Evolution of the solidification structure during hot forming

Identification – characterization and modelling

Laurent LANGLOIS

Context

- Manufacturing route of a bar

Image SIFCOR

Sound products

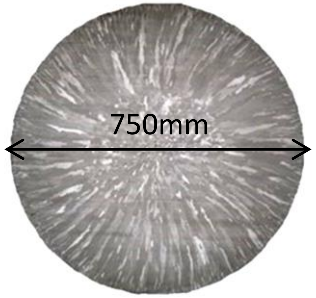
(low impact of defects on mechanical properties)

- Casting ➔ Chemical composition

- Conversion ➔ Metallurgical structure

Context: Casting processes

Continuous Casting



Cross section
of a bloom

Shrinkage porosities

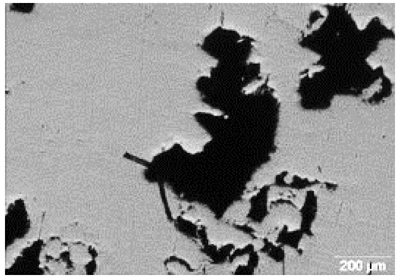


Image Topcast Engineering

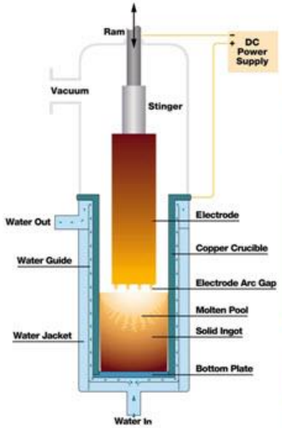
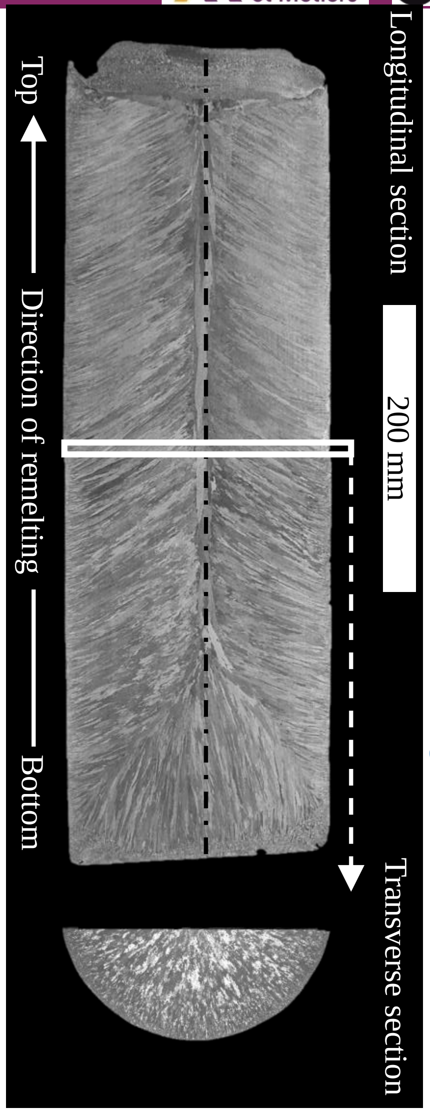


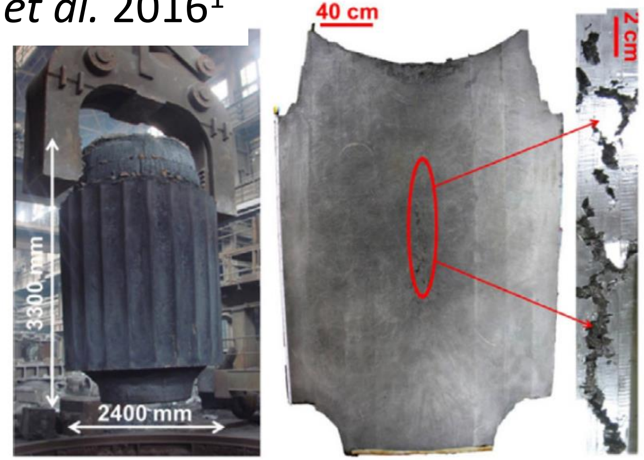
Image Totalmateria

VAR



Macrostructure of the as-cast ingot

Chao *et al.* 2016[1]



Casting

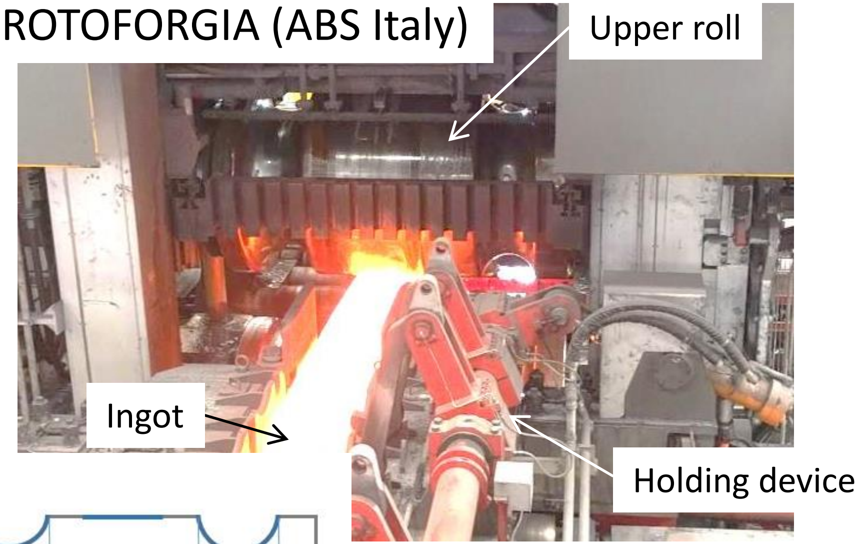
[1]Chao et al 2016, Investigation on the void closure efficiency in cogging processes of the large ingot by using a 3-D void evolution model, Journal of Material Processing Technologie

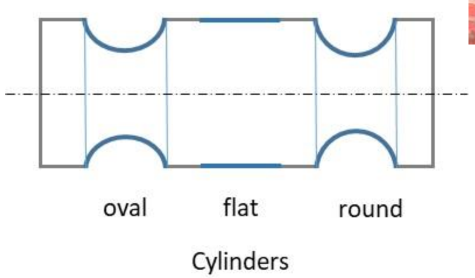
Context: Conversion processes

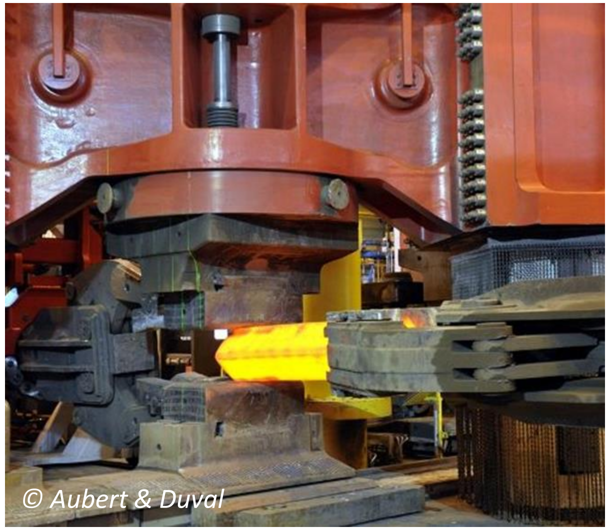
LUNA (ABS, Italy)

Hot rolling

ROTOFORGIA (ABS Italy)

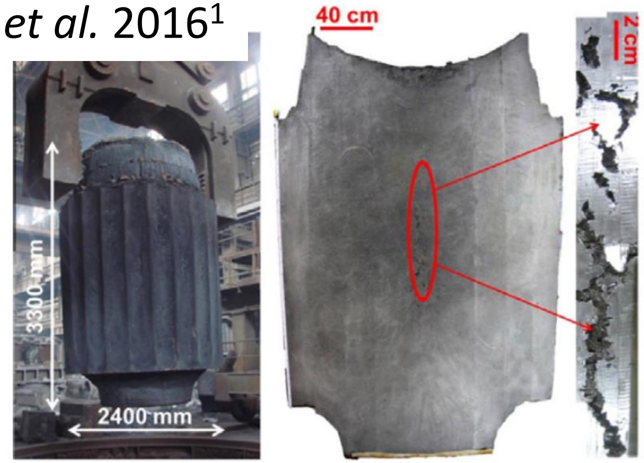






Cogging operation

Chao *et al.* 2016[1]



Forging of a casted billet

[1]Chao et al 2016, Investigation on the void closure efficiency in cogging processes of the large ingot by using a 3-D void evolution model, Journal of Material Processing Technologie

Context and objectives

Objective: Prediction of the material structure by the numerical simulation : design of the conversion route

- Void closure (shrinkage porosities, blowhole)

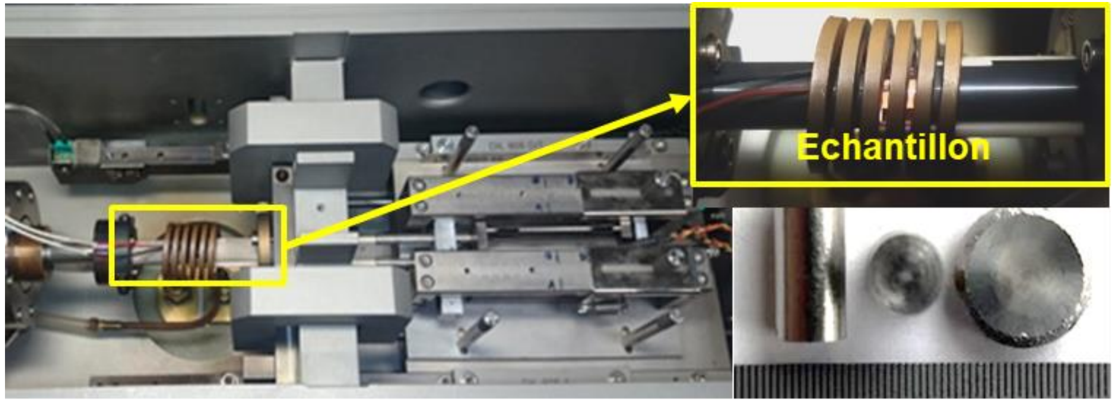
- Recrystallisation from elongated oriented grains to equiaxe small grain
- Control of phase ratio

Industrial context

- Productivity and size of the industrial facilities ➔ In-situ experimentation is not possible
- The size of the products doesn’t allow the use of some investigation methods (X-Ray Tomography…)

Thermomecanical simulators :

Gleeble machine, Plastodilatometer



(Pondaven 2021[1])

Initial diameter of the sample 5 mm

- Monotonic and unidirectional loading (compression test)
- Good control of the thermomechanical loading

In-Situ experimentation:

Industrial facilities

(Faini *et al.* 2018[2])

- Very good representativeness
- Applied loading estimated through FEM simulation of the industrial process

[1]Pondaven, Corentin. 2021. « Contribution à l'étude du phénomène de fermeture de porosités en laminage à chaud : mise en place d'une modélisation expérimentale et numérique à représentativité améliorée ». Thèse de doctorat

[2]Faini, F, A. Attanasio, et E. Ceretti. 2018. « Experimental and FE analysis of void closure in hot rolling of stainless steel ». *Journal of Materials Processing Technology*

Context and objectives

Objective: Prediction of the material structure by the numerical simulation : design of the conversion route

Method: Implementation of a **reduced scale** experimentation for the characterization and the modelling of the structure evolution

- Development of a forming test **representative** of the **hot forming process** with respect to the **evolution phenomenon**
  - Experimental implementation
  - Numerical simulation

(Banaszek et Stefanik 2006[1] ; Kukuryk 2019[2])

Application to Shrinkage porosity closure

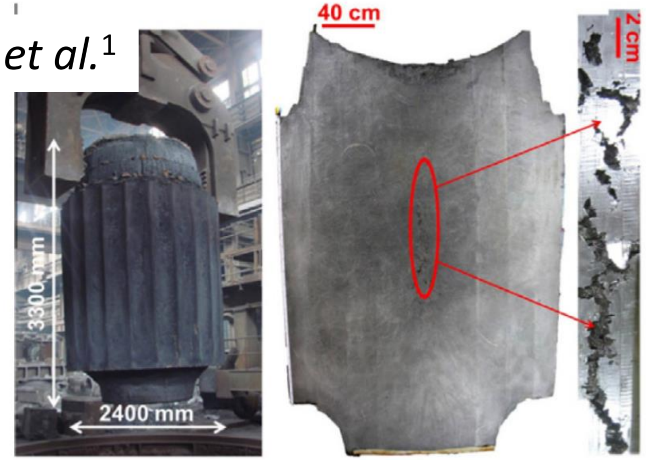
Thèses Damien Chevalier[3] (12 - 2016) et Corentin Pondaven[4] (01 - 2021)

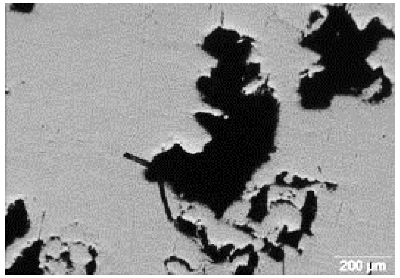
[1]Banaszek, G., et A. Stefanik. 2006. « Theoretical and laboratory modelling of the closure of metallurgical defects during forming of a forging ». *Journal of Materials Processing Technology*
[2]Kukuryk, M. 2019. « Experimental and FEM analysis of void closure in the hot cogging process of tool steel ». *Metals*
[3]Chevalier, Damien. 2016. « Contribution à la compréhension du couplage thermomécanique en laminage à chaud sur l'évolution des défauts de coulée ». Thèse de doctorat
[4]Pondaven, Corentin. 2021. « Contribution à l'étude du phénomène de fermeture de porosités en laminage à chaud : mise en place d'une modélisation expérimentale et numérique à représentativité améliorée ». Thèse de doctorat

Shrinkage porosities: Low alloyed steel

- Geometry
  - Size, aspect ratios, orientation
  - Geometrical details: “tortuosity”

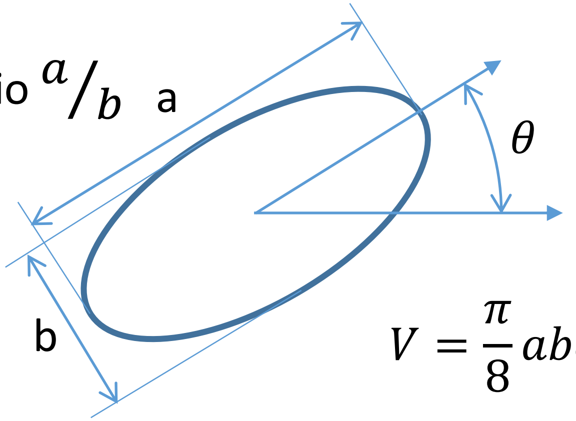
Chao *et al.*[1]





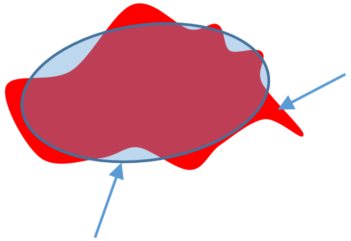
- Physical properties
  - Vacuum,
  - no oxide at the internal surface

Geometrical state variables commonly used



$$V = \frac{\pi}{8} abc$$

Simplified case of an ellipsoidal void



[1]Chao et al 2016, Investigation on the void closure efficiency in cogging processes of the large ingot by using a 3-D void evolution model, Journal of Material Processing Technologie

State of the art : the thermomechanical loading

Forming process:

- Deformation under compressive stress state
  - Modelling : Thermomechanical parameters
    - $\sigma_H, \sigma_0, \varepsilon$
    - Combination: $\frac{\sigma_H}{\sigma_0} = tri$ (Tanaka *et al.*[1])
    - Integration: $Q = \int_0^{\varepsilon} -tri \, d\varepsilon$
- Alternation of the forming direction

Banaszek et Stefanik 2006[2] ; Lee *et al.* 2011[3]

Temperature, plastic strain rate are second order parameters

Industrial rolling mills : succession of stands alternating the forming direction

[1]Tanaka, M., S. Ono, et M. Tsuneno. 1986. « Factors contributing to crushing of voids during forging ». *J. Jpn. Soc. Technol. Plast.*

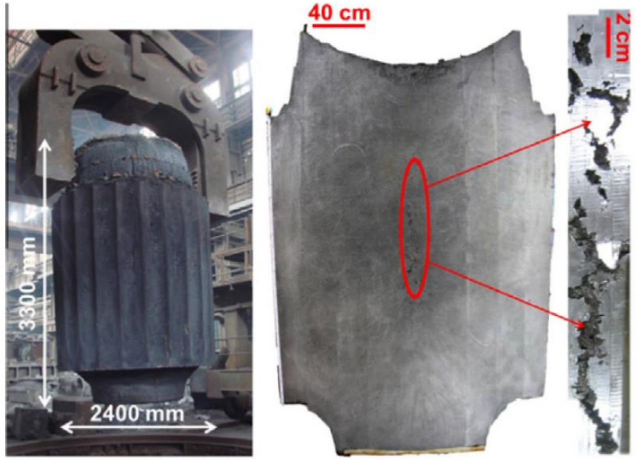
[2]Banaszek, G., et A. Stefanik. 2006. « Theoretical and laboratory modelling of the closure of metallurgical defects during forming of a forging ». *Journal of Materials Processing Technology*

[3]Lee, Y.S., S.U. Lee, C.J. Van Tyne, B.D. Joo, et Y.H. Moon. 2011. « Internal Void Closure during the Forging of Large Cast Ingots Using a Simulation Approach ». *Journal of Materials Processing Technology*

State of the art : representativeness criteria

Shrinkage porosities:

- Geometry
  - Size, aspect ratios, orientation
  - **Geometrical details: tortuosity**



- **Physical properties**
  - **Vacuum,**
  - **no oxide at the internal surface**

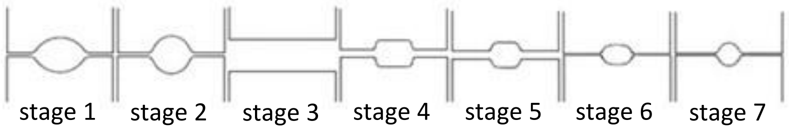
Forming process:

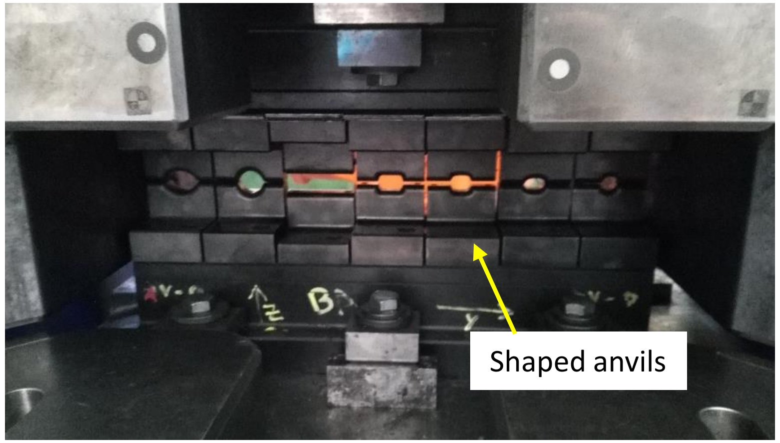
- Deformation under compressive stress state
  - Modelling : **Thermomechanical parameters**
    - $\sigma_H, \sigma_0, \boldsymbol{\varepsilon}$
    - Combination: $\boldsymbol{\frac{\sigma_H}{\sigma_0} = tri}$
    - Integration: $\boldsymbol{Q = \int_0^{\varepsilon} -tri \, d\varepsilon}$ (Tanaka et al.)
- **Alternation of the forming direction**

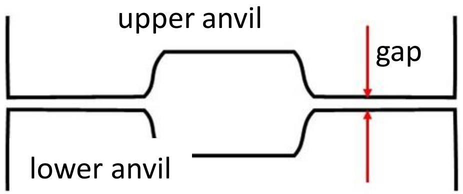
Quantification by the FEM simulation of the industrial forming process : At the center of the bar

Design of the representative forming test

Open die forging: use of shaped anvils reproducing the roll shape at a 1/10 reduction scale:
Forming temperature 1250°C

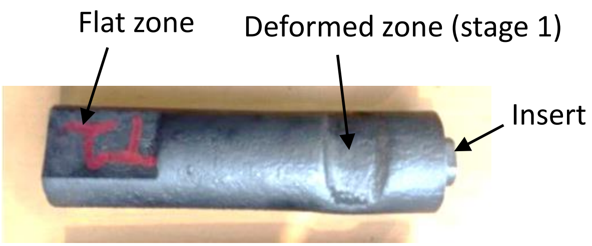




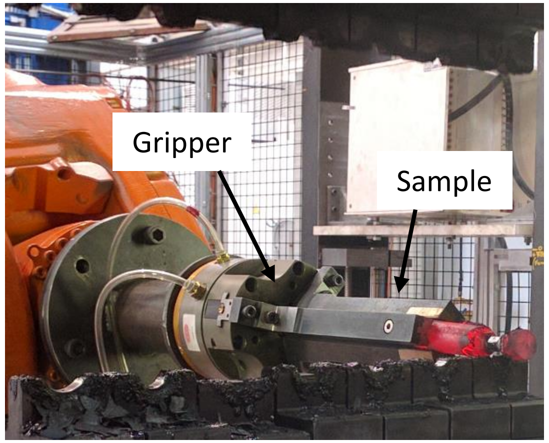


Pondaven 2021[1]

The sample:
Cylinder of dimensions (ϕ 27mm*200mm)
Possibility to introduce an insert



Robotized handling:
- Repeatability
- Reduced sample/anvil thermal exchange before forming
- Accurate application of the alternation of the forming direction



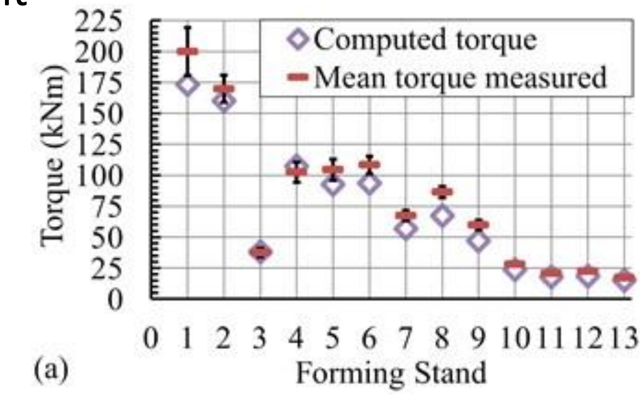
[1]Pondaven, Corentin. 2021. « Contribution à l'étude du phénomène de fermeture de porosités en laminage à chaud : mise en place d'une modélisation expérimentale et numérique à représentativité améliorée ». Thèse de doctorat

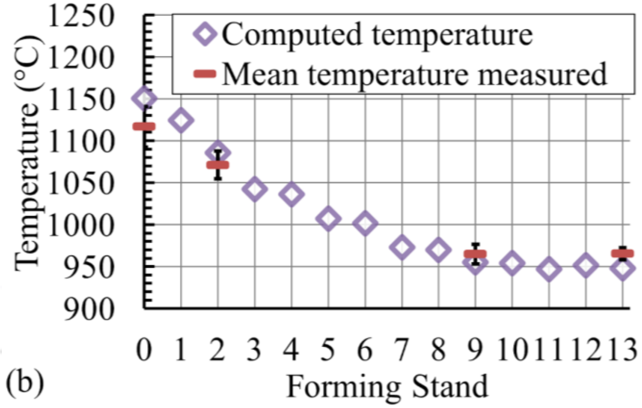
- Simulation of the industrial process and the representative forming test

Estimation of the Roll/material friction and thermal exchange coefficient

Pondaven *et al.* 2020[1]

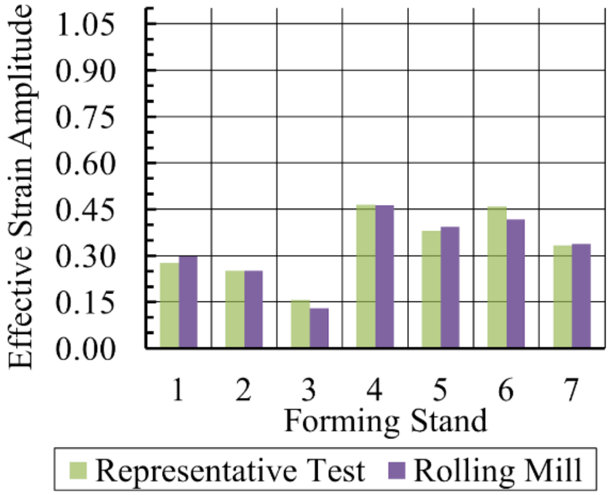
Rolling mill

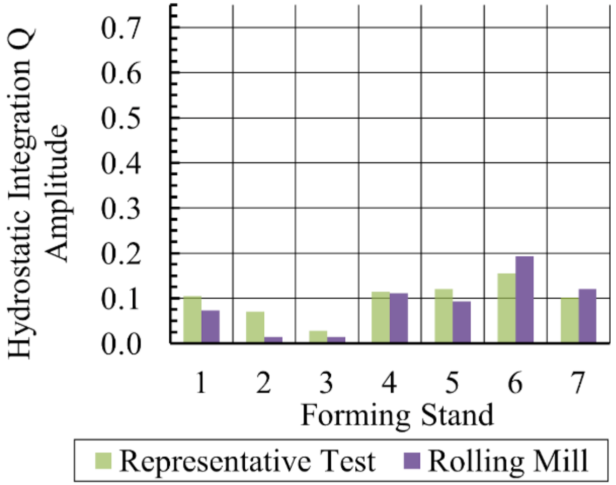




! The tension in the bar between stands is not taken into account

Comparison
Rolling mill / representative test



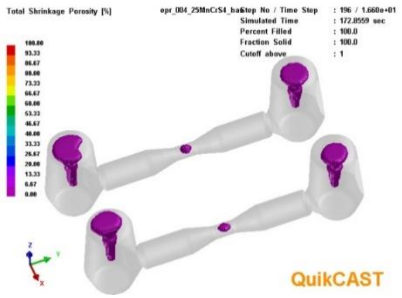


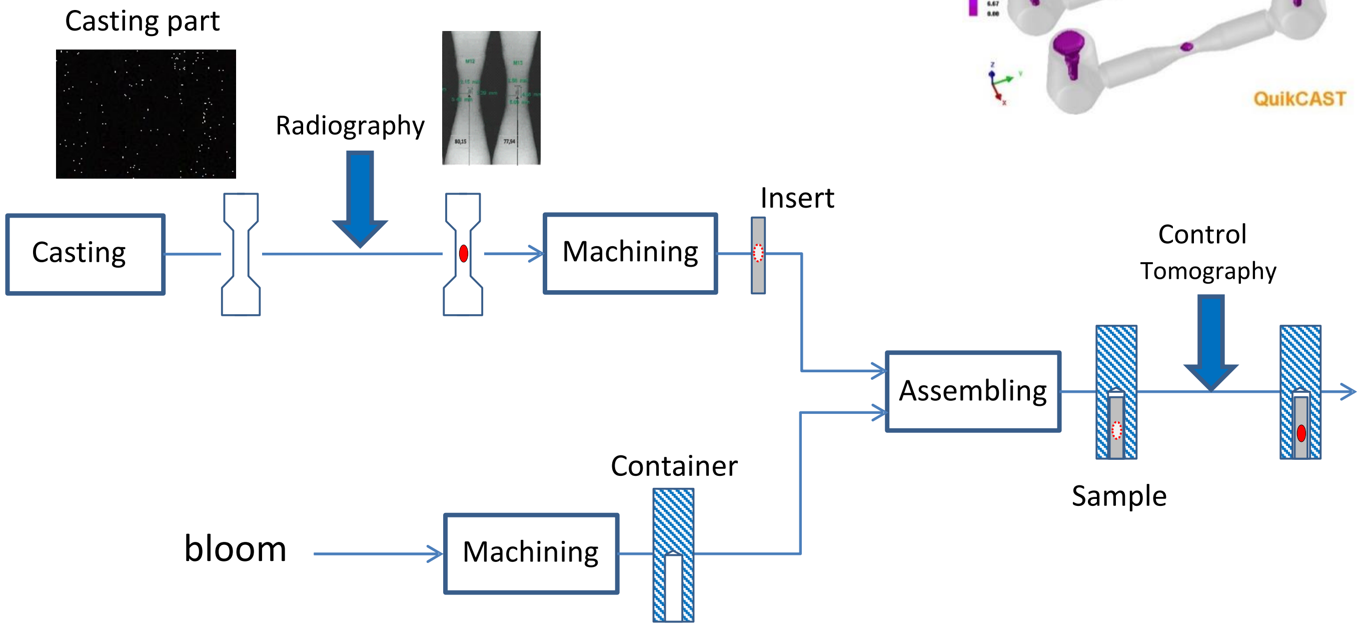
[1]Pondaven, Corentin, Laurent Langlois, Régis Bigot, et Damien Chevalier. 2020. « FEM-Based Methodology for the Design of Reduced Scale Representative Experimental Testing Allowing the Characterization of Defect Evolution during Hot Rolling of Bars ». *Metals*

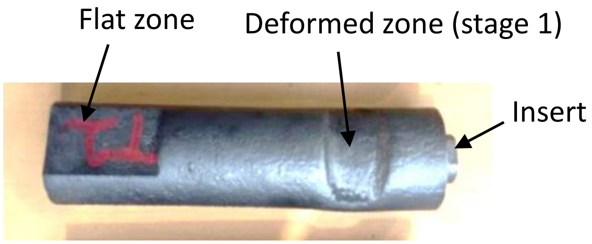
Design of the representaitve forming test

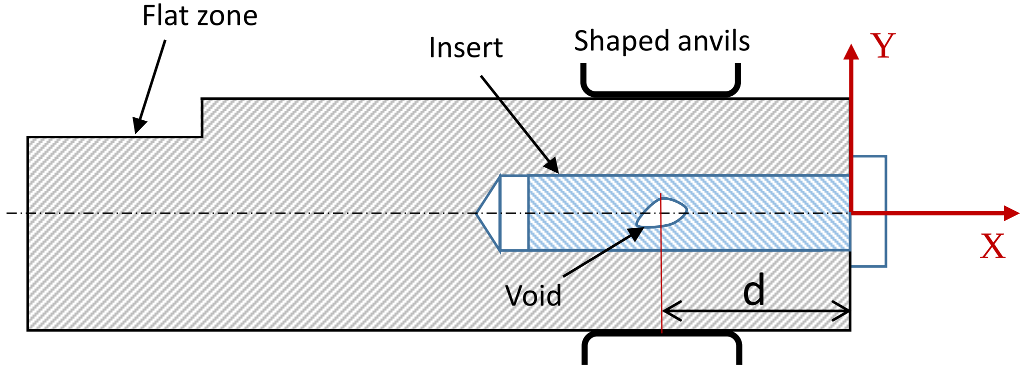
The sample containing the shrinkage porosity

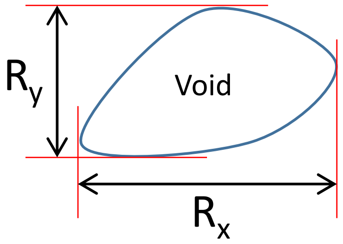
The casting process is set-up in order to generate a shrinkage porosity (CTIF[1])











Pondaven *et al.* 2021[2]

C	Mn	Si	S	P	Cr
0.25	1.17	0.20	0.03	0.03	1.1

[1] Centre Technique des Industries de la Fonderie

[2] Pondaven, Corentin, Laurent Langlois, Benjamin Erzar, et Régis Bigot. 2021. « Numerical and Experimental Simulation of Shrinkage Porosity Closure during Hot Rolling of Bars », ESAFORM2021

Design of the representaitve forming test

The representative sample:

- Contains a shrinkage porosity (obtained with the good physical phenomenon)
- Its constitutive material has a solidification grain structure (Bloom and casted part)
- The dimension of the sample is suitable with the tomography capacities in terms of accuracy

The representative forming test:

- Reproduced the plastic strain and the compressive stress state encountered in the bars during its hot rolling
- Reproduced the alternation of the forming direction

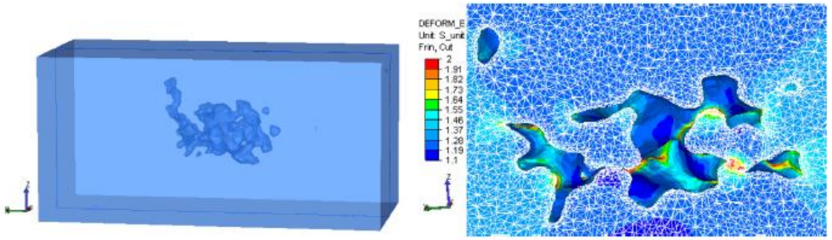
Simuation of the representaive testing

Modelling strategy

- Mean field : Field of state variable describing the porosity structure

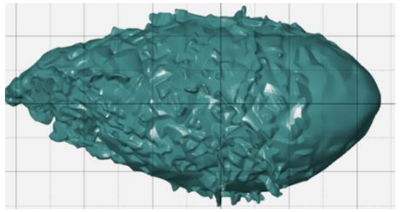
- Full field : Explicit reprensentation of the voids

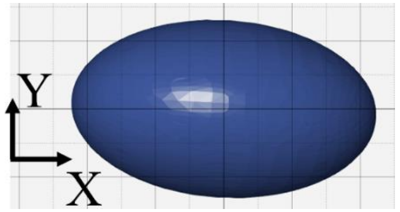
  - Scale transition (Saby *et al.* 2013[1])



(a) Initial state (b) Cutting plane at 14% height reduction

  - « real » or equivalent geometry (sphere, ellipsoïd, …)





[1]Saby, M., M. Bernacki, E. Roux, et P. -O. Bouchard. 2013. « Three-dimensional analysis of real void closure at the meso-scale during hot metal forming processes ». *Computational Materials Science*

Simuation of the representaive testing

Simulation with FORGE NxT© Sofware with a full field model: Explicit representation of the void

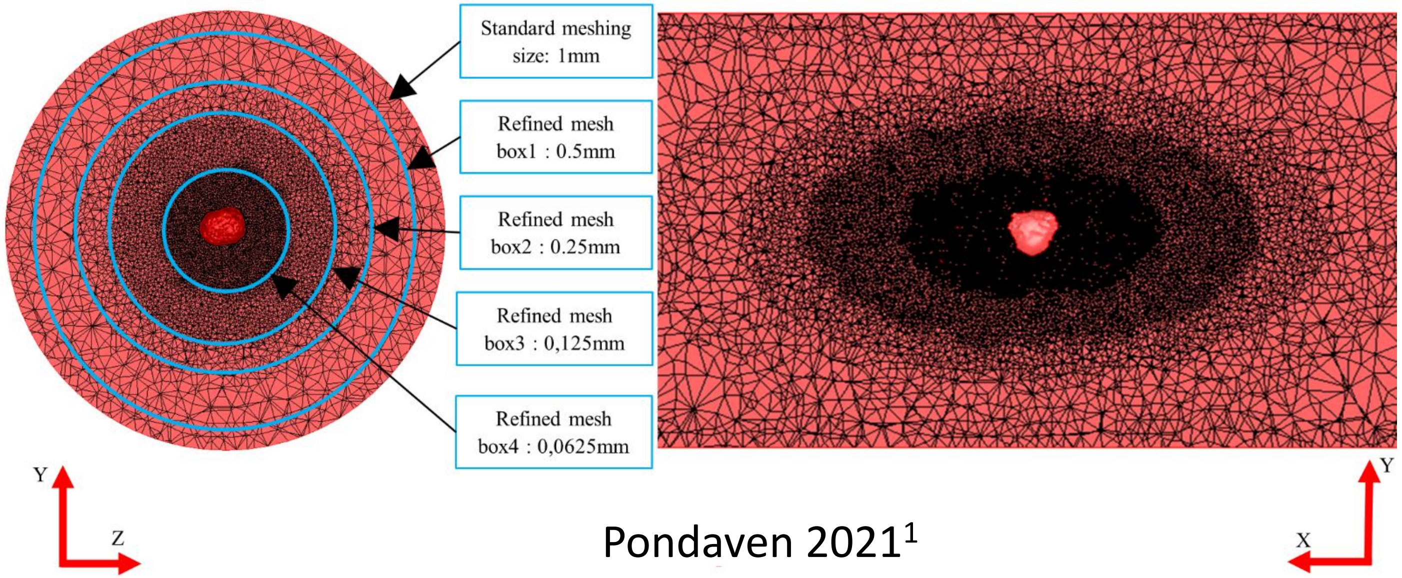
Plasticity: Hansel Spittel law with 5 coefficients

A1	m1	m2	m3	m4
1321.9	-0.00257	-0.1941	0.1468	-0.06521

Anvil/sample Friction and thermal exchange coefficients

Coulomb µ	Tresca m	Emissivity	Thermal exchange environment $W.m^{-2}.K^{-1}$	Thermal exchange anvils $W.m^{-2}.K^{-1}$
0.4	0.8	0.88	10	2000

Mesh size: To follow the volume reduction of the void as far as possible



Pondaven 2021[1]

Four concentric mesh boxes.

Not deformed zone: 1mm

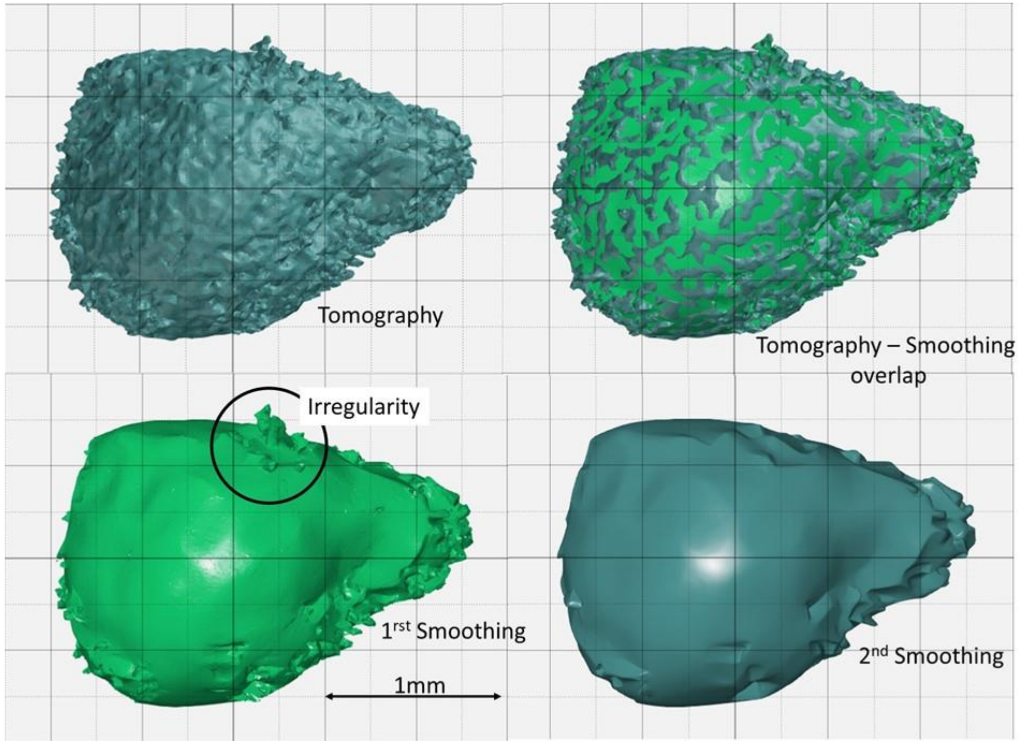
Vicinity of the void: 0.0625mm

[1]Pondaven, Corentin. 2021. « Contribution à l'étude du phénomène de fermeture de porosités en laminage à chaud : mise en place d'une modélisation expérimentale et numérique à représentativité améliorée ». Thèse de doctorat

Simuation of the representaive testing

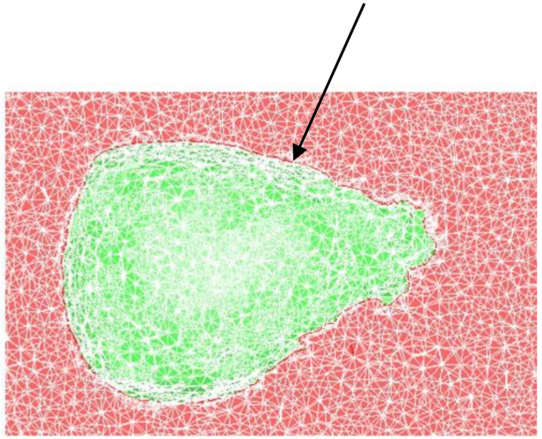
Explicit representation of the shrinkage porosity

Surface geometry details / mesh size



The internal surface of the void can get into contact with itself during the closure.

- Self contact driven by unilateral sticking condition: (No slipping is allowed at the contact but if the contact pressure in equal to zero, possibility to unstick)



Pondaven 2021[1]

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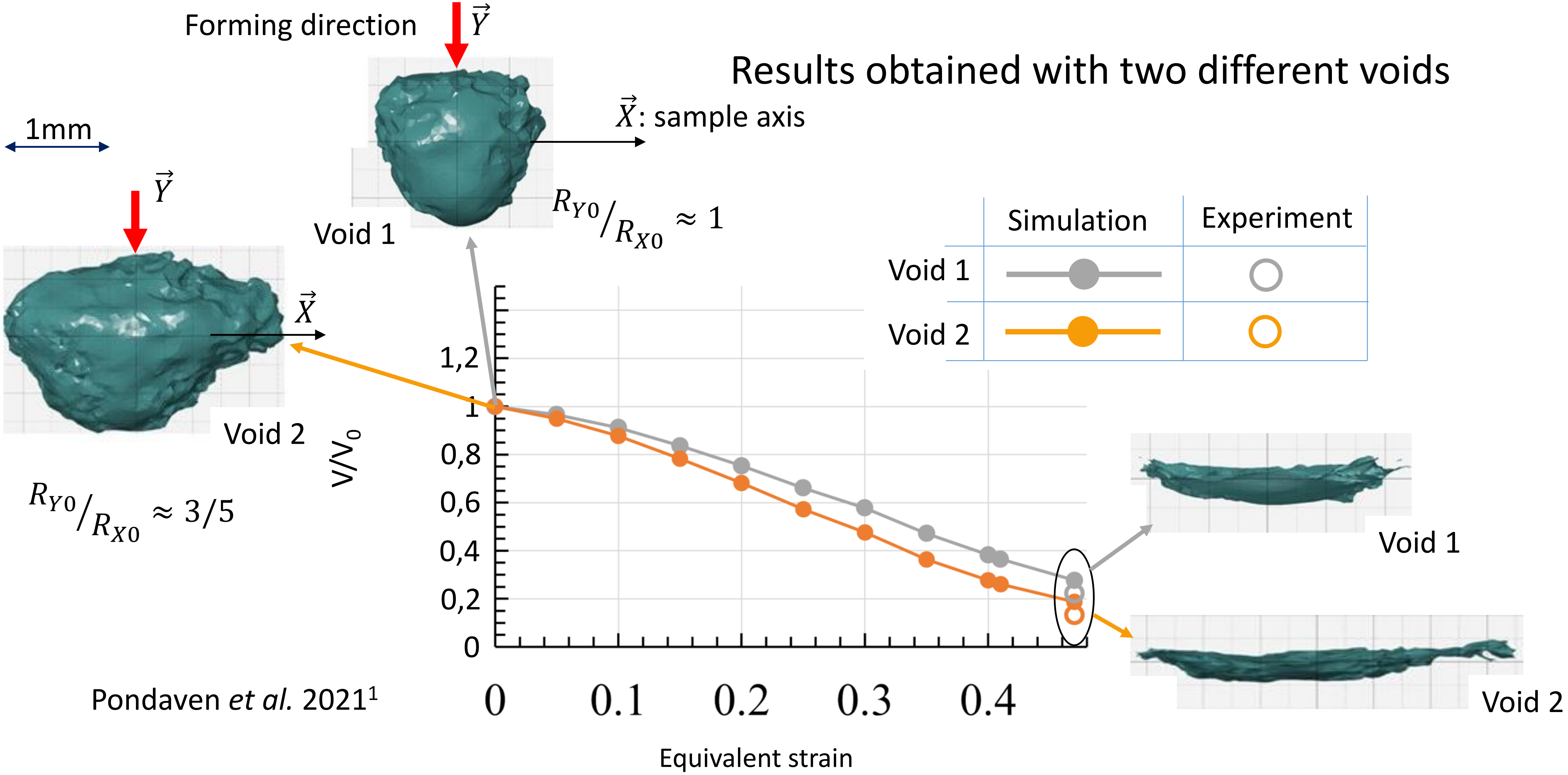
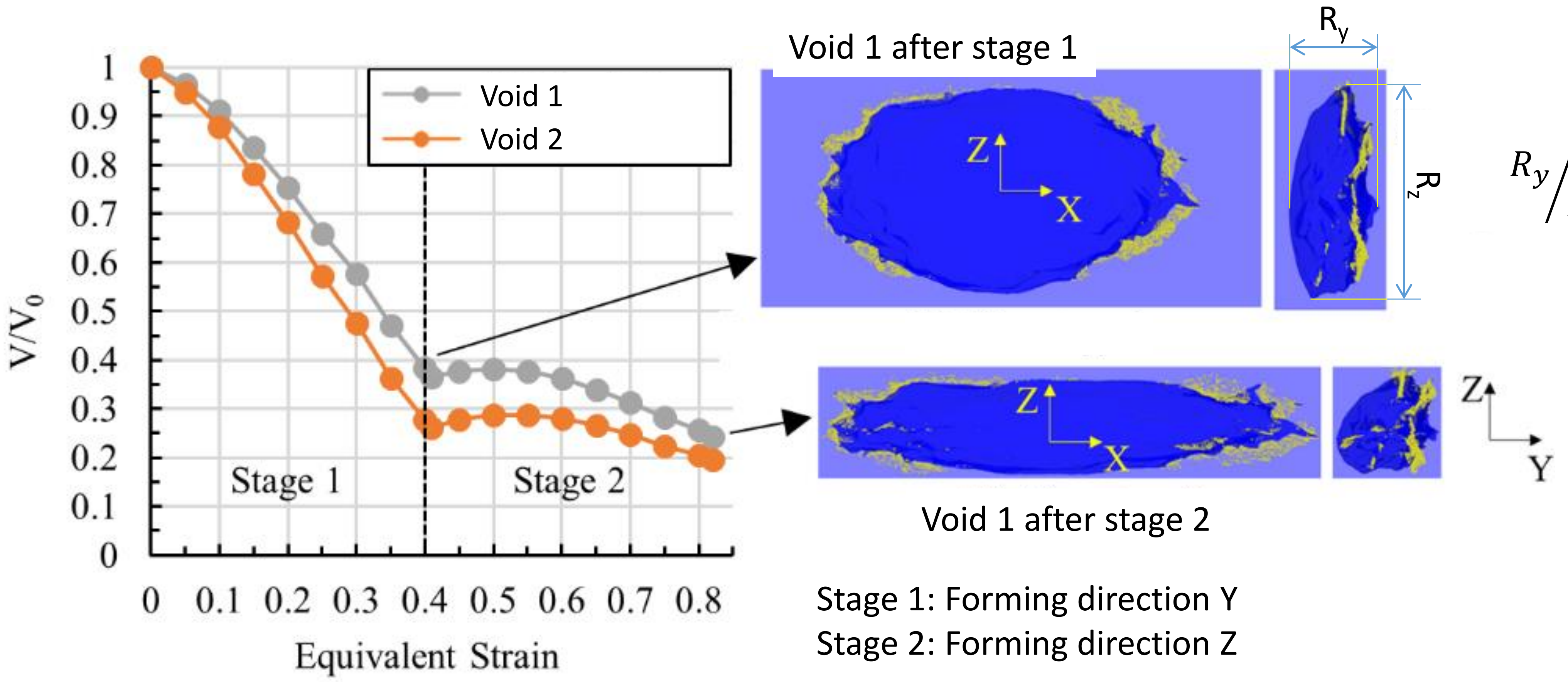
Results obtained with two different voids



Pondaven *et al.* 2021[1]

[1] Pondaven, Corentin, Laurent Langlois, Benjamin Erzar, et Régis Bigot. 2021. « Numerical and Experimental Simulation of Shrinkage Porosity Closure during Hot Rolling of Bars », ESAFORM2021

Results and discussion



$R_y / R_z < 1$

Stage 1: Forming direction Y
Stage 2: Forming direction Z

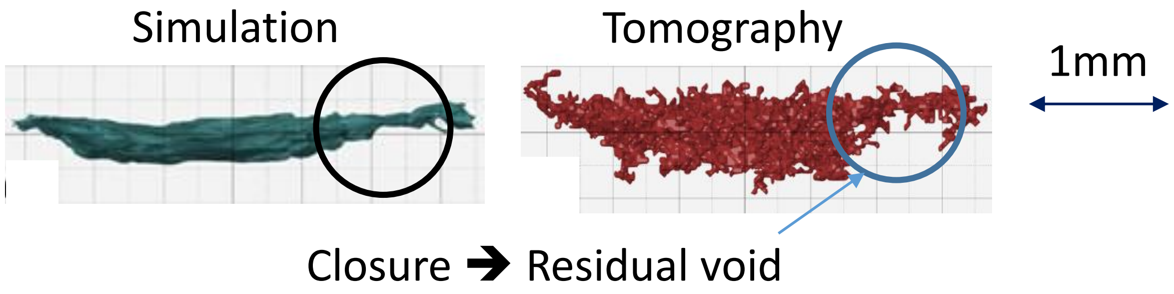
The void volume increases at the beginning of the second stage.

➔ Aspect ratio of the void with respect to the forming direction

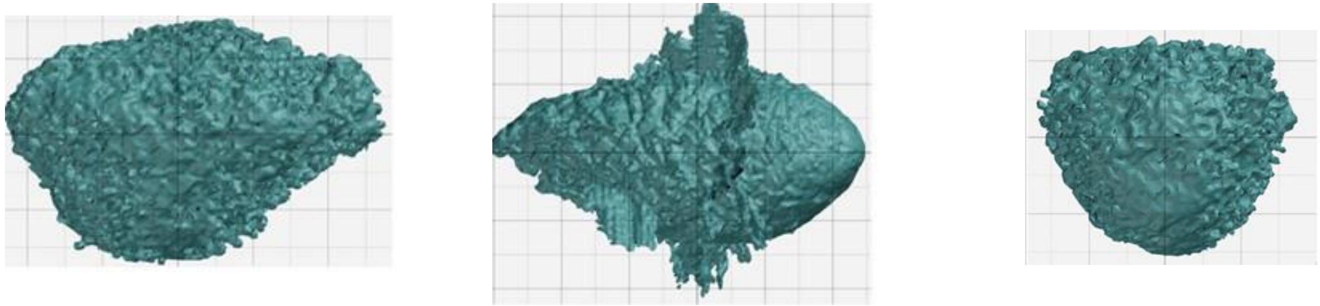
Conclusions

- Experimental and numerical results are in quite good accordance.

- Only the first stage of the void closure : FEM and tomography limitations



- Relevant parameters describing the geometry of the voids according to its closure



Modelling of the industrial process: mean field model

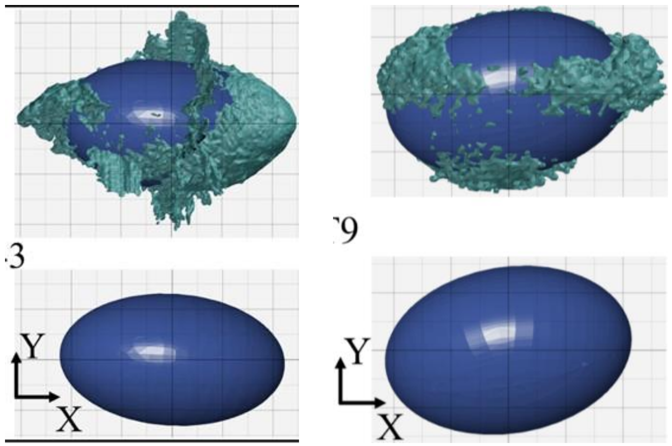
Influence of the loading parameters
(for a given void)

Influence of the void geometry
(for a given loading)

Standard Shaped anvils: To simplify the experimental procedure
A set of different forming routes
Voids : Generate a population of different voids
(Volume, semi-axes of the equivalent ellipsoïd,…)

Validation of the full-field model by comparison with experiments

Data learning methods : Data generated by the full field model



Context and objectives

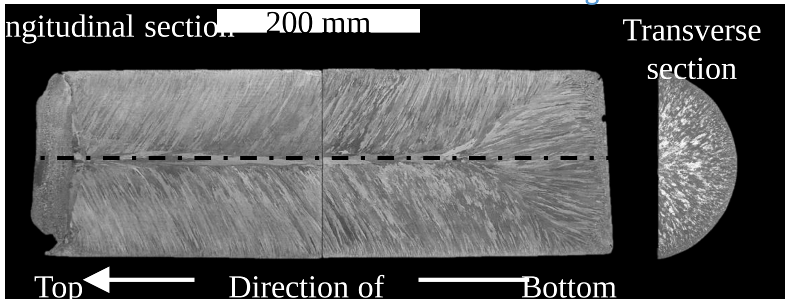
Objective: Prediction of the material structure by the numerical simulation : design of the conversion route

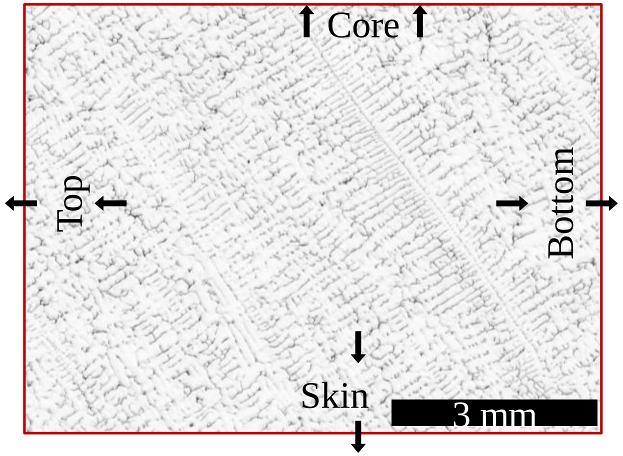
- Void closure (shrinkage porosities, blowhole)
- Recrystallization from elongated oriented grains to equiaxe small grain

PHD d'Arthur Paquette: Aubert et Duval, AFRC

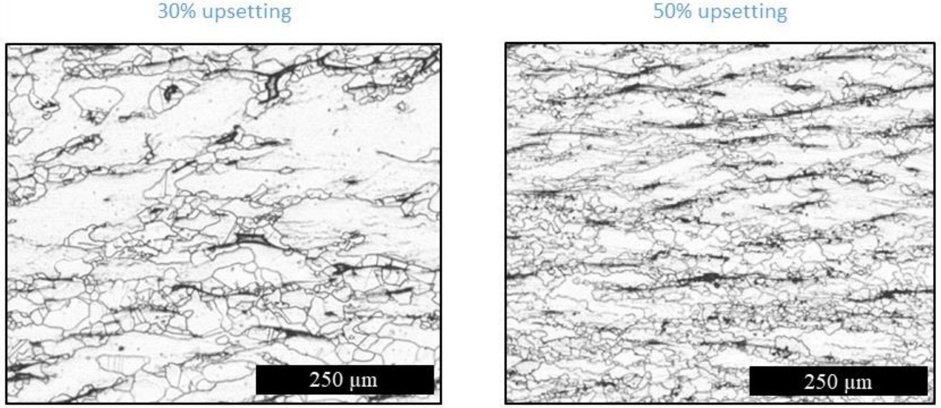
Identification and characterization of the recrystallization of VIM/VAR 316 stainless steel during upsetting and cogging

Macrostructure of the as-cast ingot





Representative microstructure of the axial samples at 1200°C.



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Références:

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