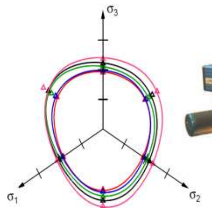
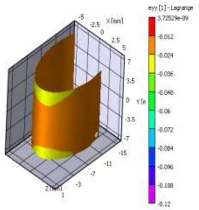
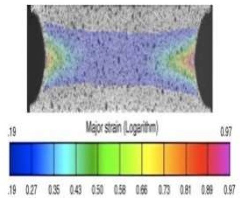
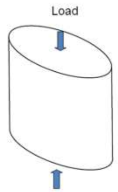
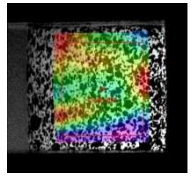
UNIVERSIDAD DE LA FRONTERA
Facultad de Ingeniería y Ciencias









Effect of small strain rate variations on the identification of the compressive behaviour of Ti6Al4V

V. Tuninetti[1], P. Flores[2], C. Medina[2], L. Duchêne[3], A. M. Habraken[3,4]

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[3] *ArGEnCo Department, MSM Team, University of Liège, Belgium, {anne.habraken,l.duchene}@uliege.be*
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14 eme Colloque National en calcul des structures
13-17 mai 2019, Giens (Var), France

Outline

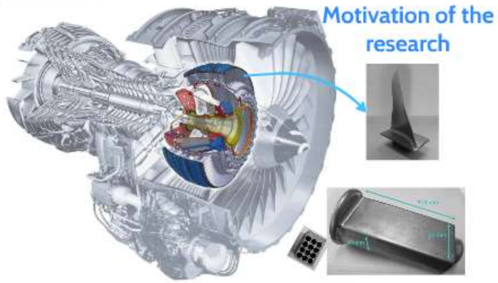
- Introduction
- Method for full range constant strain rate test
- Effect of the strain rate variations on the mechanical behavior of Ti6Al4V
- Validation of the method
- Conclusions and perspectives

Introduction

Chemical and power industries

high flexibility (low modulus)
excellent corrosion and fatigue resistance

Aerospace industry



high strength to weight ratio at low to moderate temperatures

Applications and features of TA6V

Medical industry

good biocompatibility,
excellent corrosion and fatigue resistance

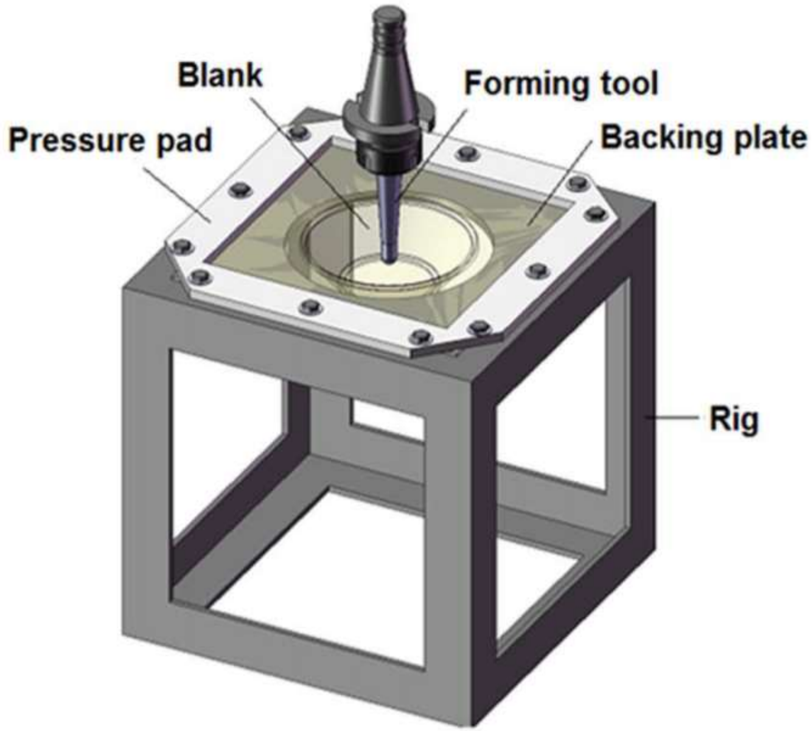
Defense

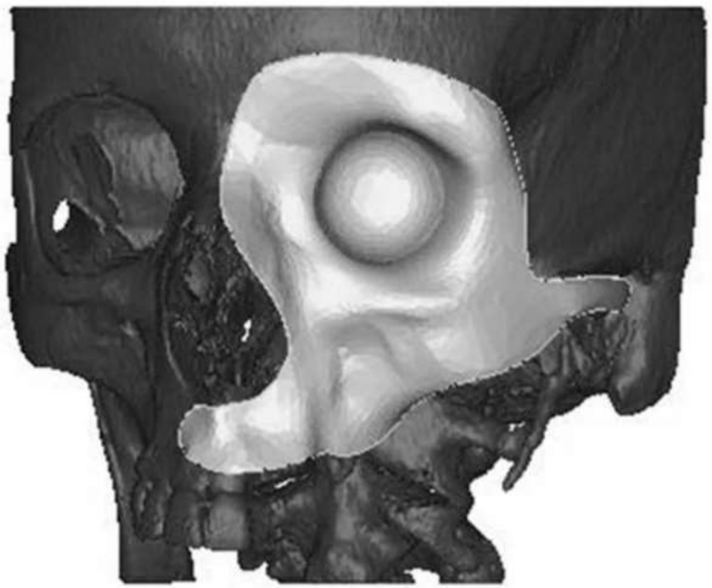
Recreational use

high strength to weight ratio,
good ballistic/impact capability

Introduction

Single Point Incremental Forming for skull implant





Conventional Computer Numerical Control (CNC) milling machine

Why is so important to determine and to model the mechanical behavior of metals and alloys?

- Design and optimization of manufacturing processes of metals with permanent shape deformation
  - e.g. sheet pile

- Estructural integrity of components
  - FBO Engine test

How to determine the mechanical behavior of metals and alloys?

- Mechanical tests:
  - Tensile tests
  - Compression tests
  - Biaxial tests
  - Shear, plane strain
  - Etc.

How to model the mechanical behavior of Ti64 alloy or other metals?

Matematical formulations

Phenomenological laws

- Based on macroscopic observations: load, stress, strain, displacement fields

Physically based laws

- Based on micromechanics: Slip systems, nucleation, viod growth, grain growth, etc.

Modeling of mechanical behavior of materials by using Finite Element Method

Material input data from experiments

Young moduli

Poisson coefficients

Stress strain curves

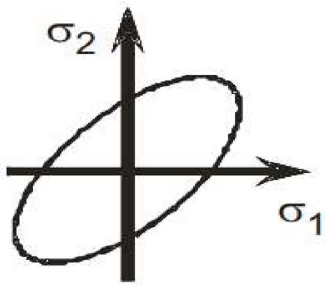
Lankfords (anisotropy)

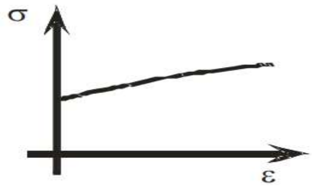
Initial yield points

Strain fields (DIC)

Etc.

Characterization of mathematical models

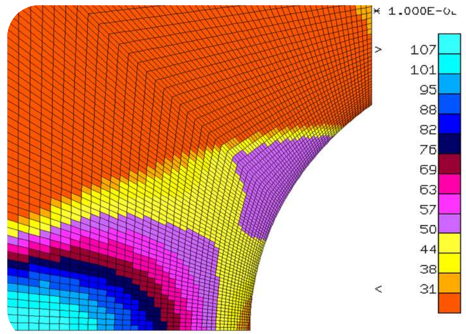


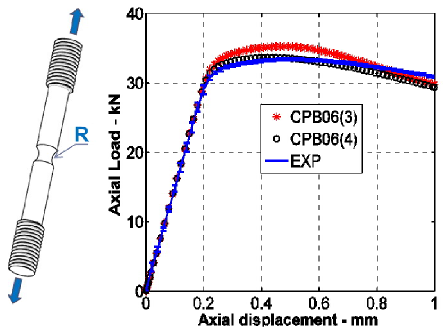


$$F_1 = \left(|\Sigma_1| - k\Sigma_1\right)^a + \left(|\Sigma_2| - k\Sigma_2\right)^a + \left(|\Sigma_3| - k\Sigma_3\right)^a$$

$$\bar{\sigma} = \exp(-P_1\bar{\varepsilon})\sqrt{3}P_2(\sqrt{3}\dot{\bar{\varepsilon}})^{P_3}\,\bar{\varepsilon}^{P_4}$$

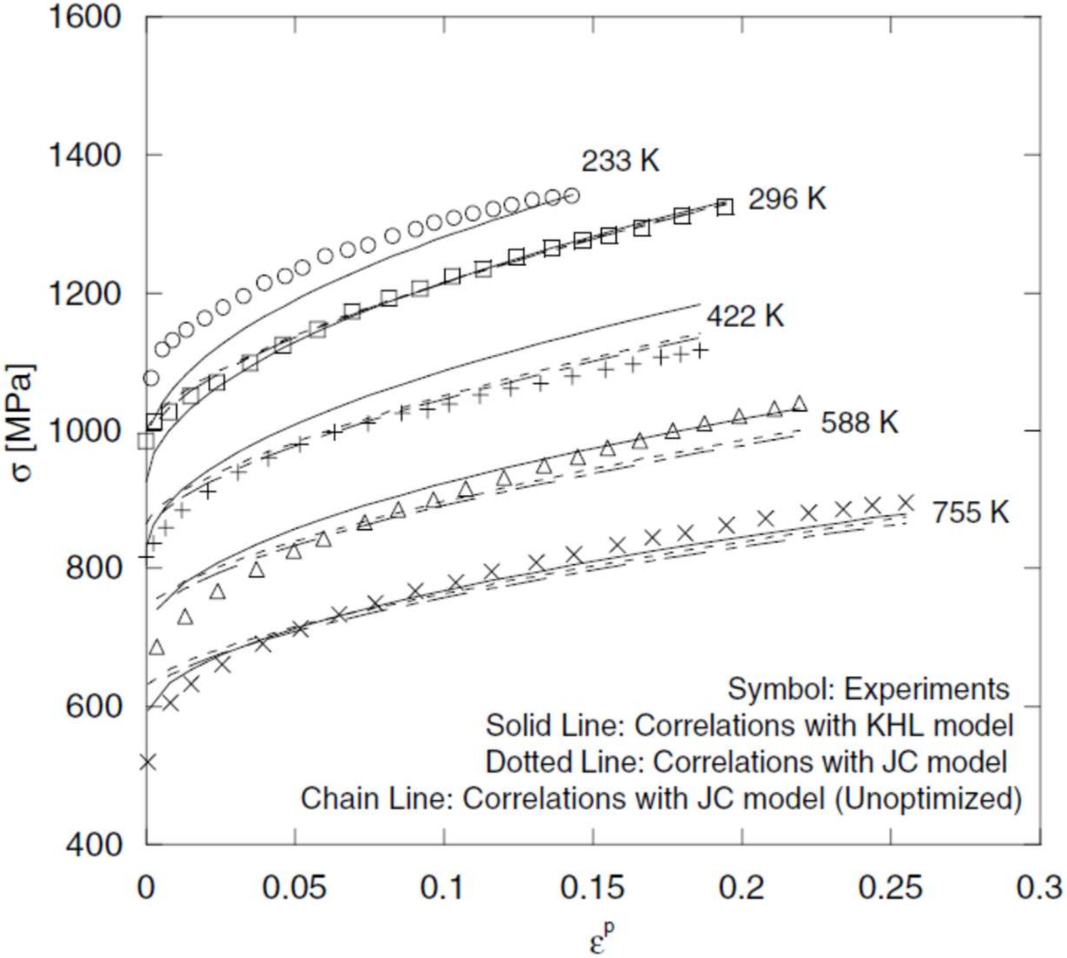
Simulations from Finite Element Software





Introduction
State of the art: experimental observations

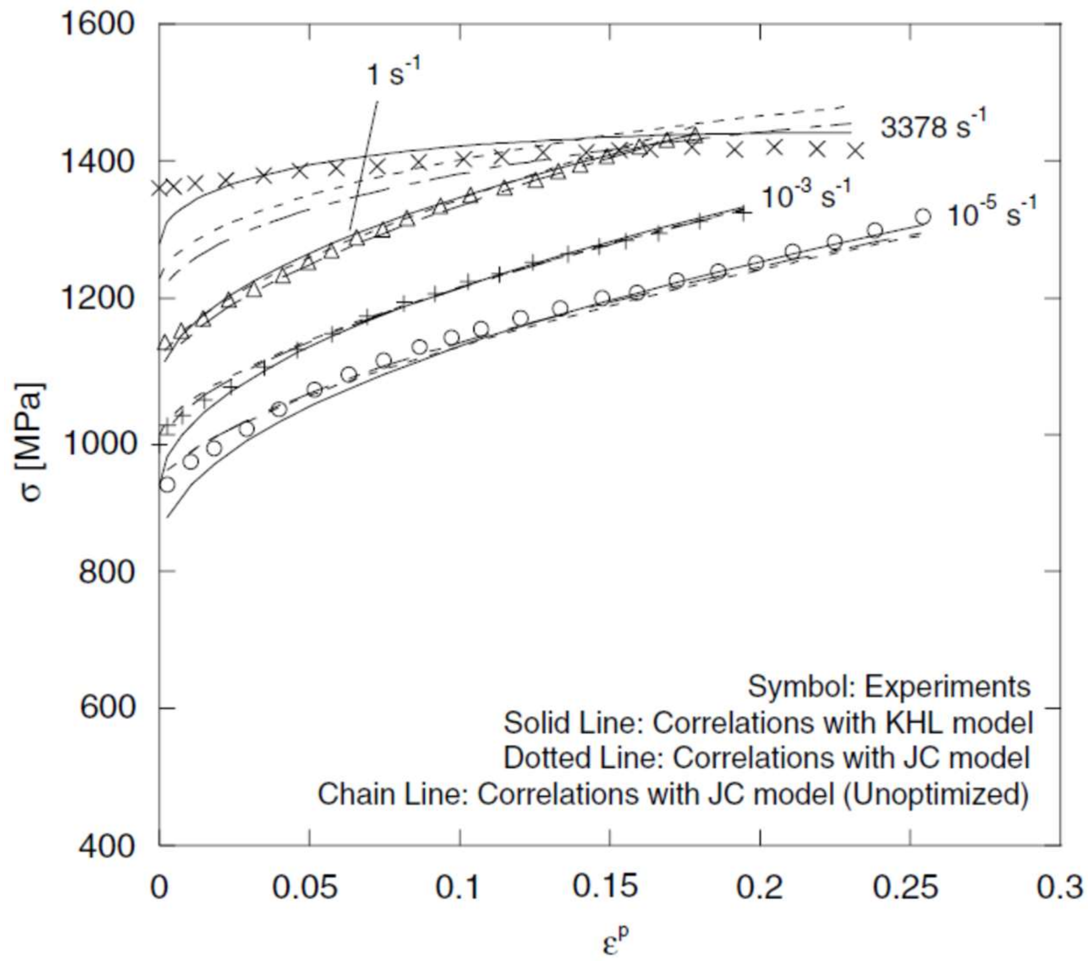
- Temperature dependent



Khan et al., 2004.

Introduction
State of the art: experimental observations

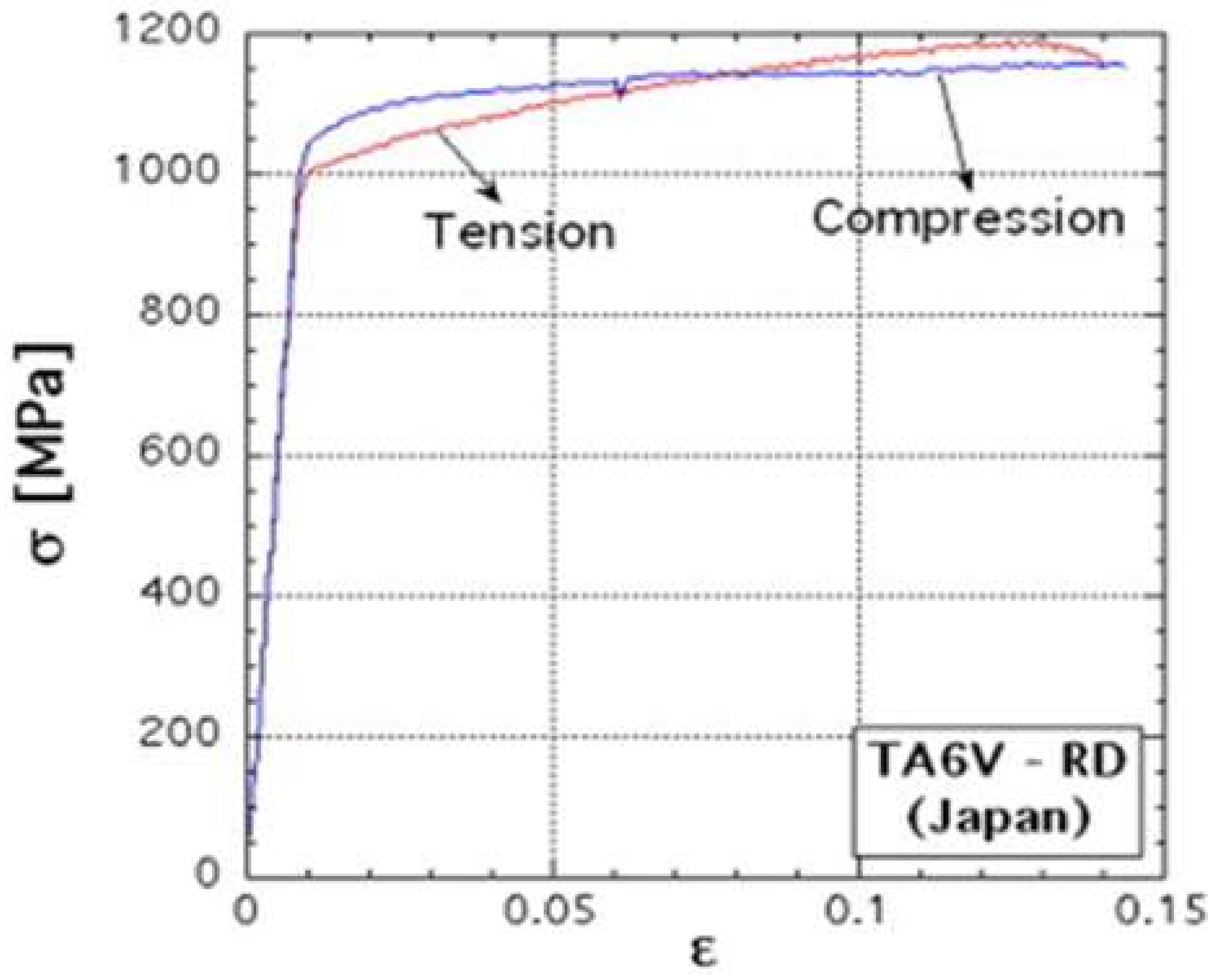
- Strain rate dependent

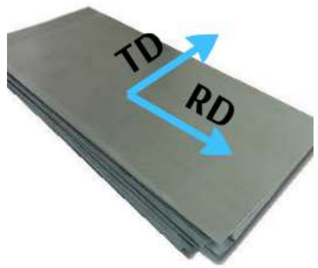


Khan et al., 2004.

Introduction
State of the art: experimental observations

- Anisotropic hardening

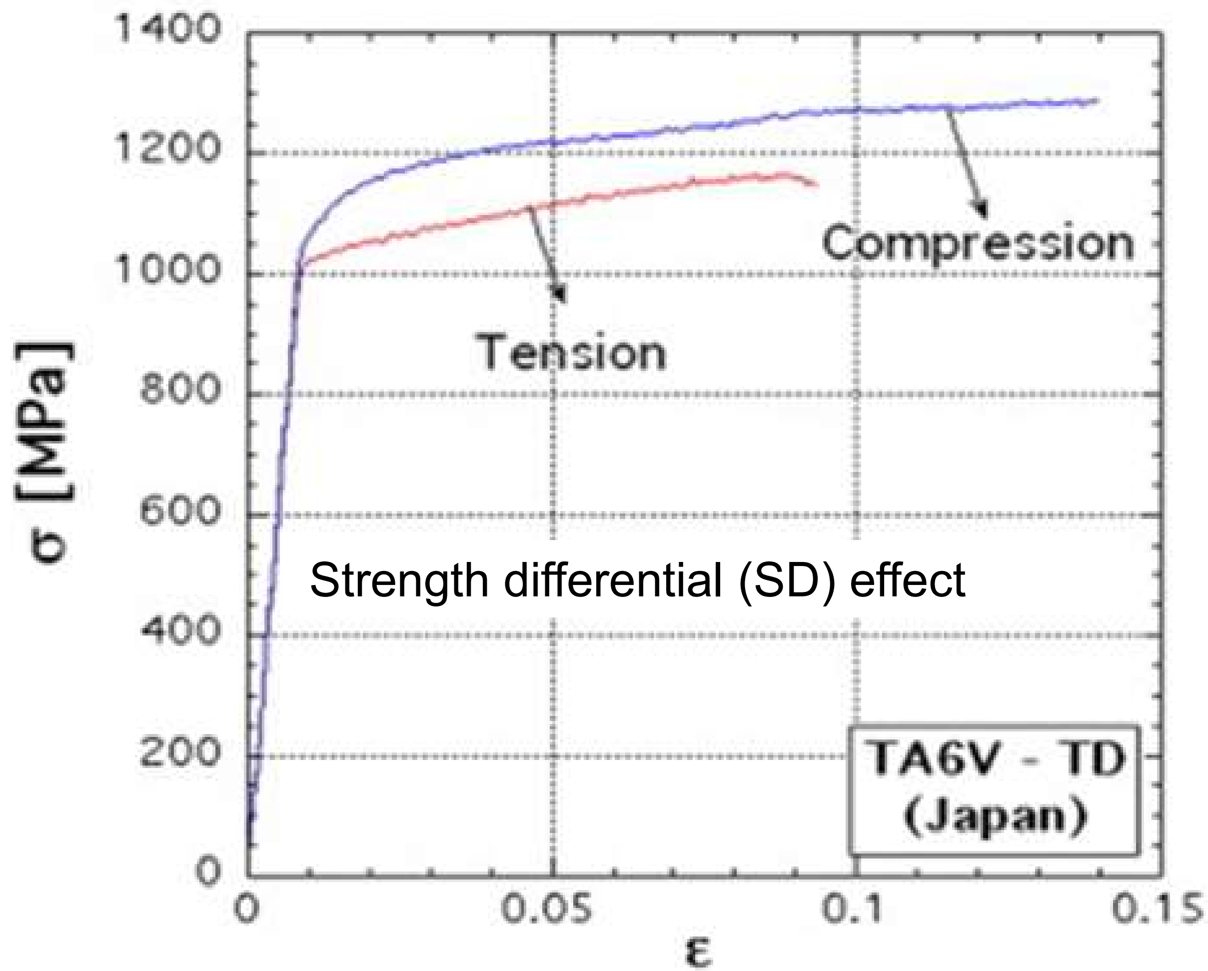


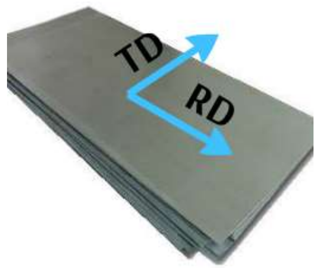


 G. Gilles et al., 2011

Introduction
State of the art: experimental observations

- Tension/compression asymmetry (yielding)

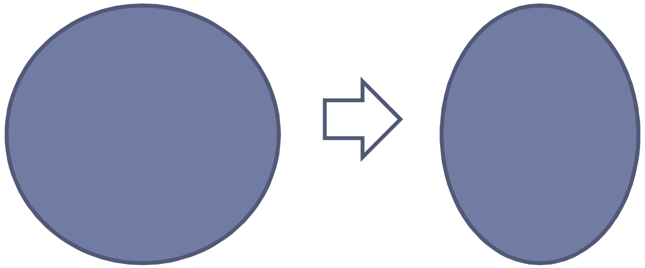




 G. Gilles et al., 2011

Introduction
State of the art: experimental observations

- Plastic anisotropy



Introduction
State of the art: constitutive modeling

- The macroscopic orthotropic yield criterion CPB06*

$$F_1 = \left(|\Sigma_1| - k\,\Sigma_1\right)^a + \left(|\Sigma_2| - k\,\Sigma_2\right)^a + \left(|\Sigma_3| - k\,\Sigma_3\right)^a$$

k takes into account the **strength differential effect** (SD)

a is the degree of homogeneity

$\Sigma_1, \Sigma_2, \Sigma_3$ are the principal values of the tensor $\mathbf{\Sigma} = \mathbf{C} : \mathbf{S}$

$\mathbf{C}$ is a fourth–order orthotropic tensor that accounts for the **plastic anisotropy**

$\mathbf{S}$ is the deviator of the Cauchy stress tensor

$$\mathbf{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix}$$

CPB06 Implemented in the Lagamine code by G. Gilles

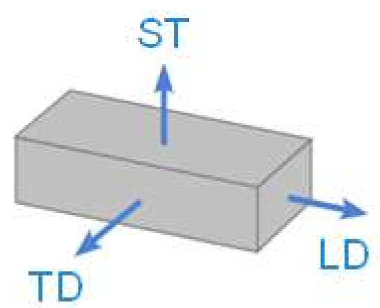
* Cazacu et al., 2006

Introduction

- Identification of the constitutive model

1. Anisotropic elasto-plastic model

- Yield criterion?
  Orthotropic CPB06 characterized at several plastic work levels, temperatures and at 10^{-3} s^{-1}
- Hardening law?
  Directional hardening: interpolation between the several yield surfaces of CPB06
- Experimental tests required for the identification:
  - **Tension** LD (several temperatures), TD and ST directions
  - **Compression** LD (several temperatures), TD and ST directions
  - **Plane strain** LD direction (plane LD-ST)
  - **Shear strain** ST direction (plane LD-ST)



Outline

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- Experimental results
- Validation of the method
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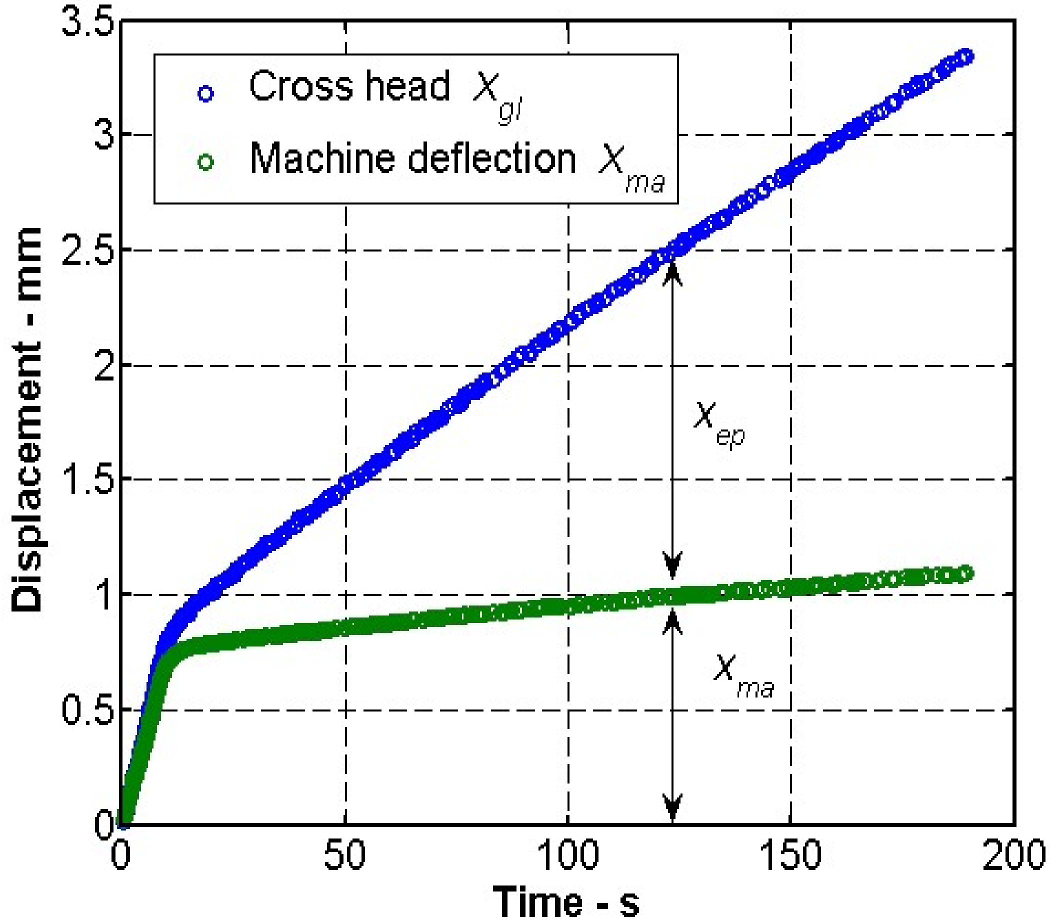
Experimental developments
Implementation of tests at constant strain rate

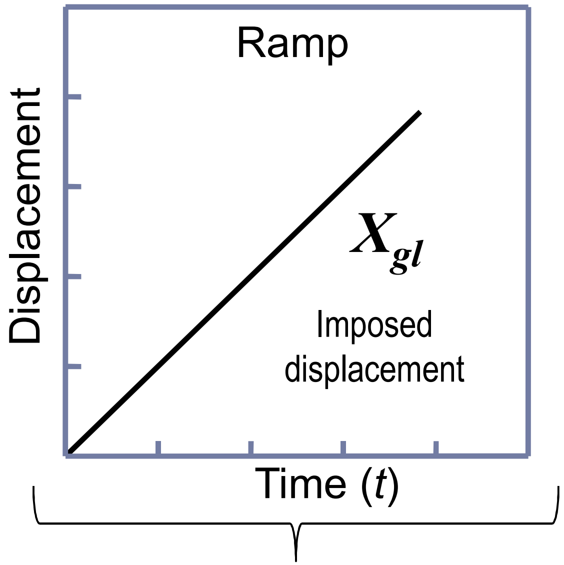
- **Machine vs specimen deformation durinf compression test**

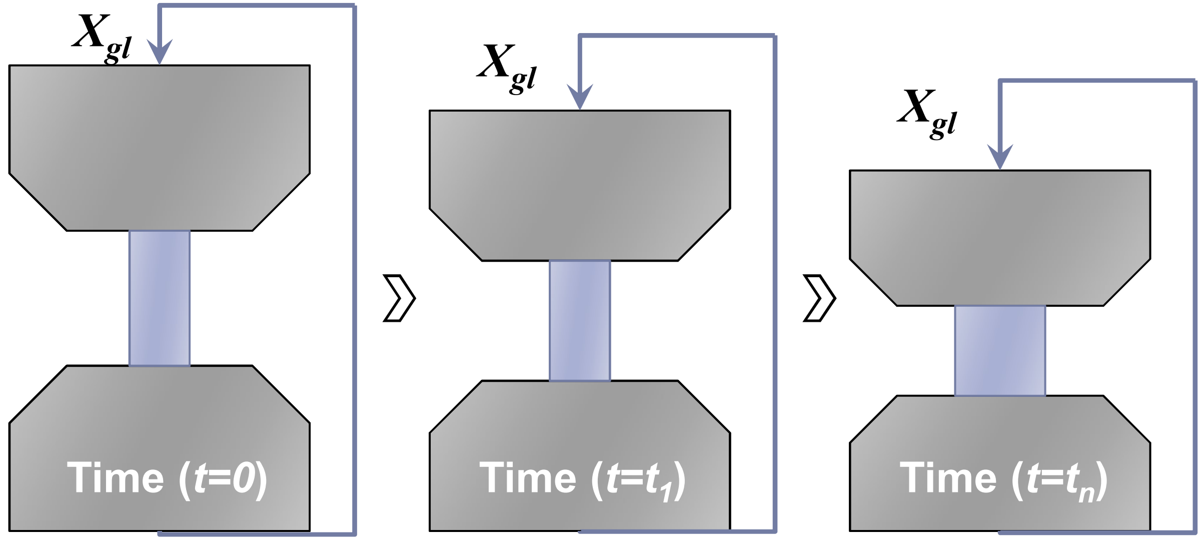


SCHENCK Hydropuls 400 kN press

Experimental developments
Implementation of tests at constant strain rate

- **Tests at constant die speed** (former method at MSM lab)



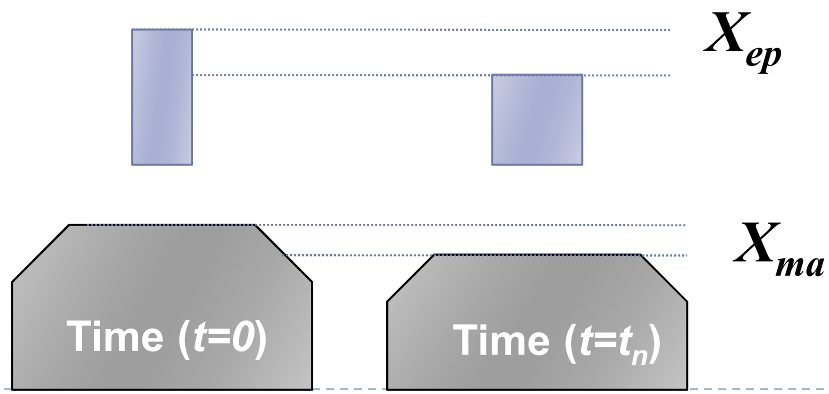


=

Deformation of the specimen
(Unknown)

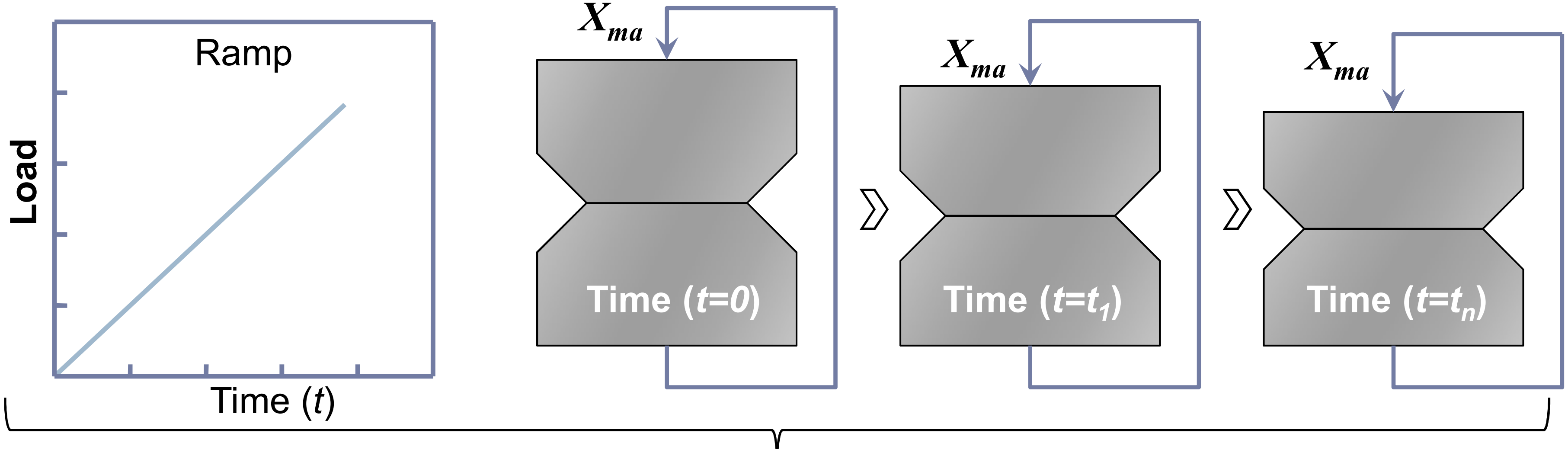
+

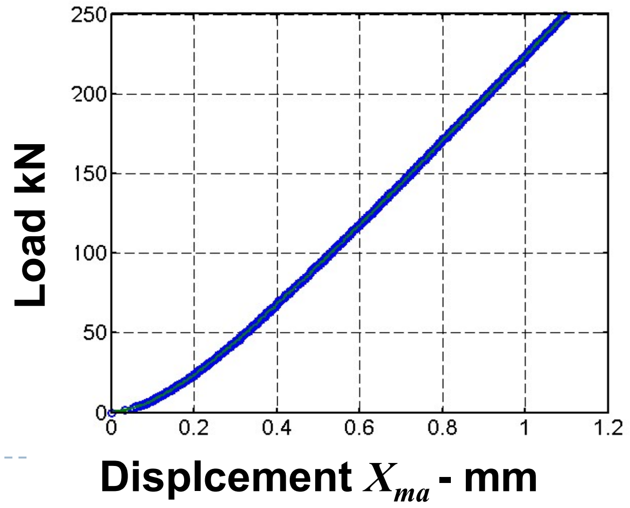
Deflection of the machine
(Unknown)



Experimental developments
Implementation of tests at constant strain rate

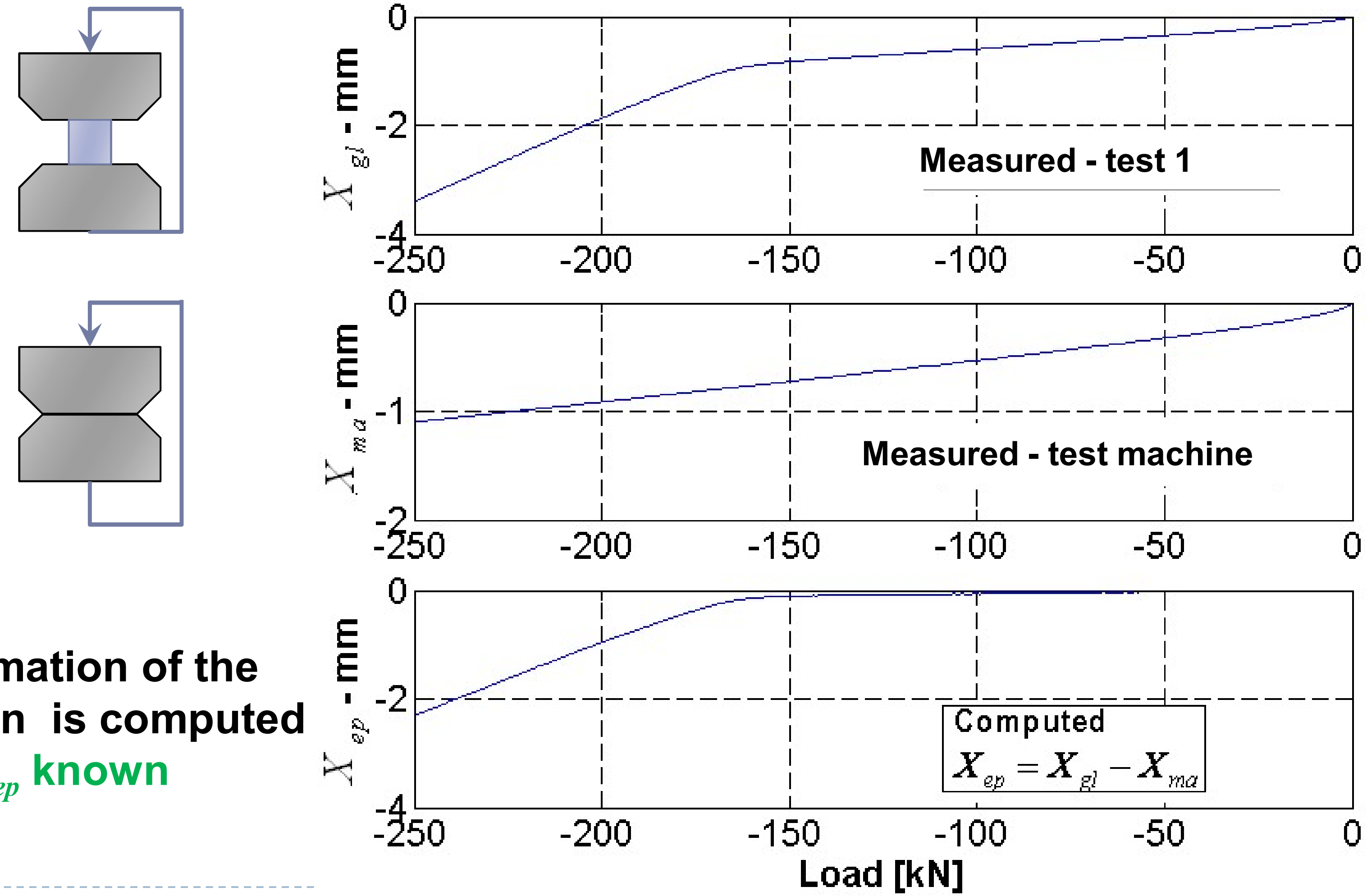
- Deflection of the machine (test without specimen)





Experimental developments
Implementation of tests at constant strain rate

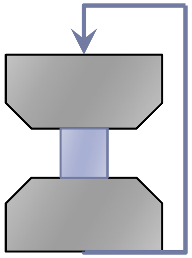
- Computation of the deformation of the specimen



Deformation of the specimen is computed
X_{ep} known

Experimental developments
Implementation of tests at constant strain rate

- Strain vs time computation

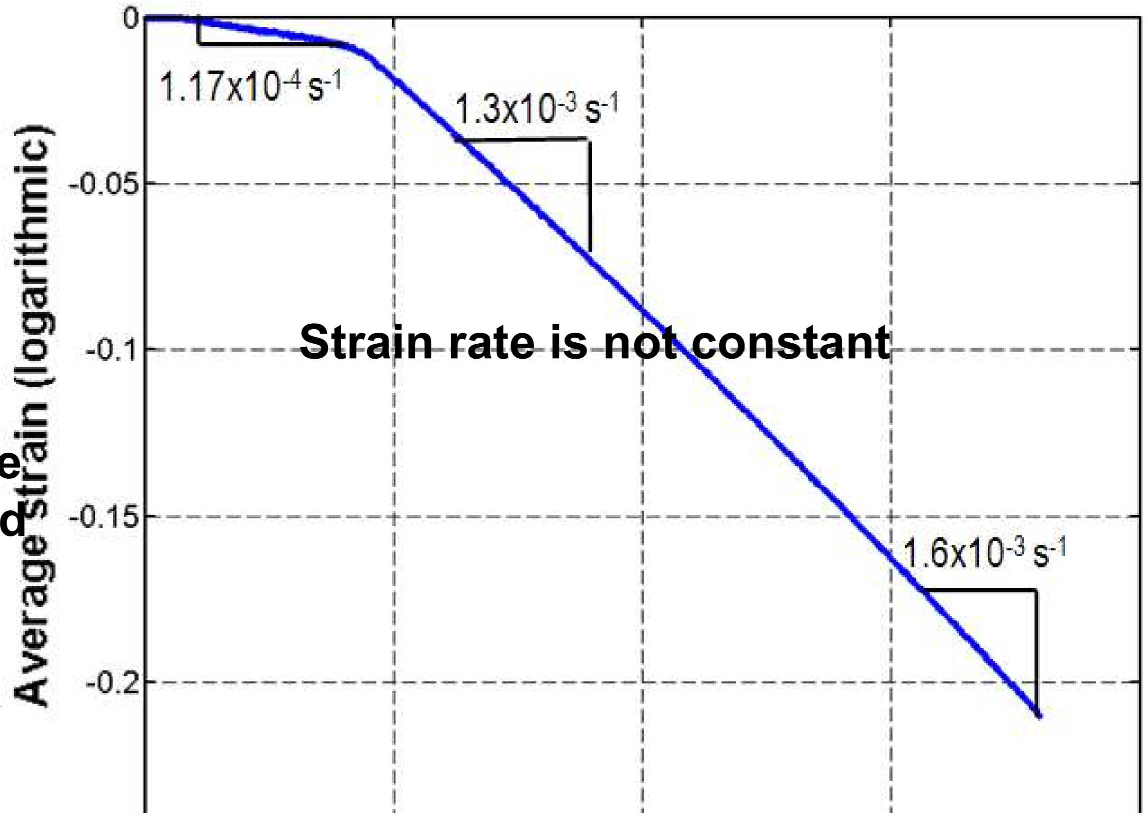


$$\varepsilon(t)=\ln\left(\frac{H_0+X_{ep}(t)}{H_0}\right)$$

H_0 = initial height

Strain evolution on the specimen is computed from X_{ep} known

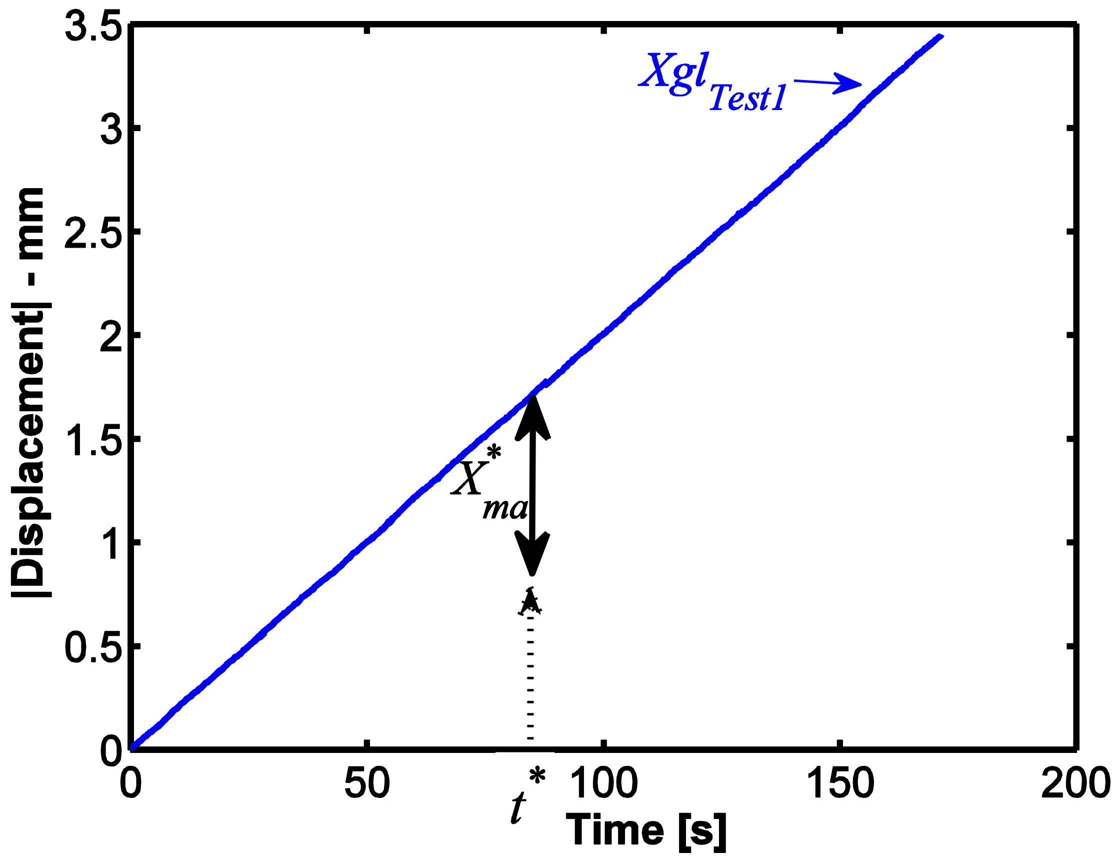
test at constant die speed + machine deflection forgotten



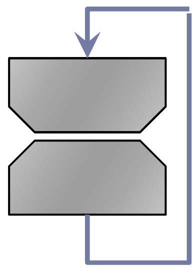
Experimental developments
Implementation of tests at constant strain rate

- At the Time t^* the machine deflection (X^*_{ma}) is known

(for test at constant die speed)



$$X_{ma}(t^*, X_{gl}) = X_{ma}(X_{gl})$$

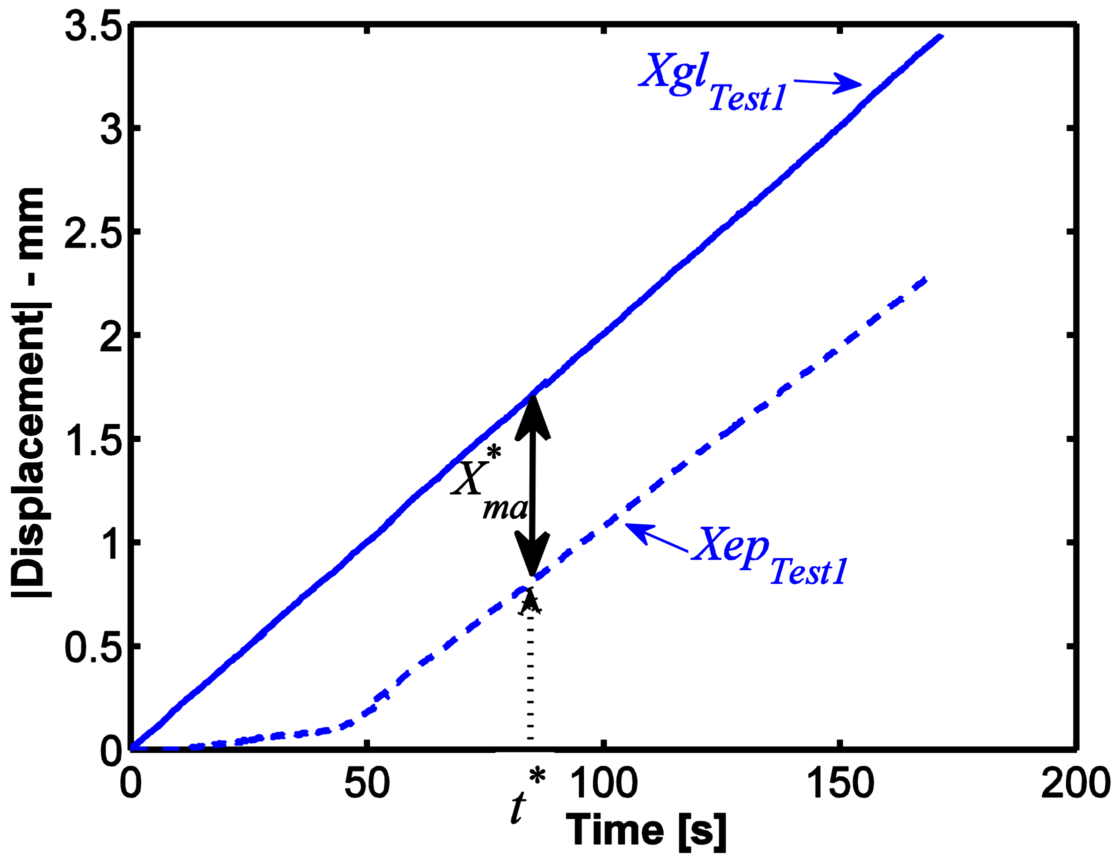


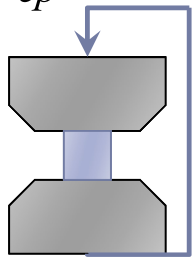
Experimental developments

Implementation of tests at constant strain rate

- So we can compute the deformation of the specimen (X_{ep})

(for test at constant die speed)



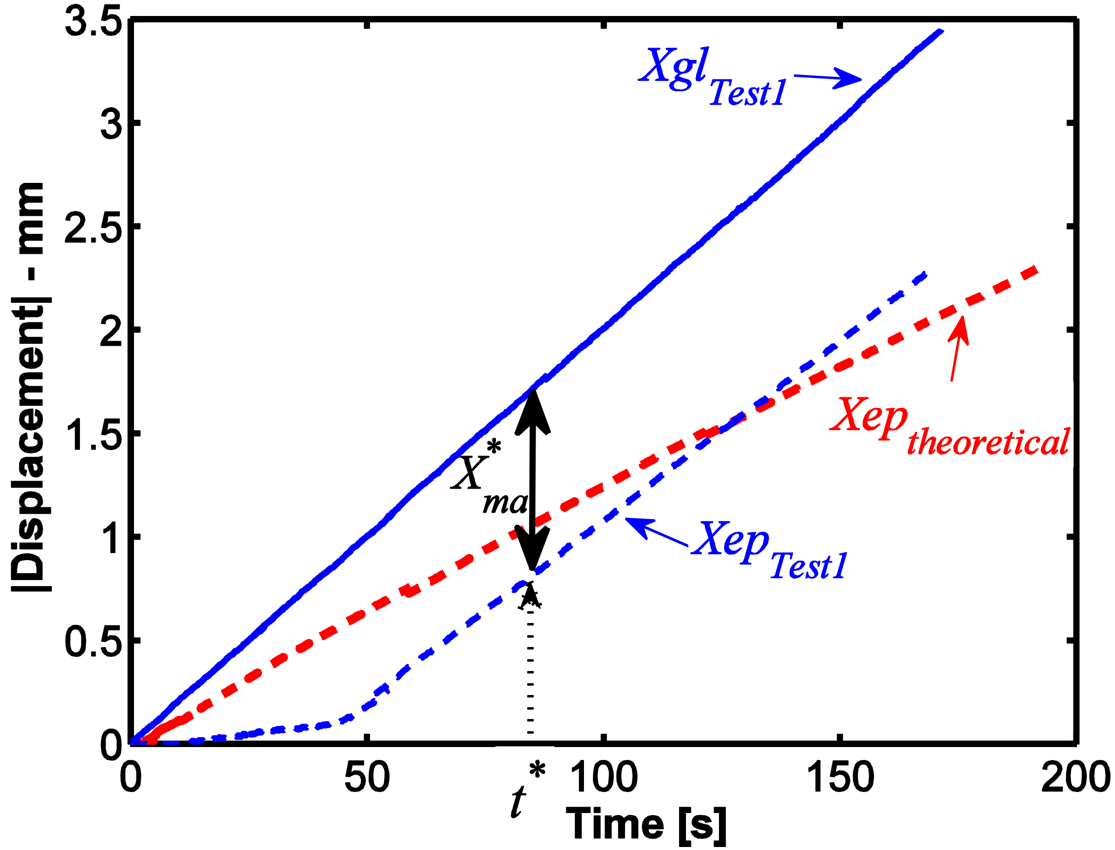


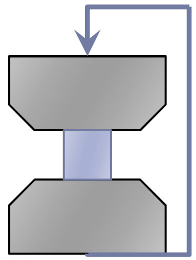
$$X_{ep\text{Test1}}(t) = X_{gl\text{Test1}}(t) - X_{ma}(t)$$

Experimental developments
Implementation of tests at constant strain rate

- Also, theoretically we know ($X_{ep\ Theoretical}$) for constant strain rate

(for a test at constant strain rate)



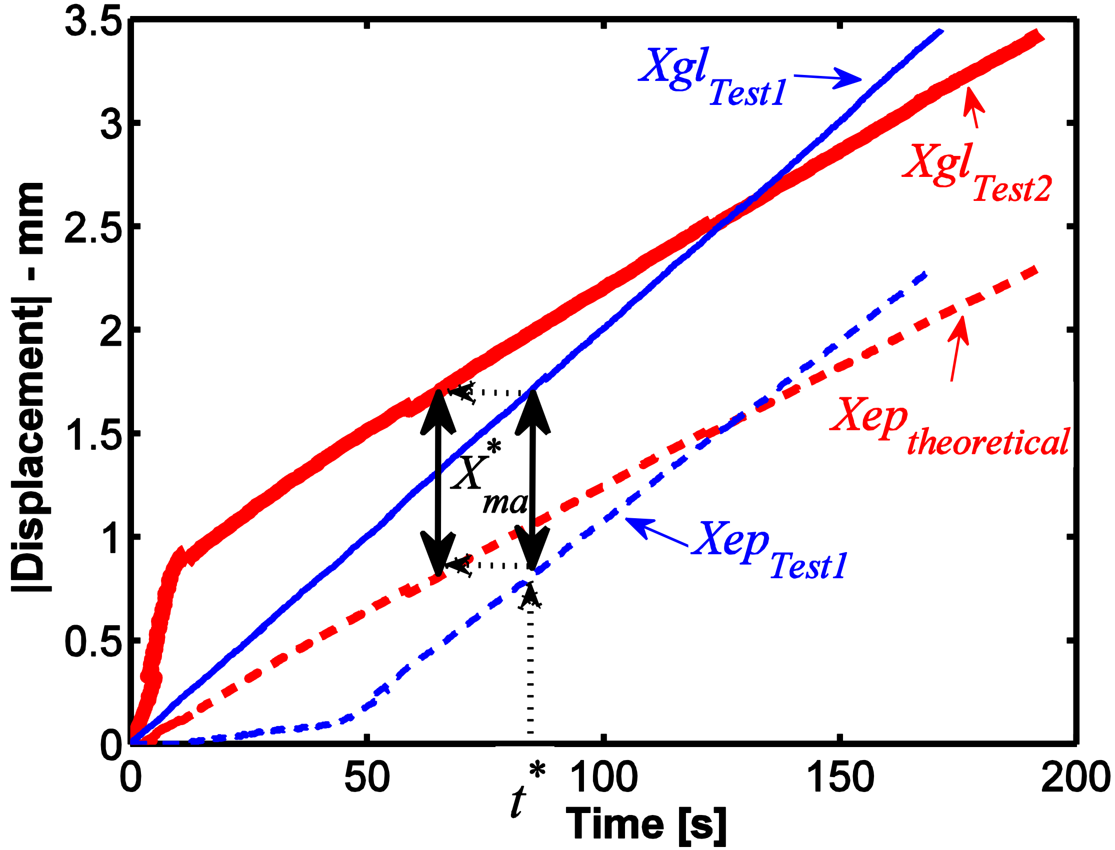


$$X_{ep}(t) = H_0(\exp(\dot{\varepsilon}\, t) - 1)$$

Experimental developments
Implementation of tests at constant strain rate

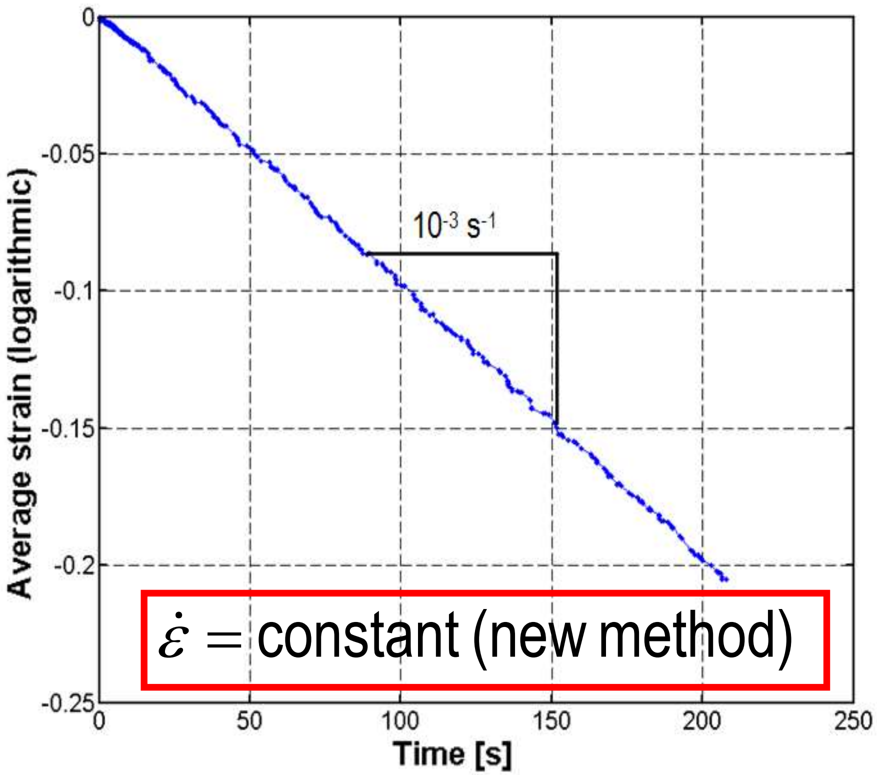
- Globlal displacement $X_{gl\ Test\ 1}$ is computed

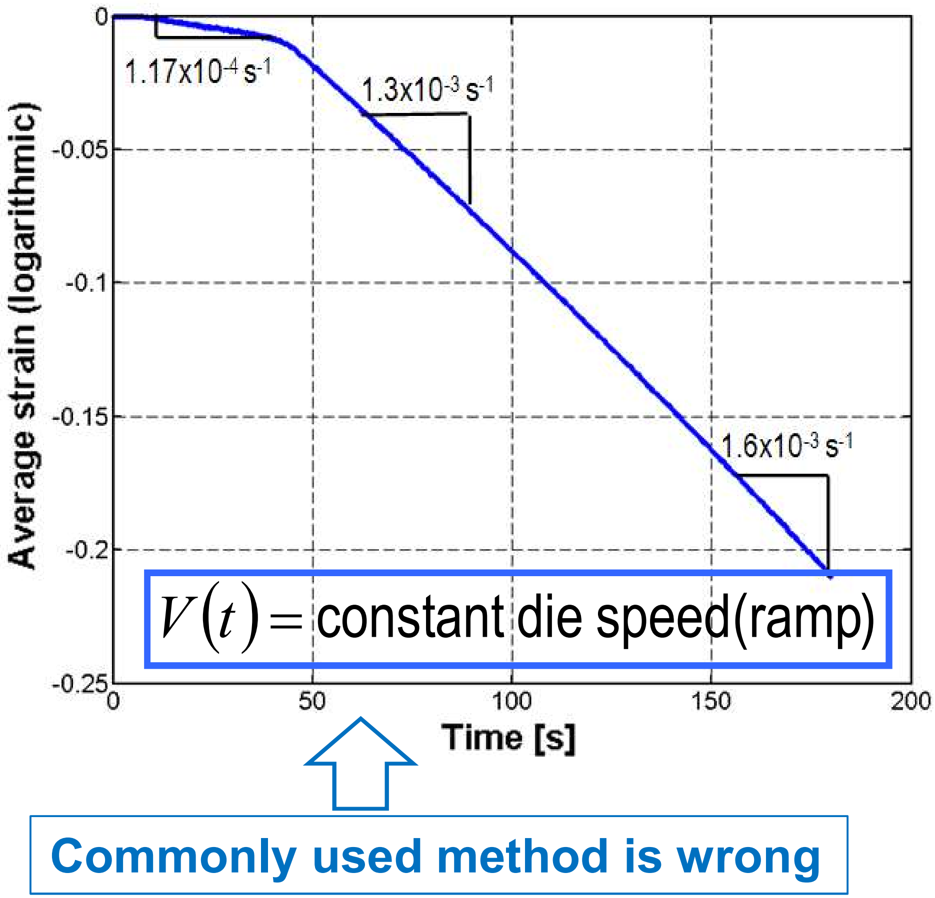
(for the second test at constant strain rate)



Experimental developments
Implementation of tests at constant strain rate

- Comparison constant and non-constant strain rate tests





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Experimental developments
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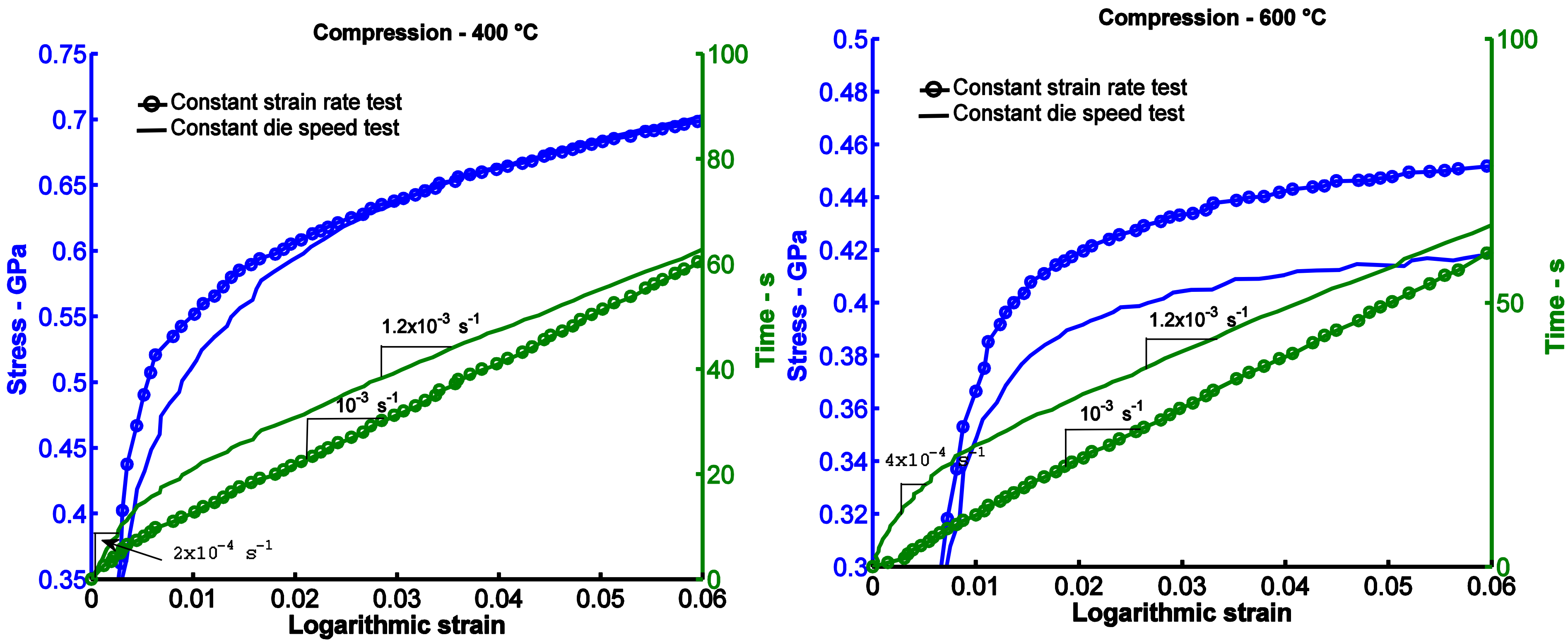
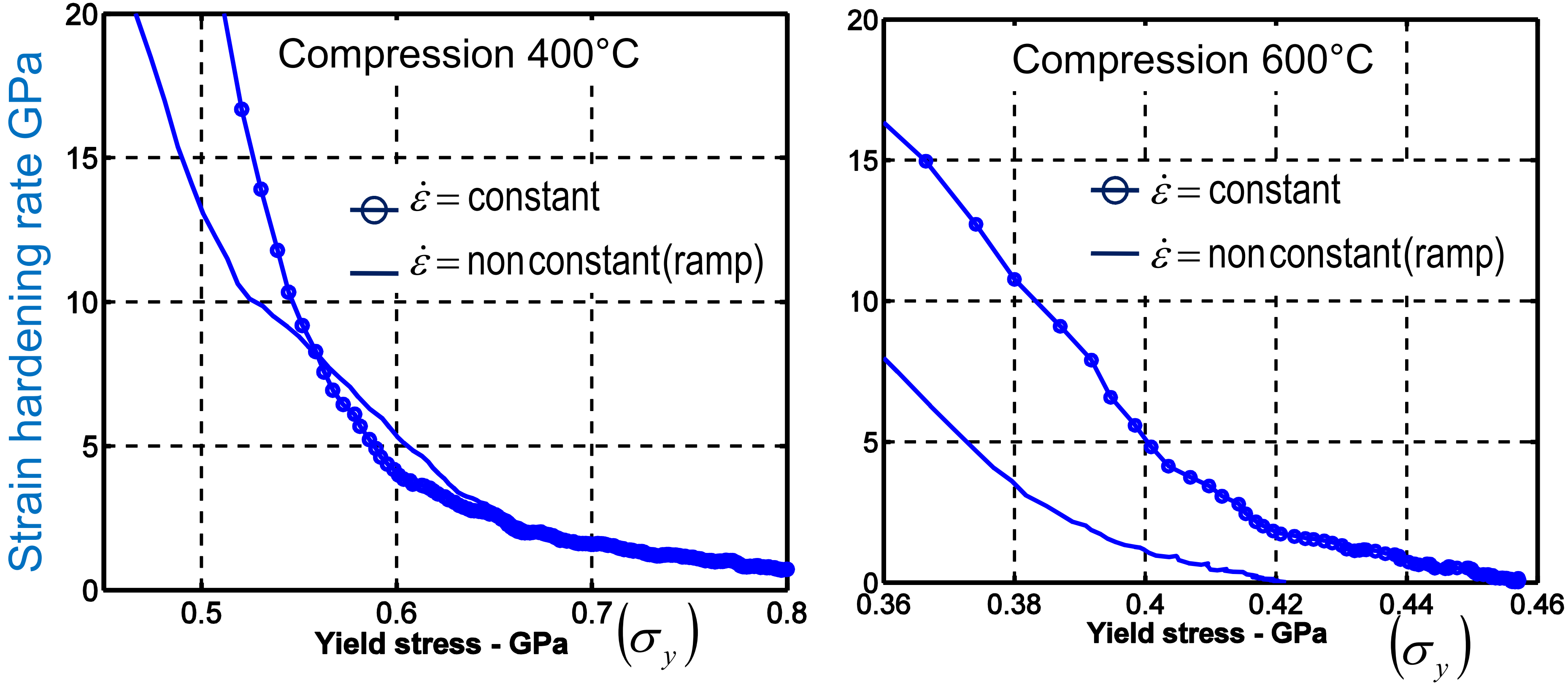
- Comparison constant and non-constant strain rate tests



Experimental developments
Implementation of tests at constant strain rate

- Important for strain hardening rate



strain hardening rate $= \partial\sigma_y / \partial\varepsilon_y^p$

Outline

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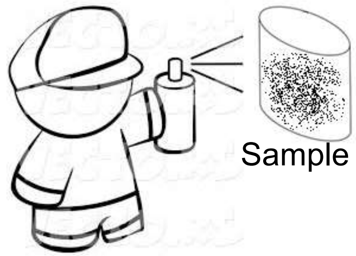
Validation of the method
Digital Image Correlation setup

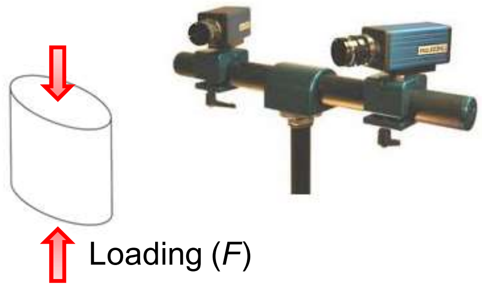
- Basic concept: DIC is measurement technique for full field non-contacting deformation and strain

Step #1: spray paint to the object (speckle pattern)



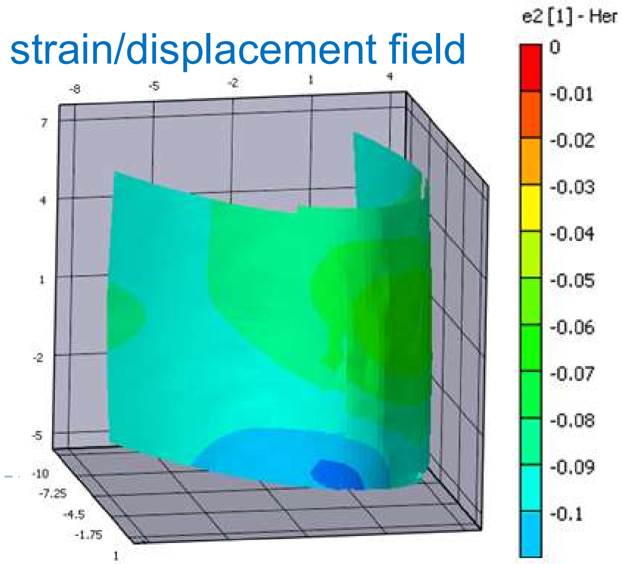
Step #2: calibration of the cameras

Step #3: record images of the event



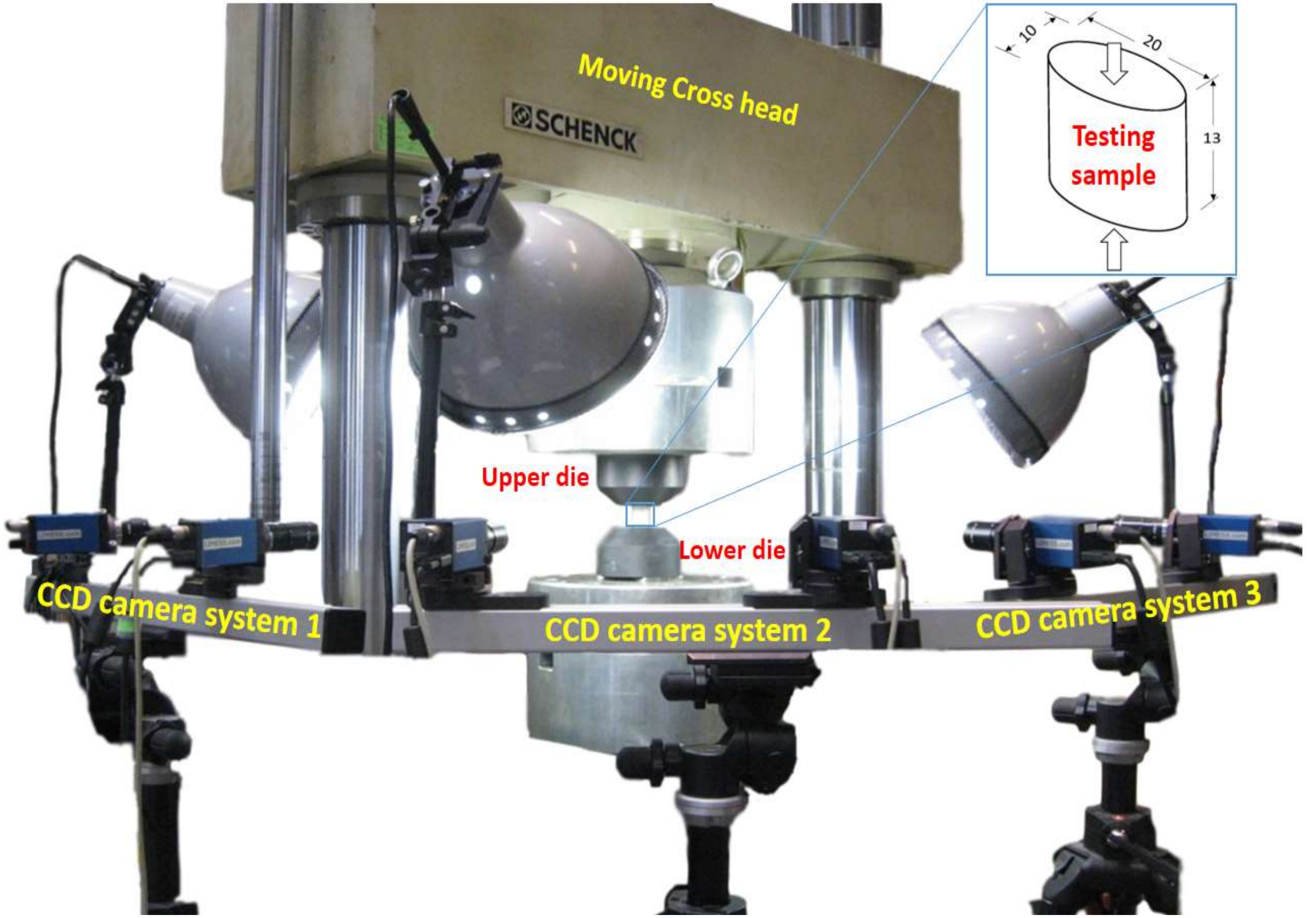
Step #4: apply the correlation method

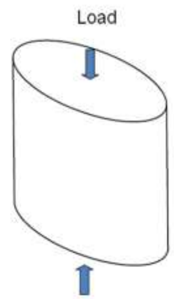
Results: strain/displacement field

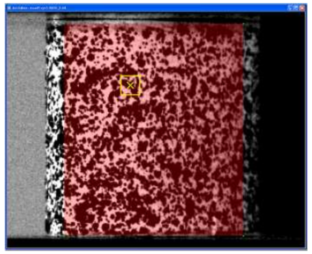


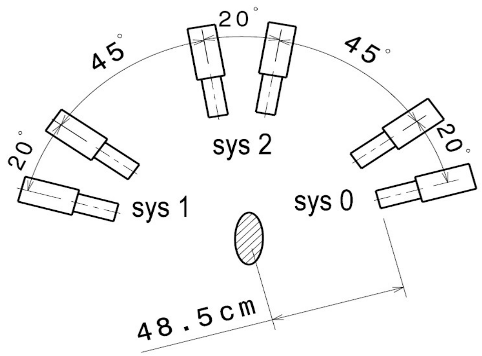
Validation of the method
Digital Image Correlation setup

- 3D-DIC systems configuration



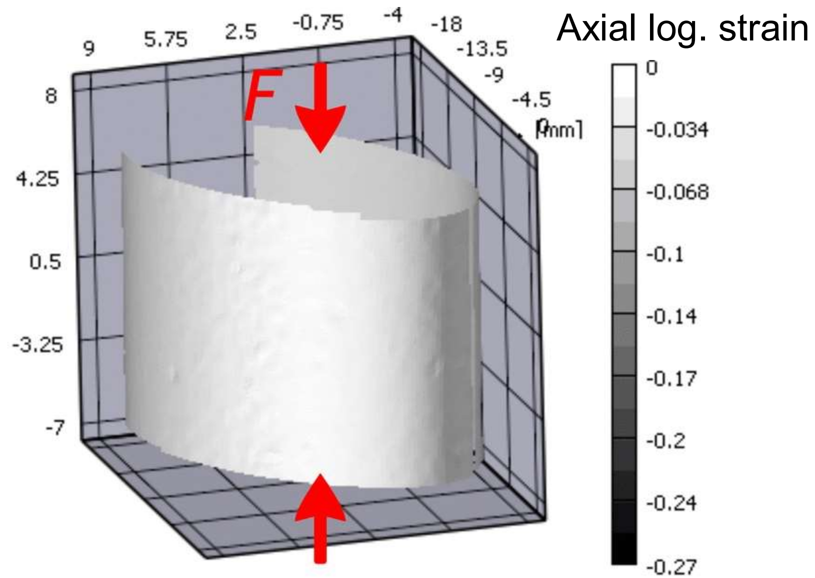


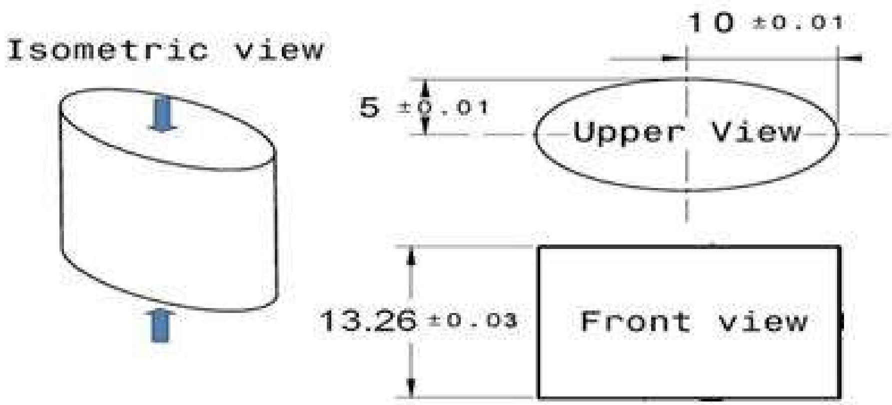




Validation of the method
Strain field by DIC measurements

- Accurate displacement measurements and strain field computations reached

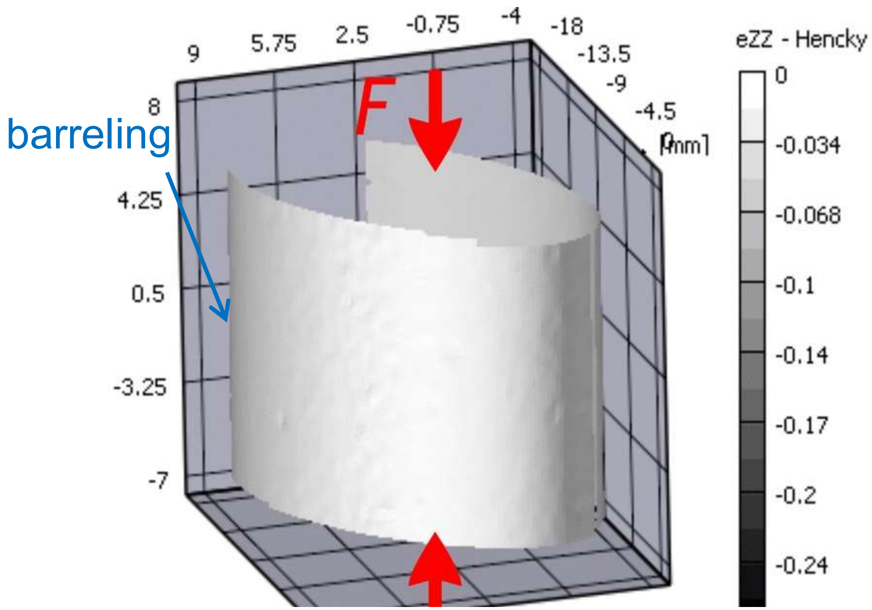


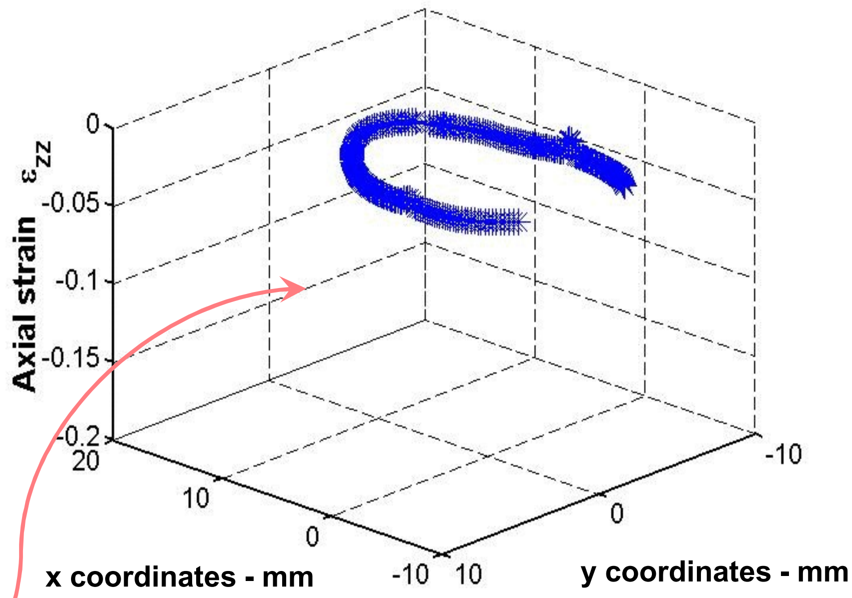


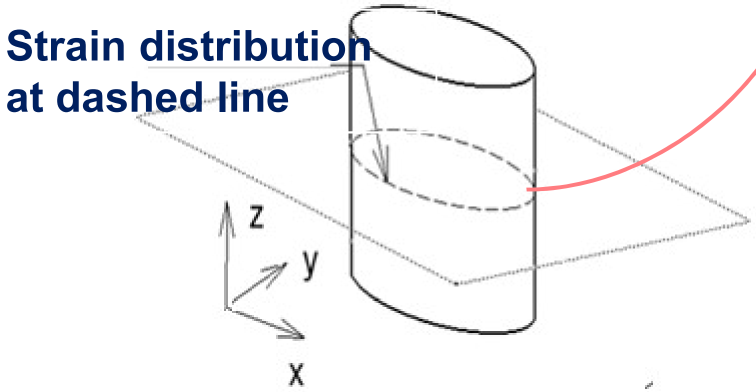
Dimensions in mm

Experimental results at RT

Compression test for plastic anisotropy characterization







Why axial ε_{zz} strain is not homogeneous ?

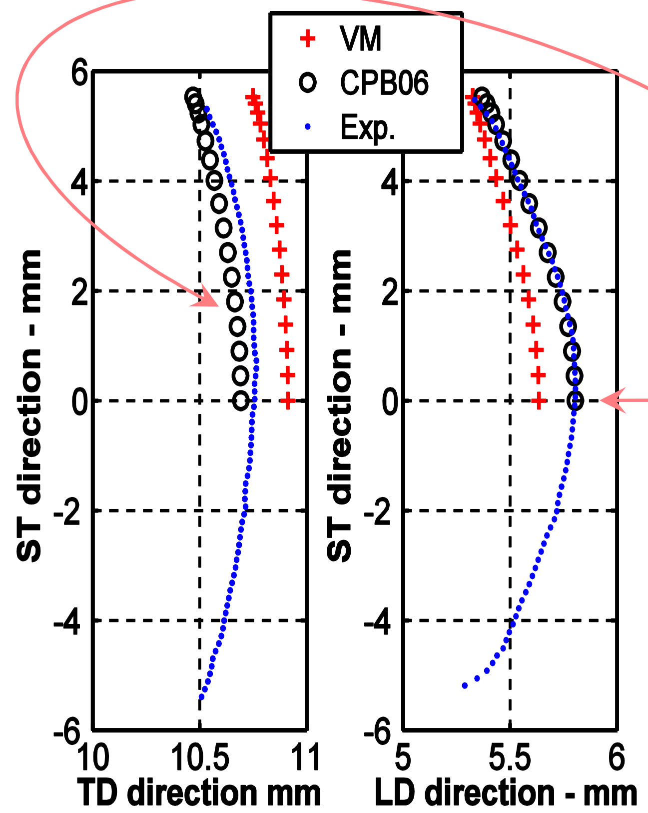
Friction effect?

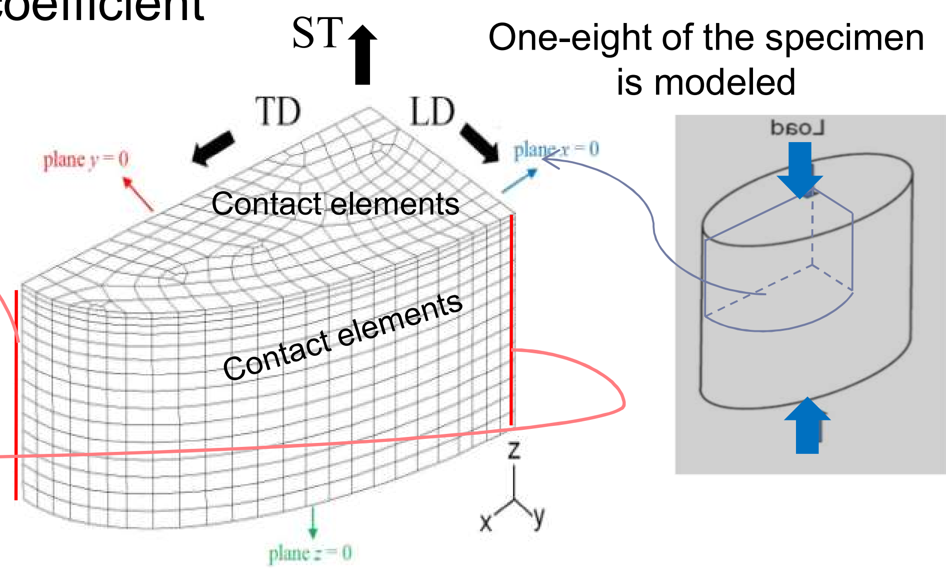
Plastic anisotropy? both ?

Why experimental axial ε_{zz} strain is not homogeneous in compression tests?

- Numerical investigations of compression tests

1. Computation of Coulomb friction coefficient



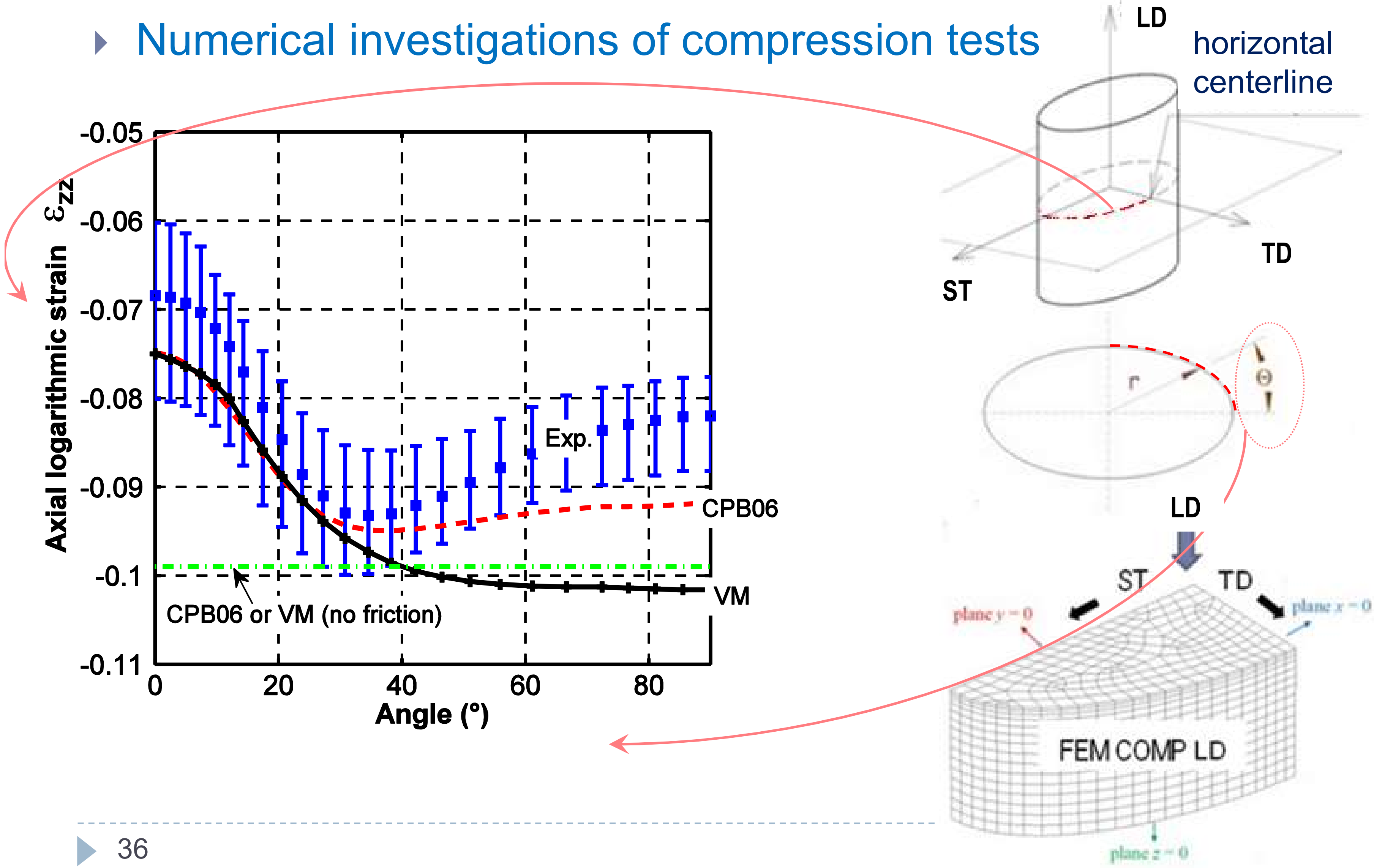


barreling is more sensitive to friction than to anisotropy

- 1st Inverse modeling of compression for computation of $\phi = 0.08$
- Iteration fitting → Load + barreling
- VM identified with compression
- Verification with CPB06(4)

Why experimental axial ε_{zz} strain is not homogeneous in compression tests?

- Numerical investigations of compression tests



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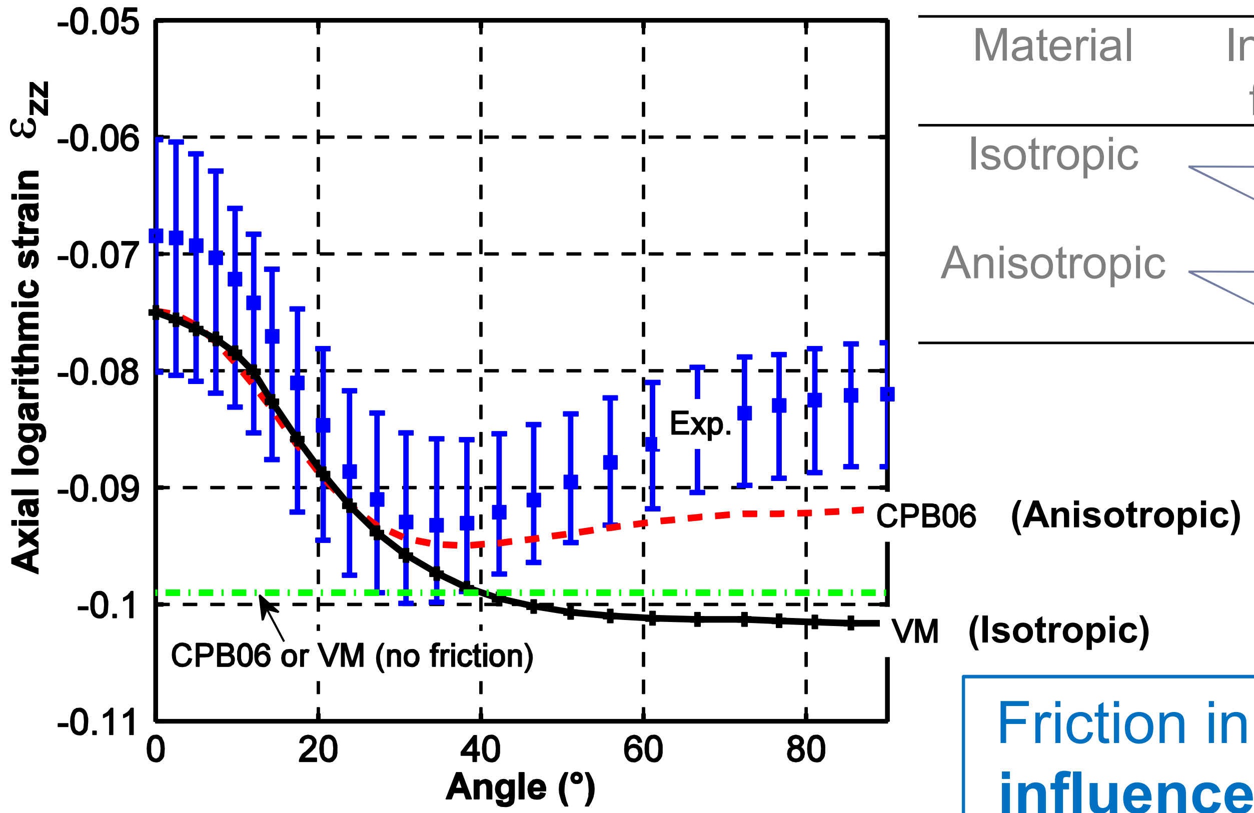
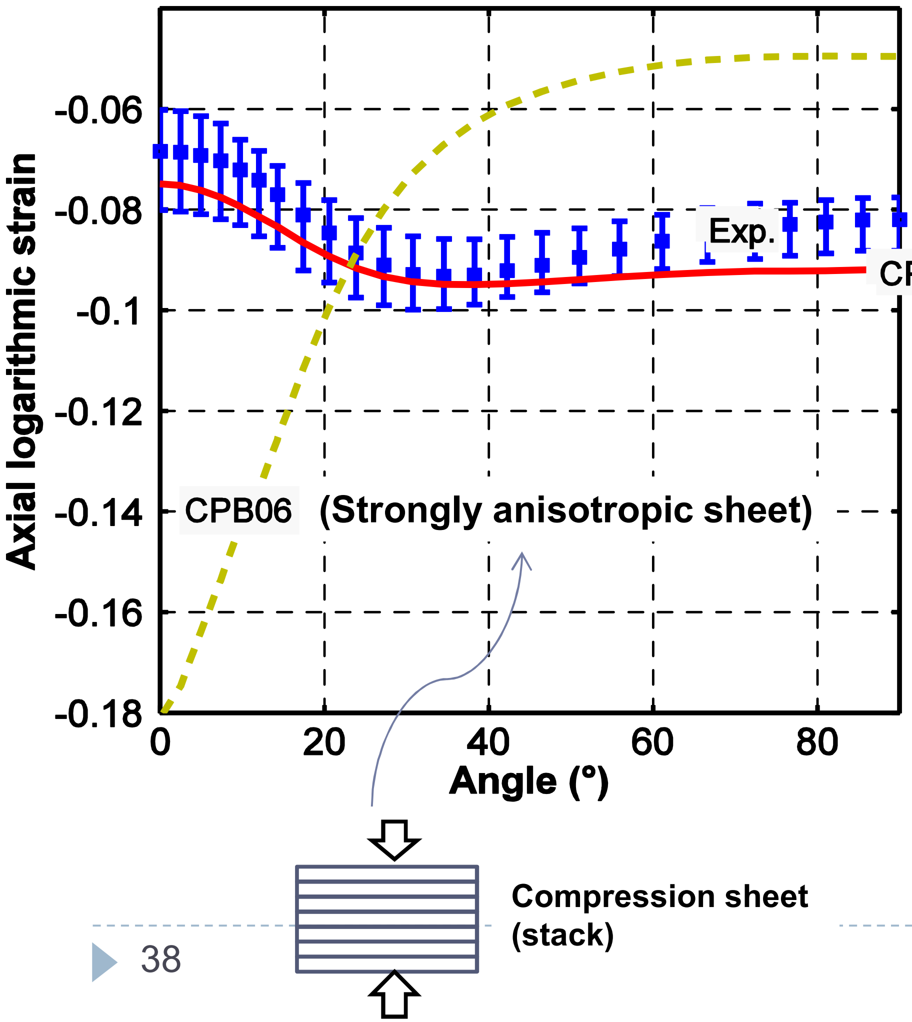


Material	Including friction	Characteristic of strain distribution
Isotropic	Yes	Inhomogeneous
	No	Homogeneous
Anisotropic	Yes	Inhomogeneous
	No	Homogeneous

Friction in compression tests **influences** the homogeneity of the axial strain field

Why experimental axial ε_{zz} strain is not homogeneous in compression tests?

- Numerical investigations of compression tests **with friction**

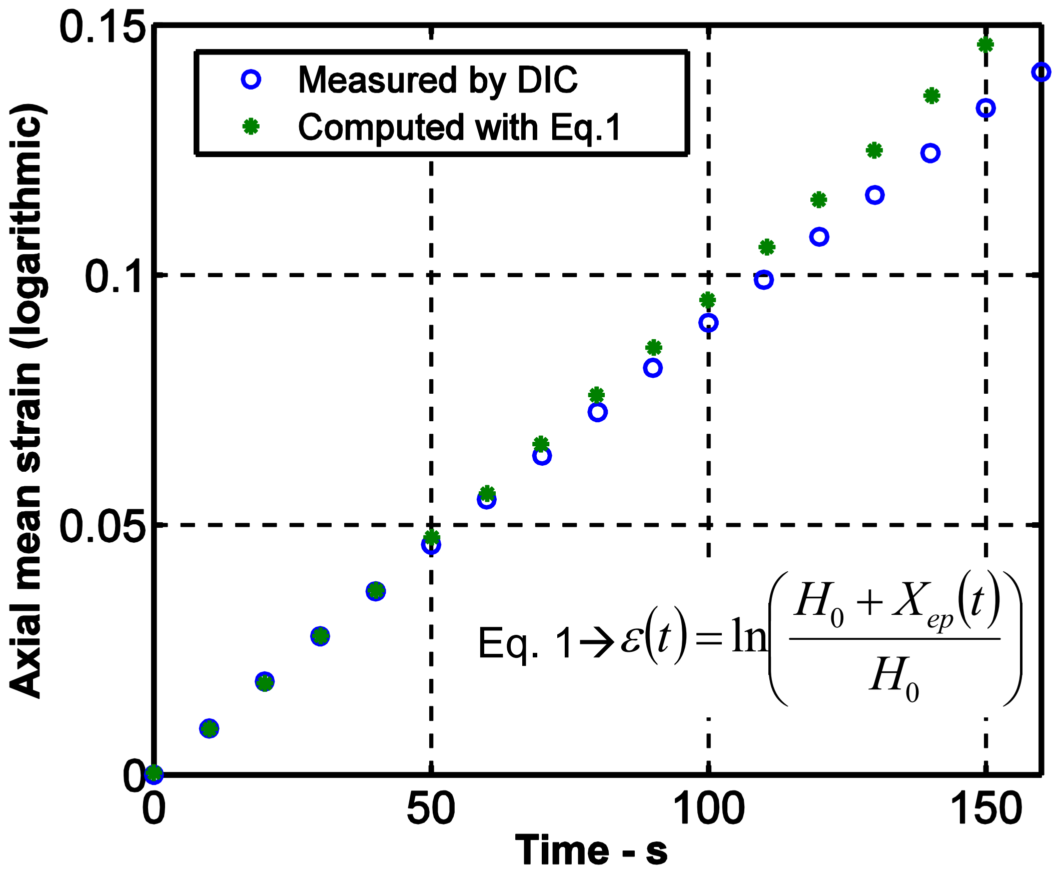


Friction enhances the visualization of the plastic anisotropy through the axial strain field in compression tests

Material	Characteristic of strain distribution
Isotropic →	Weakly inhomogeneous
Anisotropic →	Weakly inhomogeneous (different shape than isotropic)
Strongly anisotropic sheet →	Strongly inhomogeneous

Validation of the method

- Two ways of computing the strain:
  - DIC or volume conservation (Eq. 1)



Validation of the method

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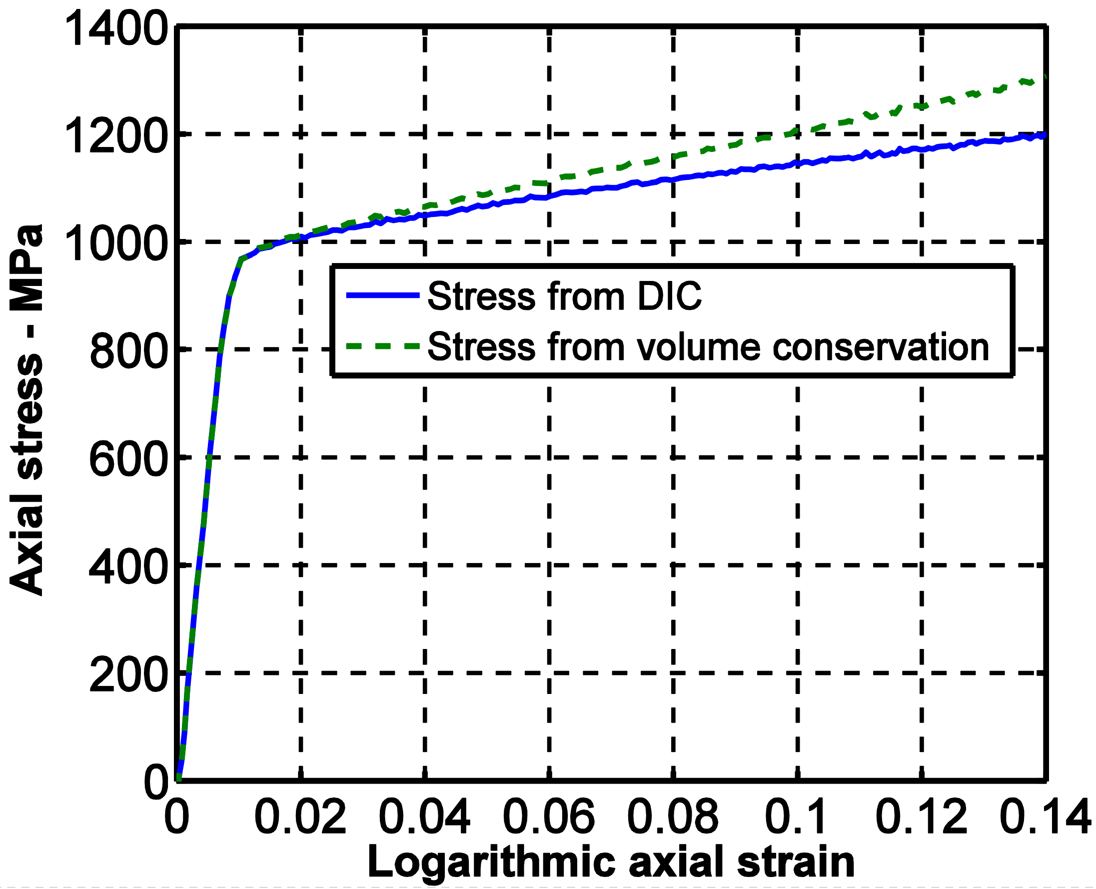

Difference caused by barreling of the sample (friction)

Outline

- Introduction
- Method for full range constant strain rate test
- Effect of the strain rate variations on the mechanical behavior of Ti6Al4V
- Validation of the method
- Conclusions and perspectives

Conclusions and perspectives

- Method for compression and tension tests at constant strain rates using testing machine without PID control
- Validation by two method, Volume conservation and DIC measurements at RT by measuring the full strain field of the sample during testing
- Effect of the strain rate variations on the mechanical behavior of Ti6Al4V
  - Mainly initial yield point
  - Stress hardening rate
- Axial strain sensitivity to the plastic anisotropy proposed for inverse identification