdot \sigma$$

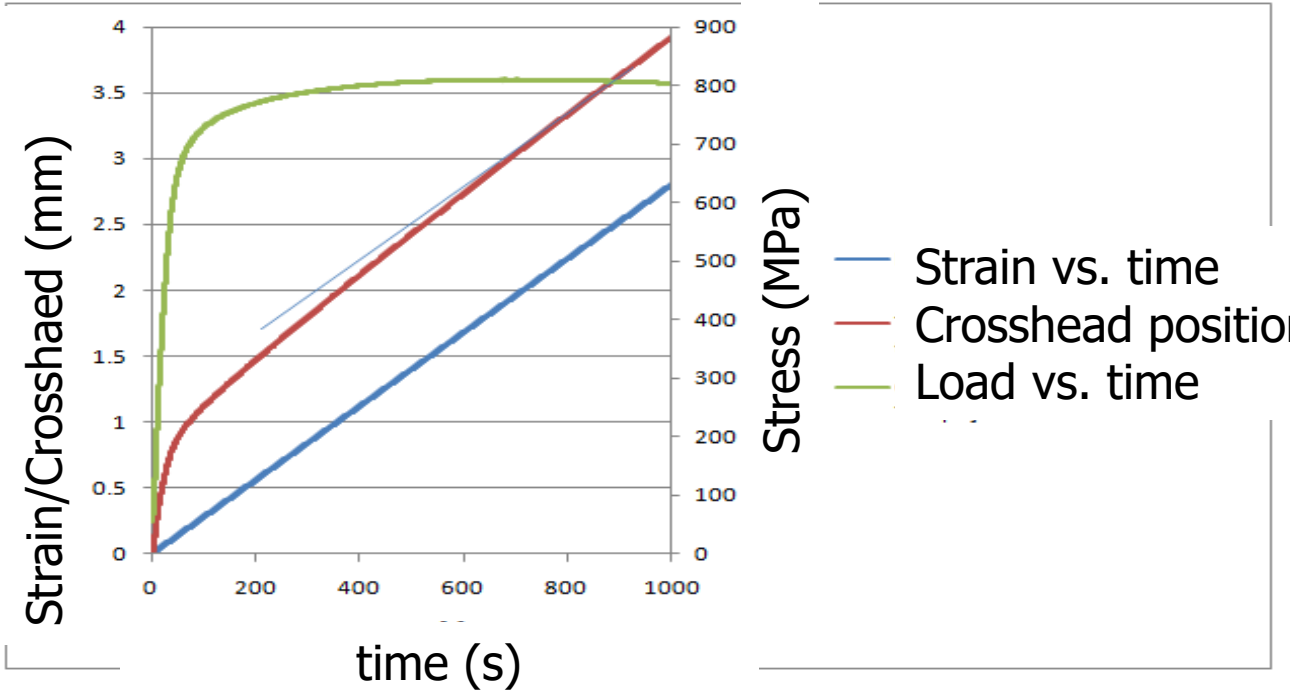
linearity between $d\sigma/d\varepsilon_p$ and σ





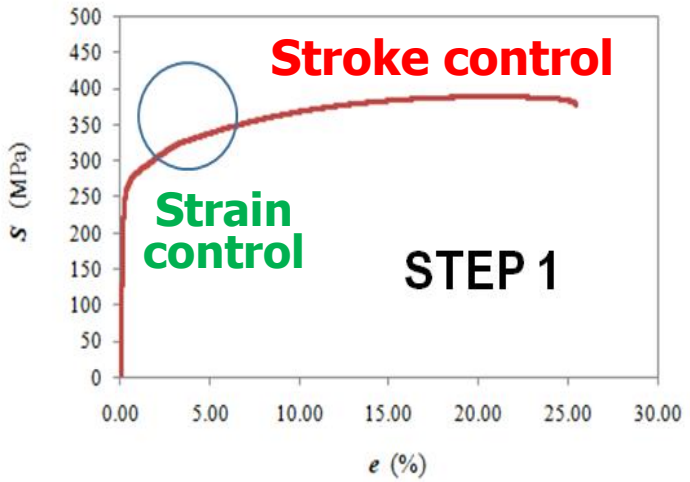
Strain rate considerations

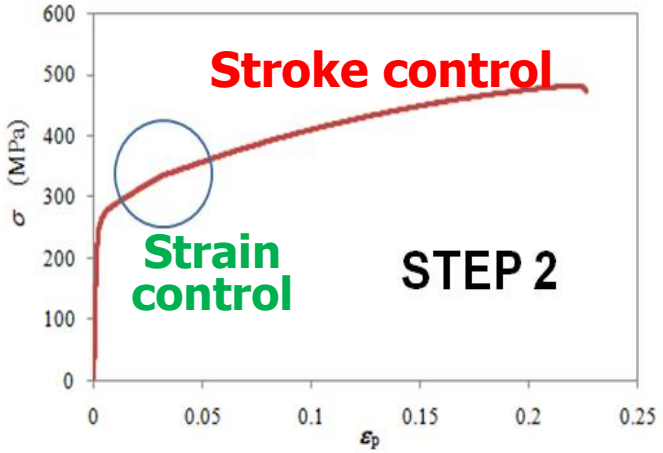
It is important that the tensile tests are carried out at a constant strain rate, i.e. in **<u>strain control</u>** and not in **<u>crosshead control</u>**.



Strain rate considerations

Example:
Strain control up to 3% only, then crosshead control (slower deformation rate).





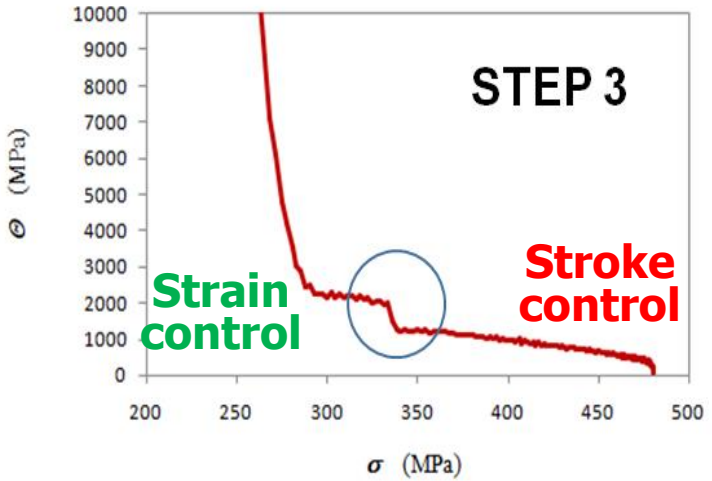
Strain control
Vs.
Stroke control



GJS400
heavy section

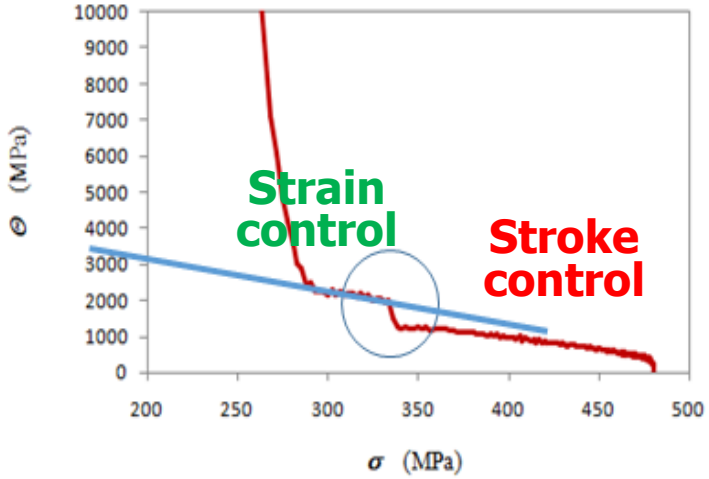
Strain hardening rate:
$\Theta = d\sigma/d\varepsilon_P$

Strain hardening analysis



Strain rate considerations

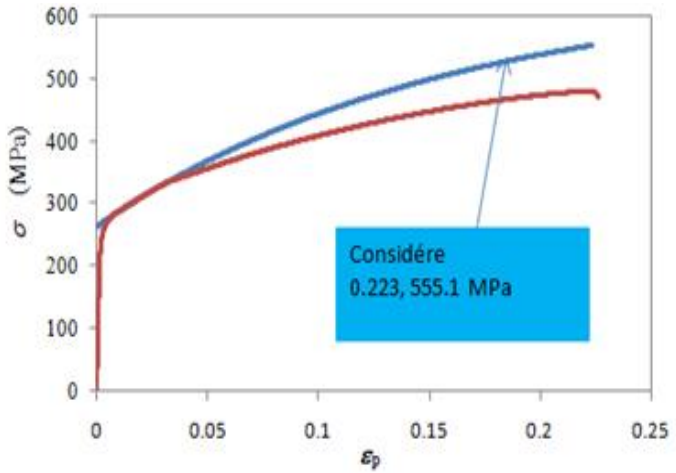
Going backwards from strain hardening analysis

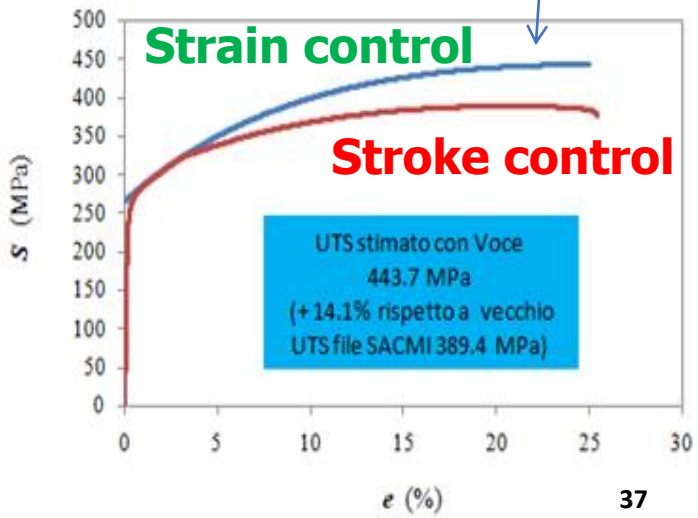


Blue curve should be the real behaviour: UTS +14.1%

Example:
strain control up to 3% only, then crosshead control (slower deformation rate).

Conclusions:
Strain hardening rate is strain rate sensitive.
Crosshead rate has to be kept constant.





Influence of Tensile Test Equipment

- The load and displacement response must reflect only the contributions of tensile specimens, and **not be influenced by the load frame and other testing equipment**.
- If **stroke control** is used, inaccuracies in the load-displacement measurements may occur, as tensile test load frames may deflect.
- Grip strength also becomes critical when high strength materials are tested.
- For instance, high strength of materials requires **more grip pressure** to prevent sample slippage through jaws:
  - Pneumatic grips and even some mechanical grips may not generate the necessary pressure.
  - **Hydraulically actuated grips** may be necessary as the strength increases.

Influence of tensile system

Tensile flat specimens of pearlitic ductile iron with two different geometries:

1. Thin flat specimens with 2.7 mm thickness;
2. Thick flat specimens with 5.7 mm thickness.

Same chemical composition and different solidification routes: thin (2.7mm) and thick (5.7mm) flat specimens had different mechanical properties measured with tensile testing in **stroke control**.

Question: there was any geometry or tensile system effect on the tensile results?



Influence of tensile system

Then 2 thick flat specimens were machined down,
so the final thickness was 2.7 mm (from the original 5.7 mm).

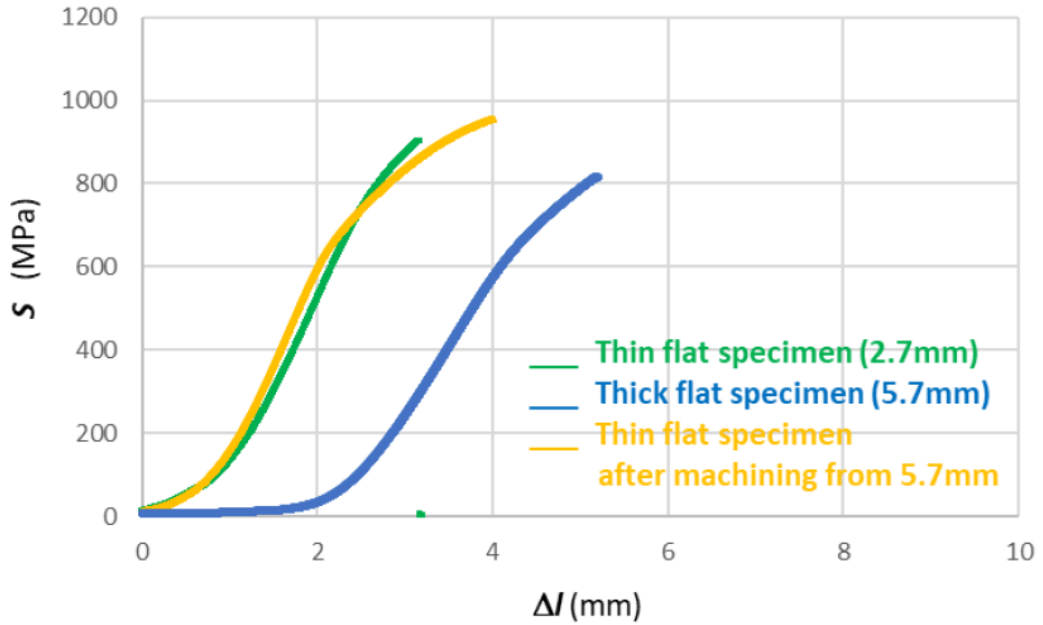
So, 6 tensile tests were carried out in stroke-control with jaws with 3 different specimen geometries:

a. 2 tests on 2 thick flat specimens 5 .7 mm thickness)
b. 2 tests on 2 thin flat specimens (2.7 mm thickness);
c. 2 tests on 2 thin flat specimen s (2.7 mm thickness) machined down from 5.7 mm flat specimens.

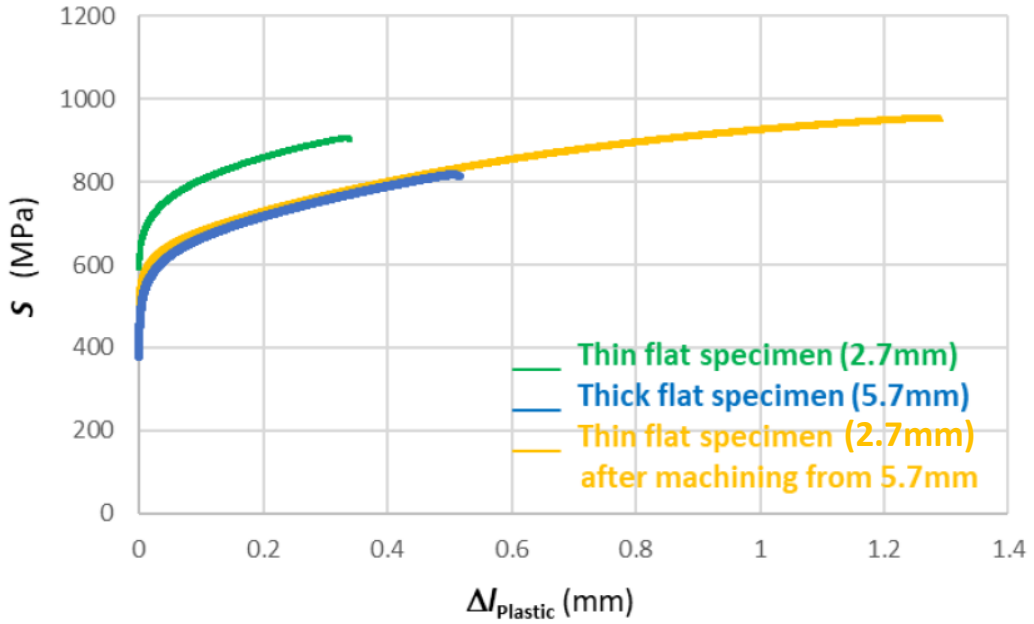




Influence of tensile system



If the elastic part of the system (**elasticity of the whole specimen + elasticity of the stroke system**) is considered and then subtracted from the curves the final curves are reported below:



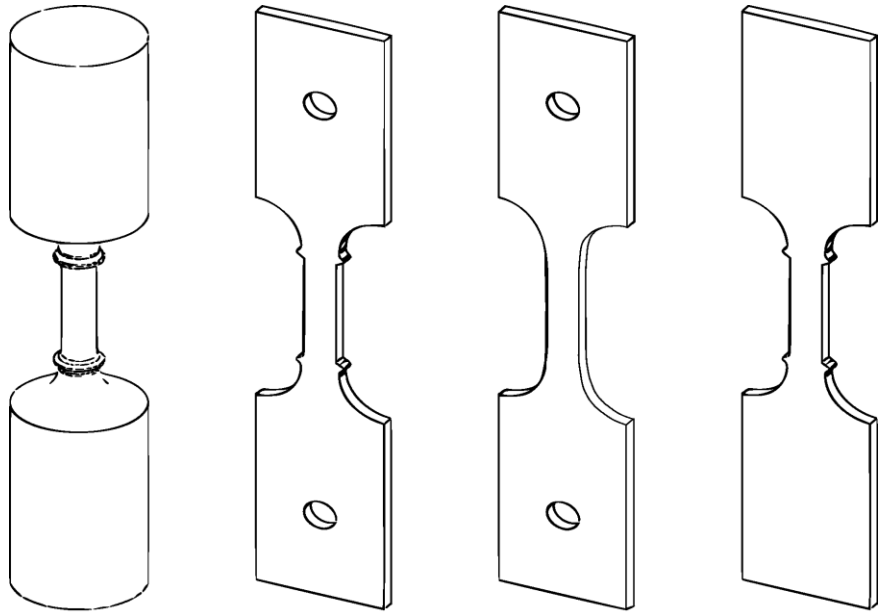
From the results above it seems that:

1. the material from the thin specimen is stronger than the material from the thick specimen.
2. BUT **the thickness of the specimen seems to affect the final elongation** at fracture reducing the measured ductility.

Influence of tensile system

- Tensile specimen geometry, but also **gripping system** can affect the tensile mechanical properties.
- Particular attention has to be paid to assess the **influence of the tensile system**, when materials produced in thin sections have to be tested and compared to materials produced through normal or thick sections.
- **Same tensile specimen geometry** should be always used (if possible)

Tensile system



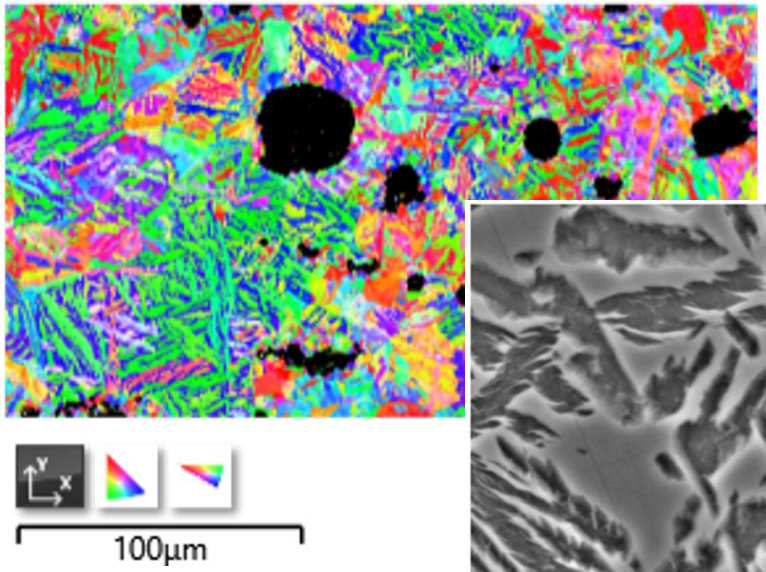
Round specimen	Flat specimen with ridges and pin end	Flat specimen with pin end	Flat specimen with serrated wedges

Gripping system + specimen geometry

Influence of tensile system

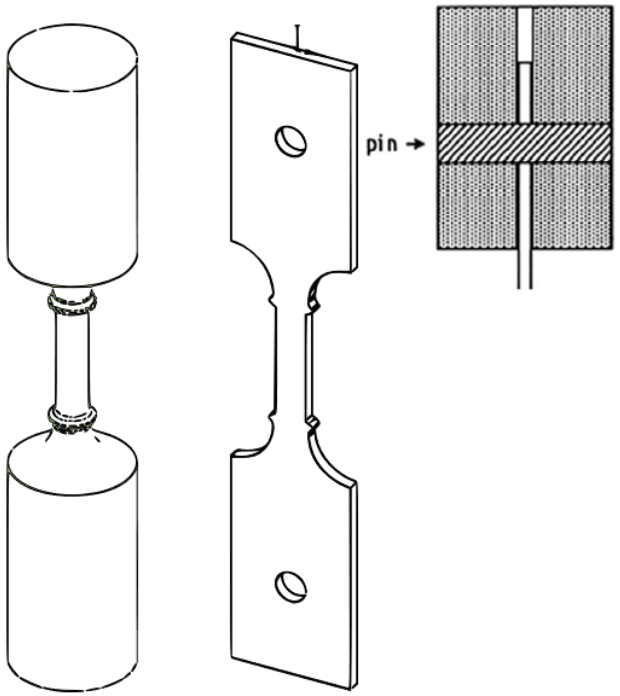
Element	C	Si	Mn	P	S	Ni	Cu
Wt Pct	3.46	2.37	0.29	0.02	0.01	1.10	0.84

Austenitization 875°C + Austempering 380°C



ADI800

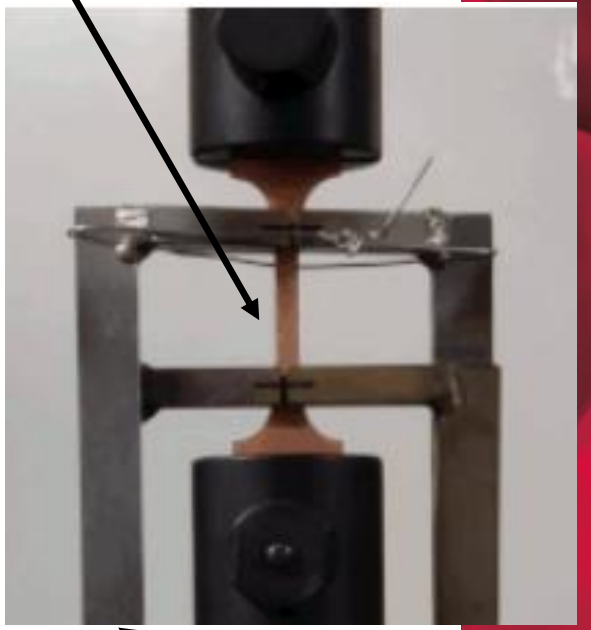
Tensile specimens geometries



ASTM E8-E8M

Specimen

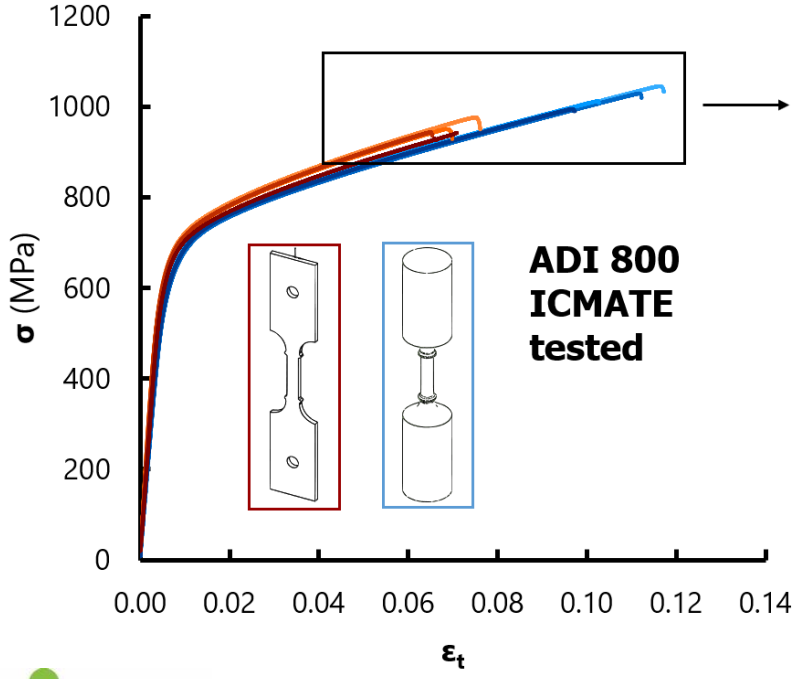
Gripping system

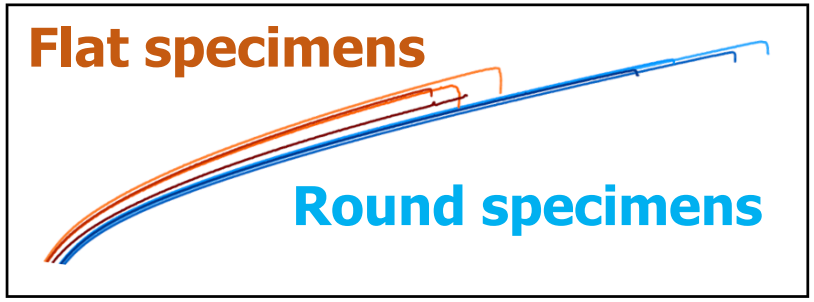


Extensimeters connected up to fracture

Influence of tensile system

Tensile tests on round and (thin-walled) flat specimens: comparison

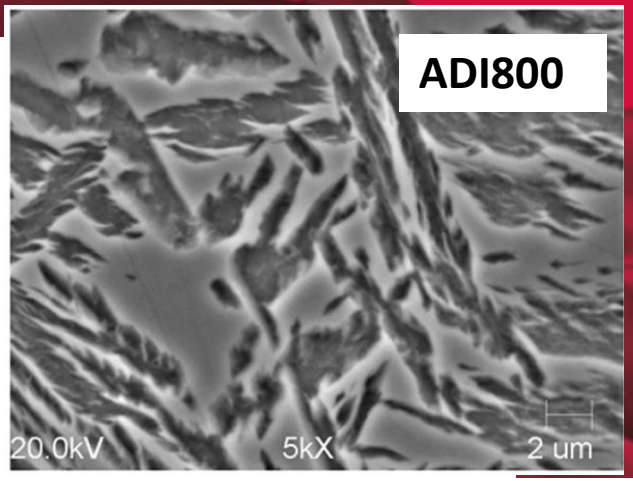




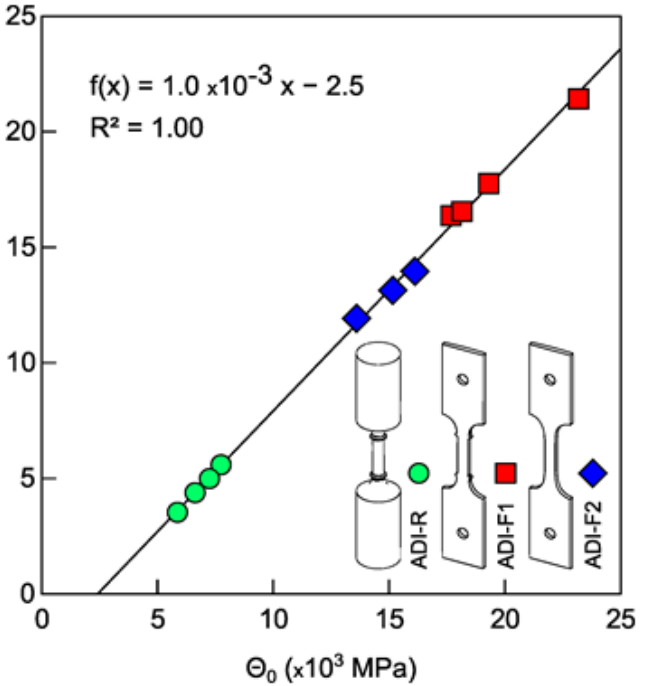
Flat specimens systematically show shorter elongations at rupture and higher strain hardening rates

Is this because of:

- Tensile specimen geometry?
- Austenite instability?
- Combination of both?

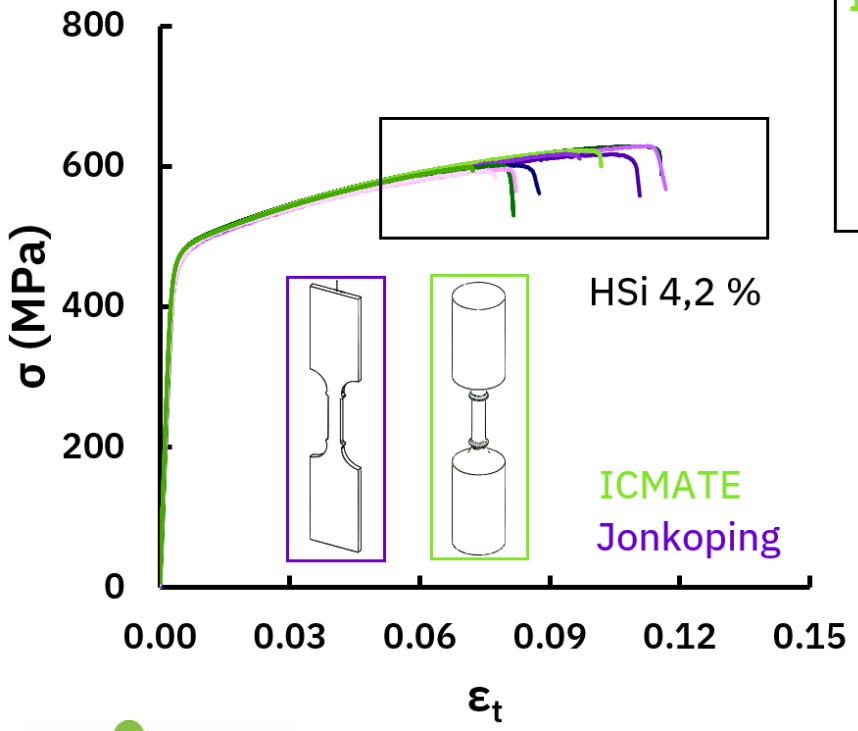


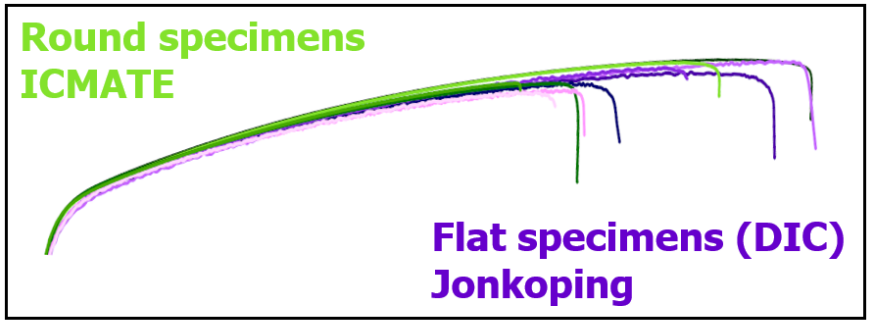
Strain hardening analysis

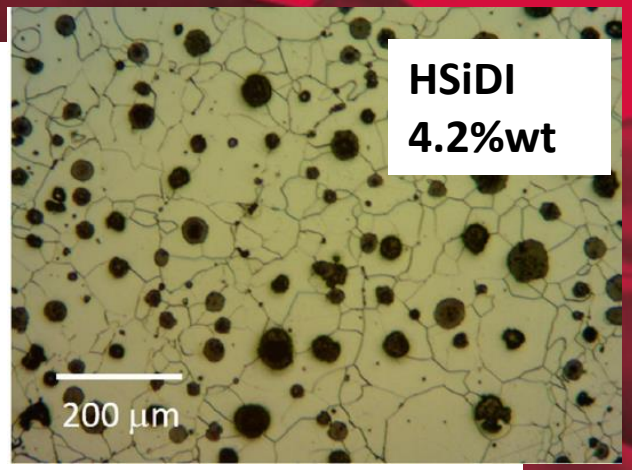


Influence of tensile system

Tensile tests on round and (thin-walled) flat specimens (DIC):
High Silicon 4.2 %wt. Ductile Iron



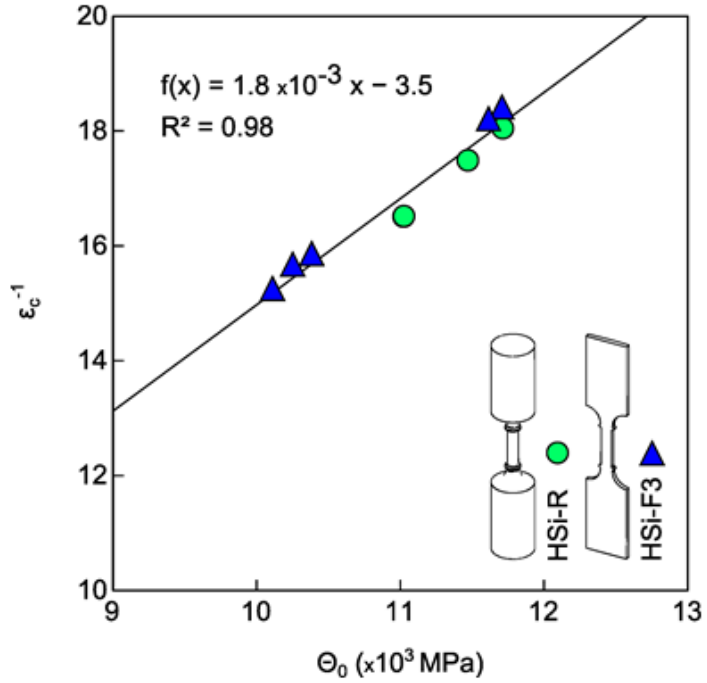




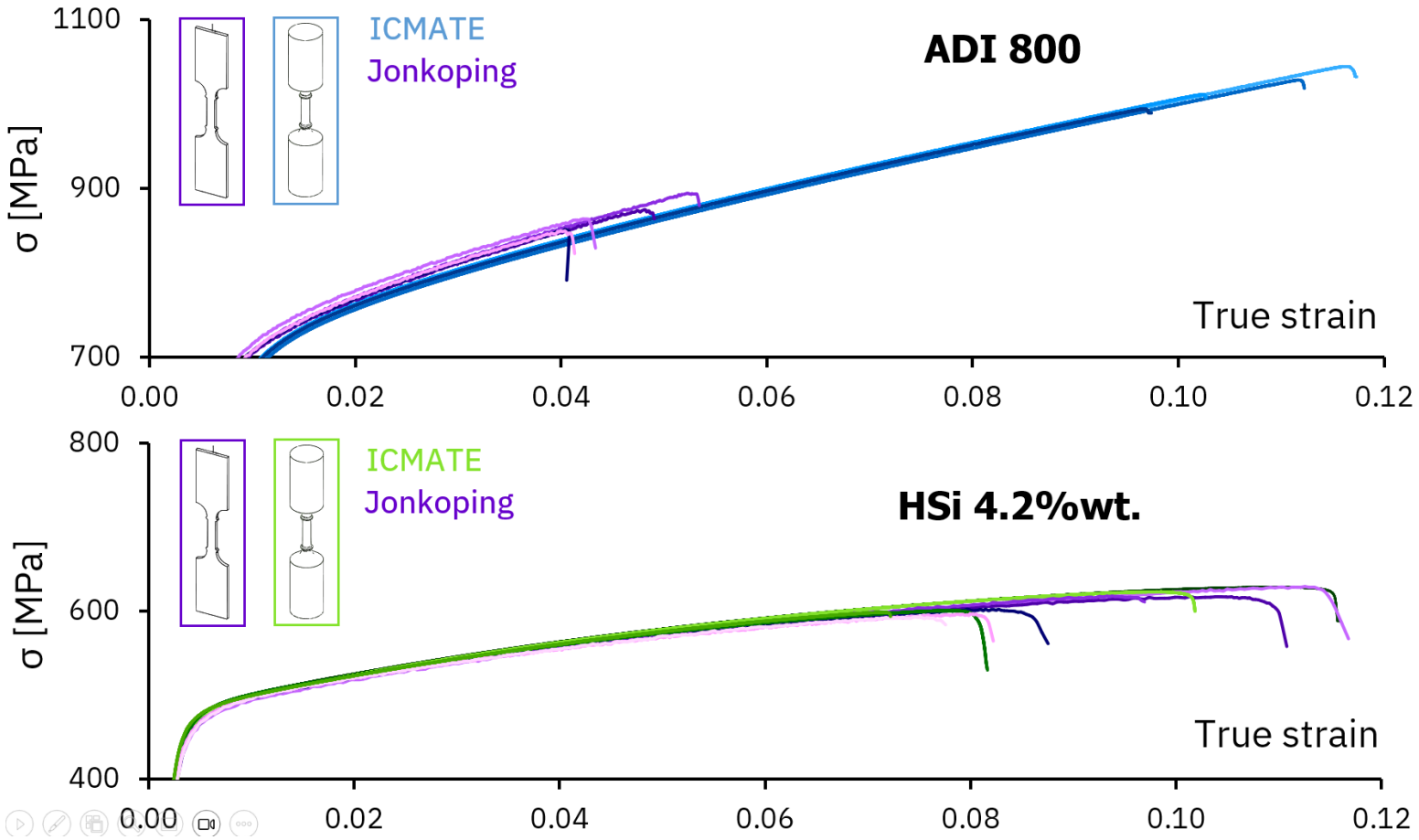
Homogeneous distribution of elongation at rupture + similar strain hardening

This confirms no geometry related differences

Strain hardening analysis



Influence of tensile system

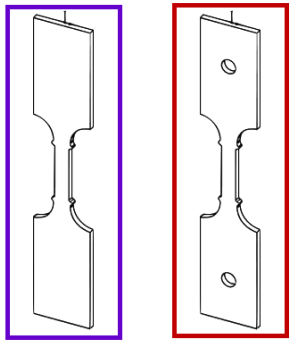


Influence of tensile system

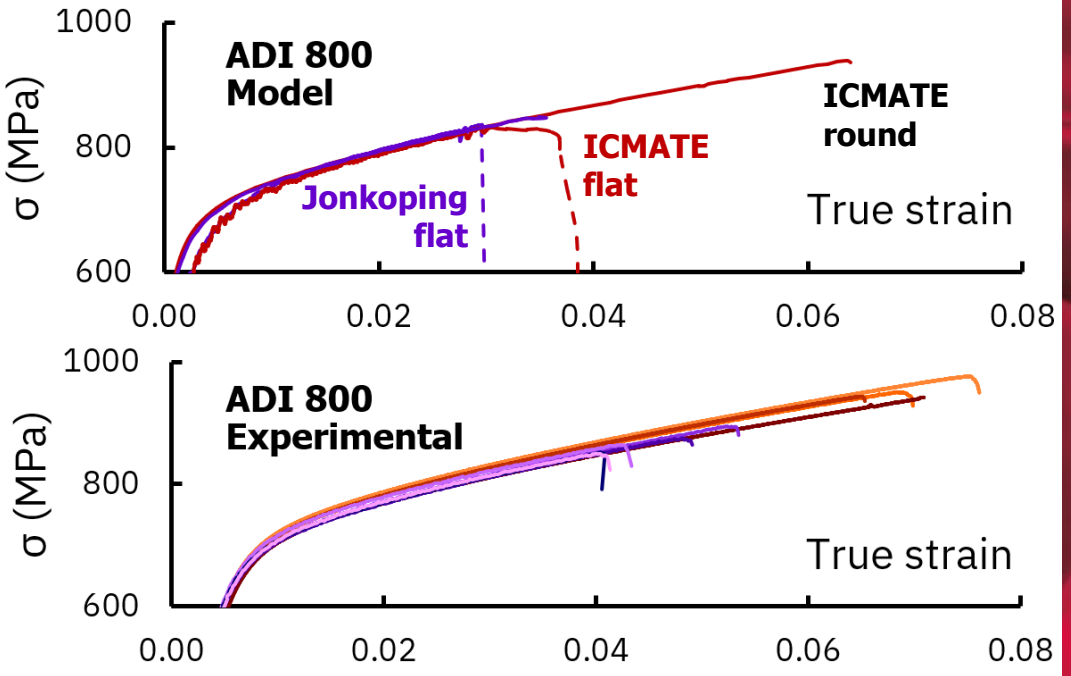
Same specimen geometry, but different gripping system increase stress intensification at the specimen wings in Jonkoping configuration: shorter elongations in Jonkoping flat specimens.

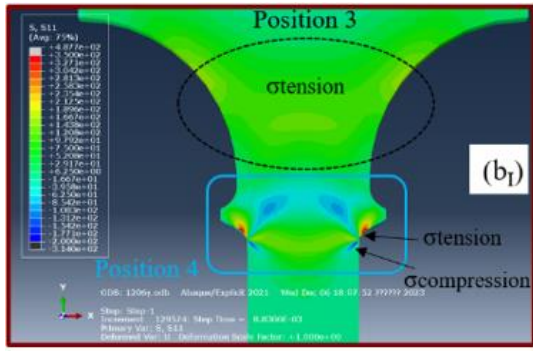
FEM does not show any effect on strain hardening rates.

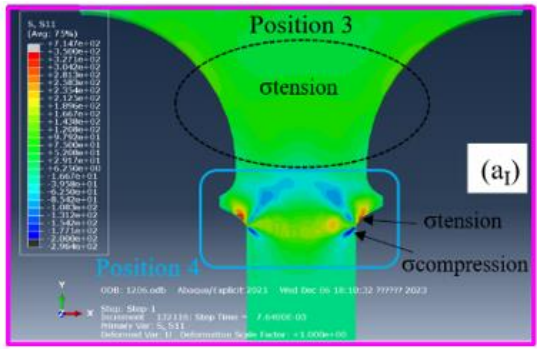
F.E.M. MODEL →

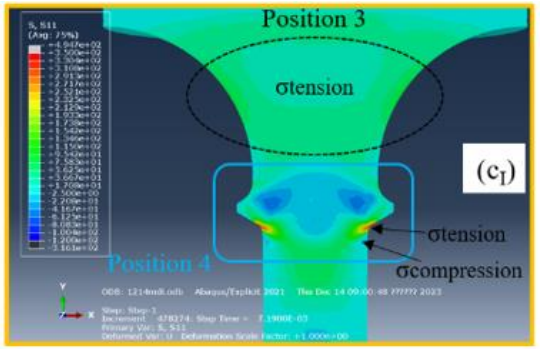


Jonkoping ICMATE









Jonkoping flat HIGHER STRESS INTENSIFICATIONS

Influence of tensile system

- Tensile specimen geometries and gripping systems **affect ADIs tensile behaviour**
- The different tensile specimen geometries and gripping systems **do not affect per se the tensile properties of materials** (HSi 4.2%wt.)
- Comparison between ADIs tensile properties (thick- and thin-walled components) to be carried out with the same (flat) tensile specimens geometries
- Tensile specimen geometries and gripping systems seem to affect the **austenite stability** triggering austenite-to-martensite transformation of ADIs.

Thanks for your attention!