

DE LA RECHERCHE À L'INDUSTRIE

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## SINGULARITIES OF TENSILE BEHAVIOR OF ADVANCED AUSTENITIC STEELS OBTAINED BY DIFFERENT COLD PROCESSES

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## ASTRID demonstrator

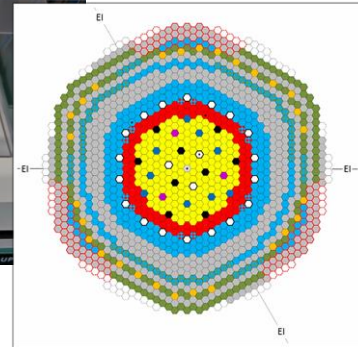
*“Advanced Sodium Technological Reactor for Industrial Demonstration”*

480-700°C, 110 dpa

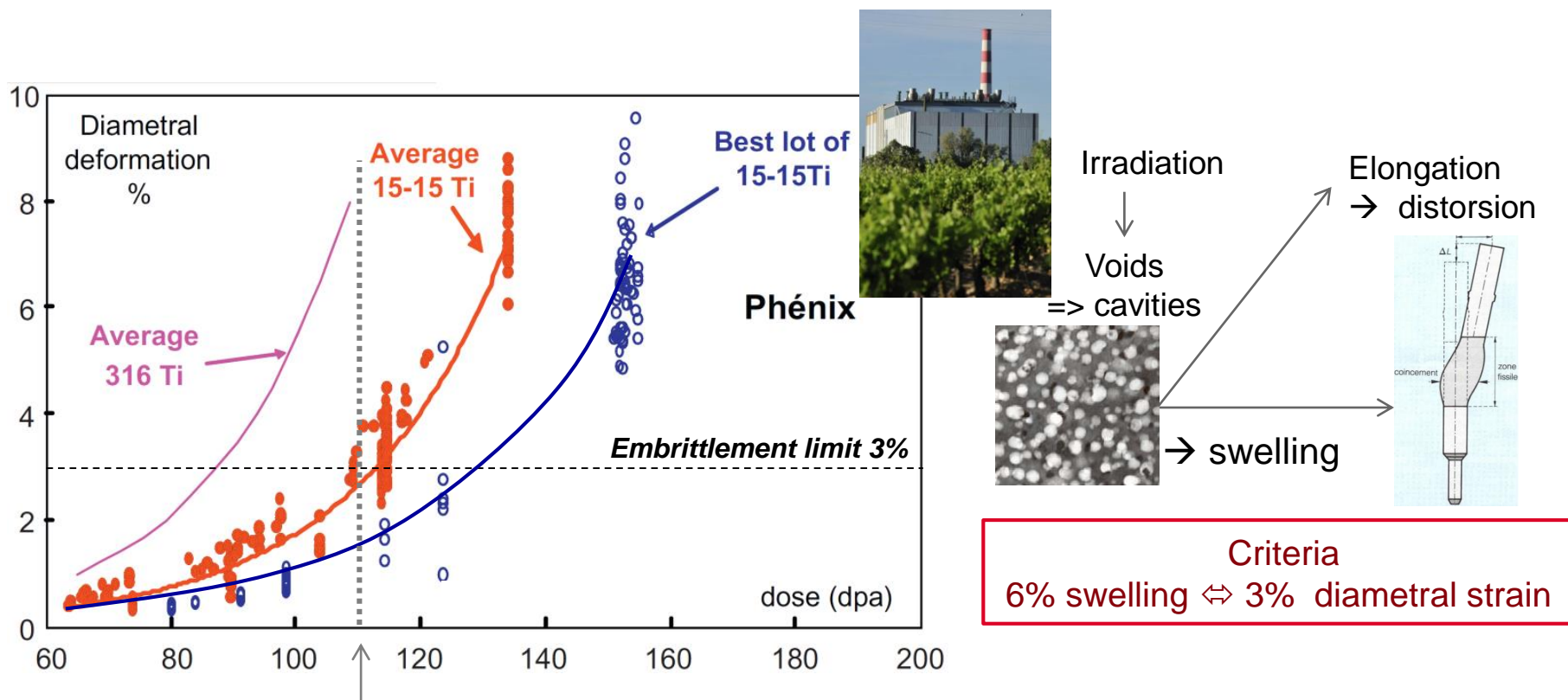
### First core components :

- Use of reference materials benefiting from a large feed-back from the previous French SFRs (Rapsodie, Phénix, SuperPhénix)
  - Austenitic steels (fuel cladding, space wire, end-plugs ...),
  - Martensitic steels (hexagonal wrapper),
  - B<sub>4</sub>C (absorbers)...
- Qualifying these materials regarding the specificities of ASTRID core
  - high dose level for equilibrium core,
  - heterogeneous core design involving lower T°C of the cladding,
  - high compacity of the fuel assembly ...

### CEA / ASTRID Project



- Optimized austenitic steel : 15%Cr - 15%Ni + Ti + Si + P (Cold Work state)
- Specification AIM1 (Austenitic Improved Material #1 : Astrid Project)  
close to opt. D9 (US), IFAC-1 (India) ChS-68 (Russia), DIN 1.4970 (Germany)



110 dpa : limit for ASTRID

[Yvon P., Carre F., JNM, 2009; 385:217  
(issue from study of JL Seran - CEA)]

**Criteria**  
6% swelling ↔ 3% diametral strain

- ✓ Several fabrication routes are conducted to produce 15Cr-15Ni cladding tubes  
Three cold processes are involved : drawing, pilgering or swaging
  
- ✓ This study investigates the effects of processing paths using various heat treatments and amount of cold work (from 17% to 37%) on the final microstructure and the tensile properties.

HEAT (VIM-VAR)



Hot Forging + Hot Extrusion



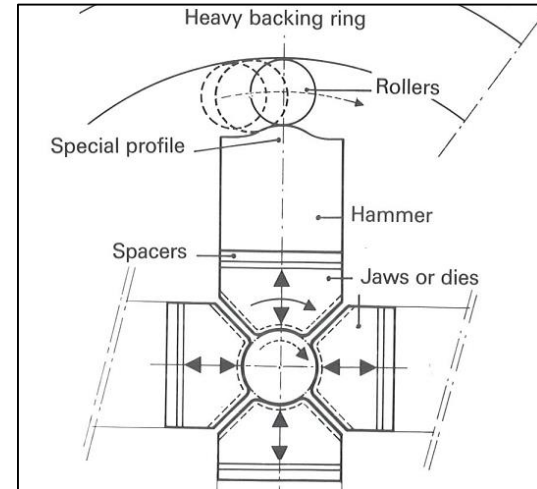
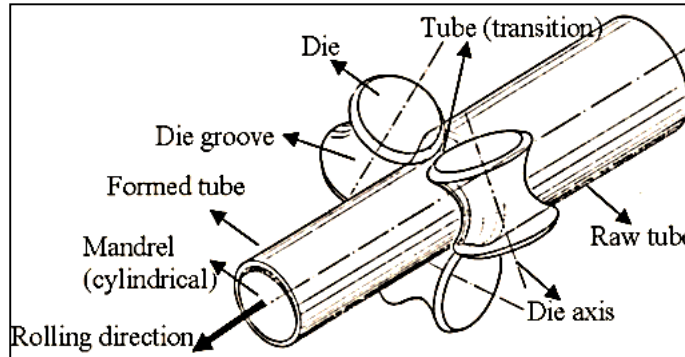
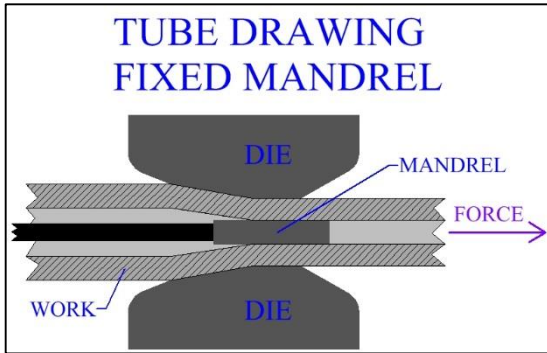
AUBERT&DUVAL



## Cold Drawing

## Cold Pilgering

## Cold Swaging



Industrial reference



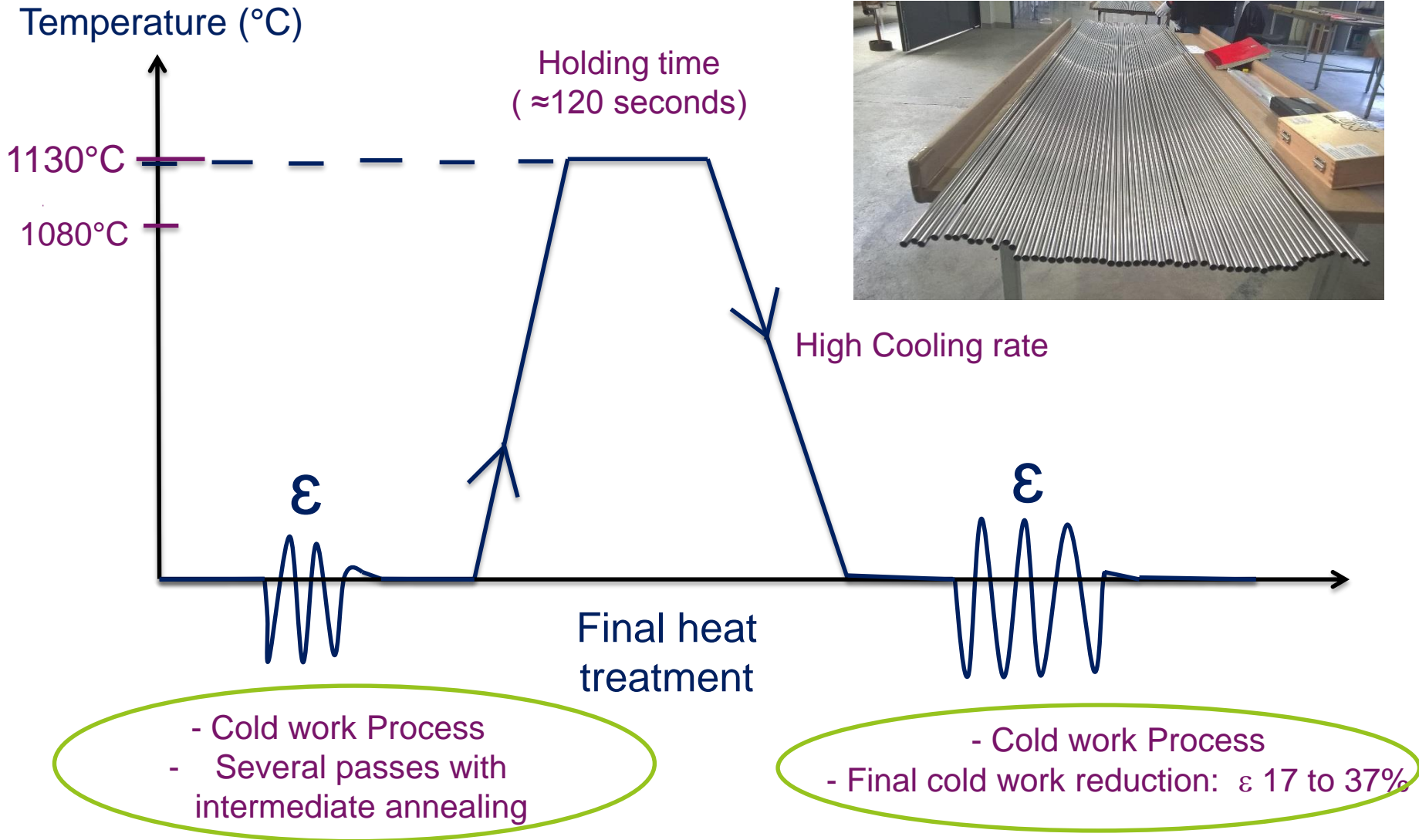
Pilgering and swaging facilities  
CEA/SRMA/LTMEx



Tensile deformation mode

Compressive deformation mode

# FABRICATION ROUTE

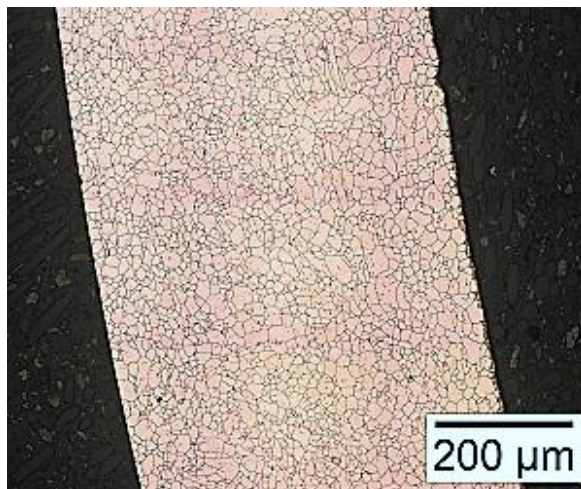


Finished tubes 15-15Tiε - Φ 10,73 mm – th: 500 μm

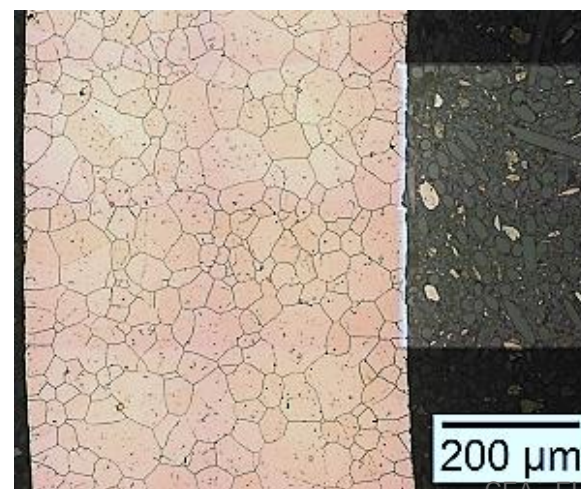
Reference	Cold work process	Final cold work (ε%)	Grain size * (μm)
AI-LA6	HPTR pilgering	23%	25 μm (G=8)
AI-Et <sub>2</sub> 8-1080	Cold drawing	17%	14 μm (G=9)
AI-Et <sub>2</sub> 8-1130	Cold drawing	17%	42 μm (G=6)
AI-Et <sub>1</sub> 4	Cold drawing	37%	-
AI-Ma4	Cold swaging	23%	32 μm (G=7)

\* Grain size measured by image analysis (visilog software)

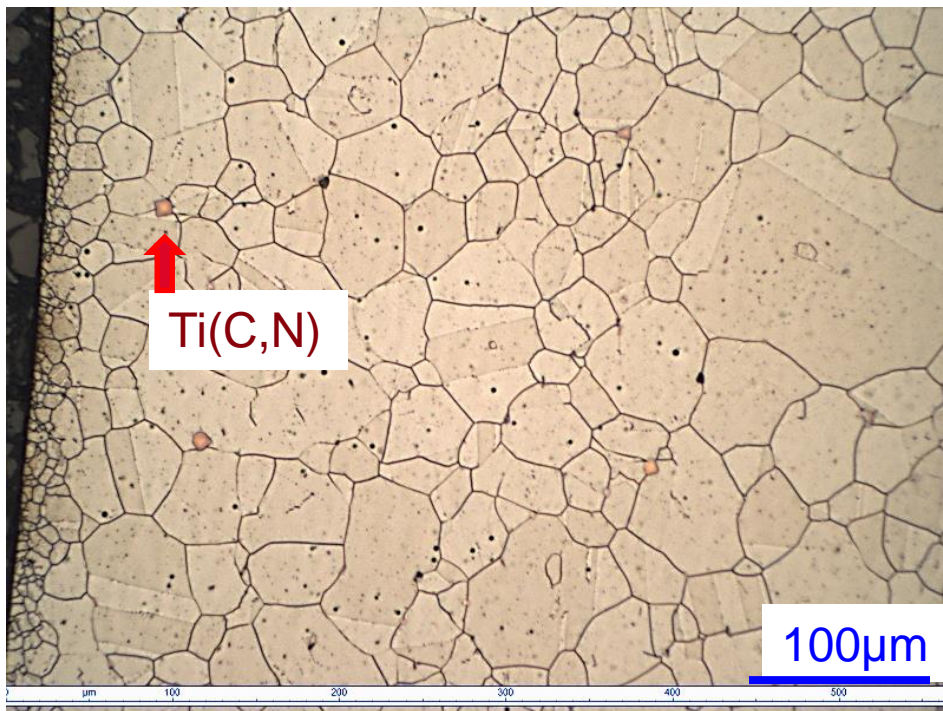
Final mill annealing  
1080°C  
Φ<sub>grain</sub> = 14 μm



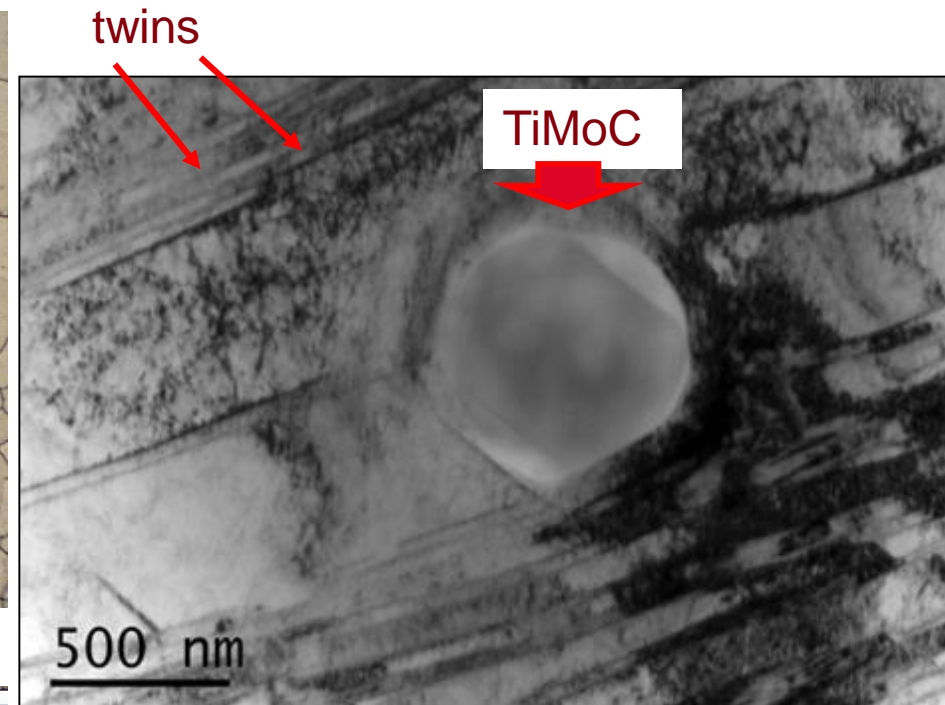
Final mill annealing  
1130°C  
Φ<sub>grain</sub> = 42 μm



- Fully austenitic (no ferrite), average grain size  $\sim$  40-45  $\mu\text{m}$
- Precipitates of TiMoC ( $\sim$  a few hundred of nm) and Ti(C,N) (a few  $\mu\text{m}$ )
- High dislocation density + mechanical twins (cold-working)



Optical micrograph – transverse direction

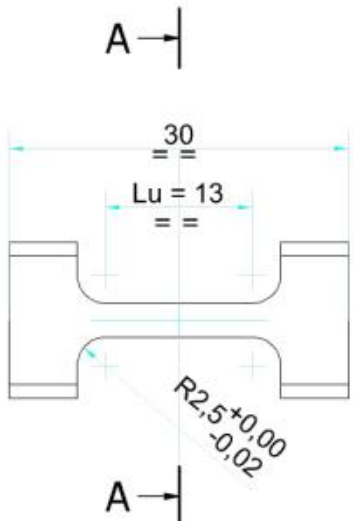


TEM micrograph

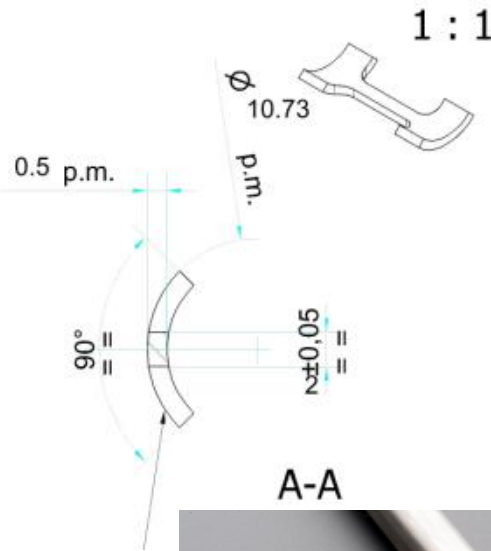


Tensile tests are performed between 20°C and 700°C – **strain rate  $3 \cdot 10^{-4} \text{ sec}^{-1}$**

Longitudinal Direction (LD)  
=> tile tensile specimens



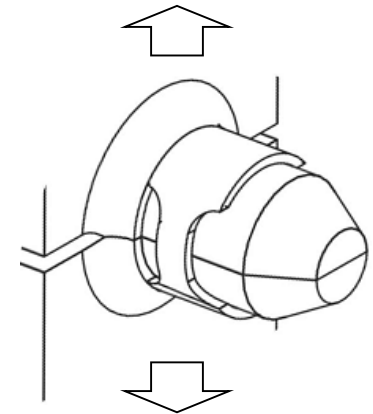
3 specimens from tube  
 $\phi$  10,73, th. 5 mm



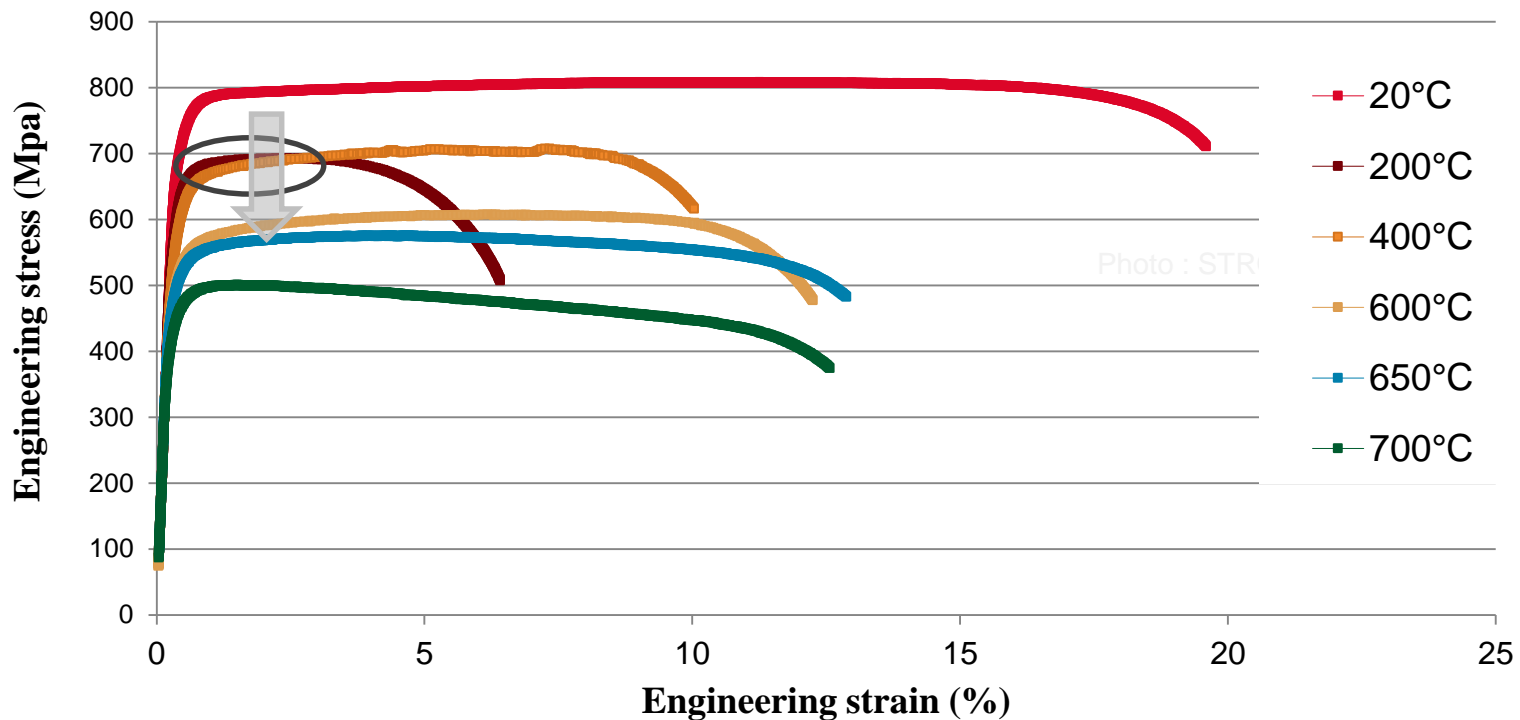
Circumferential Directions (CD)  
=> ring tensile specimens



$\Phi$  10.73 mm  
Th. 0,5 mm



Temperature dependance of the engineering stress-strain curves for 15-15Ti $\epsilon$ , cold swaging  $\epsilon$ 23% (Al-Ma-4)

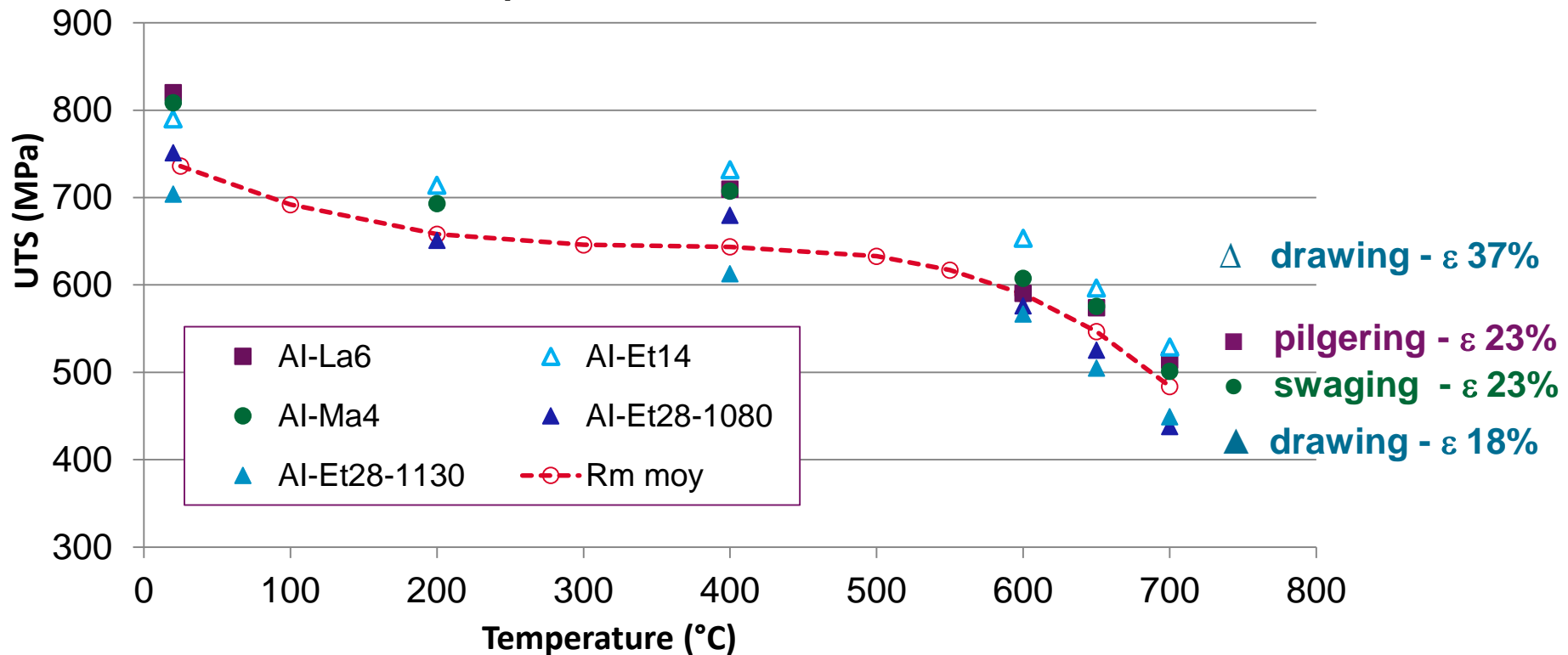


These curves show strong temperature dependencies of strength and ductility:

=> The strength decrease as test temperature raising from 20°C to 700°C,

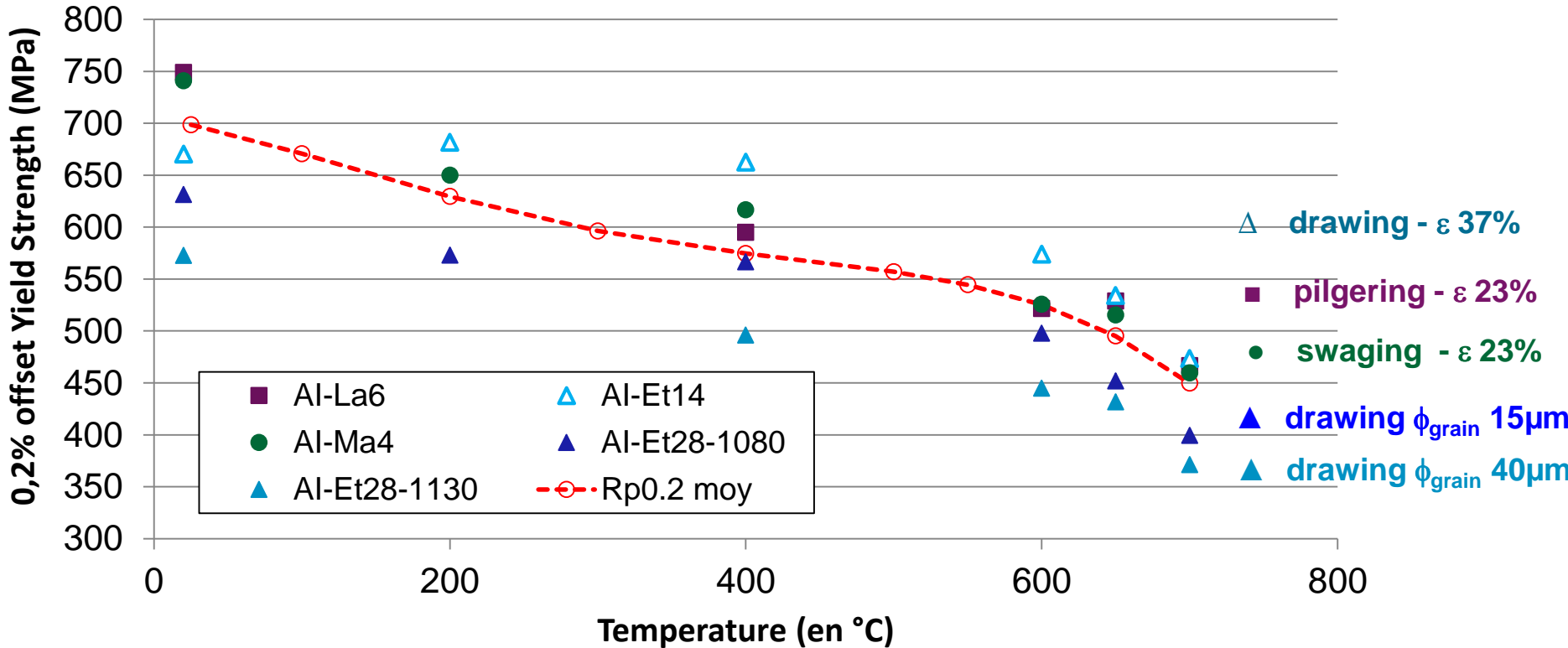
=> Contrary to most other metals, the variation of ductility is not monotonous by raising the temperature. A minimum value is obtained at about 200°C, where the 15-15Ti $\epsilon$  SS shows prompt necking at yield.

## Influence of the cold process and the % of cold work on the UTS values



- ✓ The UTS decreases linearly from 700-800 MPa below to 450-500 MPa by raising the temperature from 20°C to 700°C
- ✓ For the same cold work level ( $\epsilon = 23\%$ ) the UTS values are quite similar
- ✓ The lowest the cold work level the lowest the UTS values over the range of tested  $T^\circ$

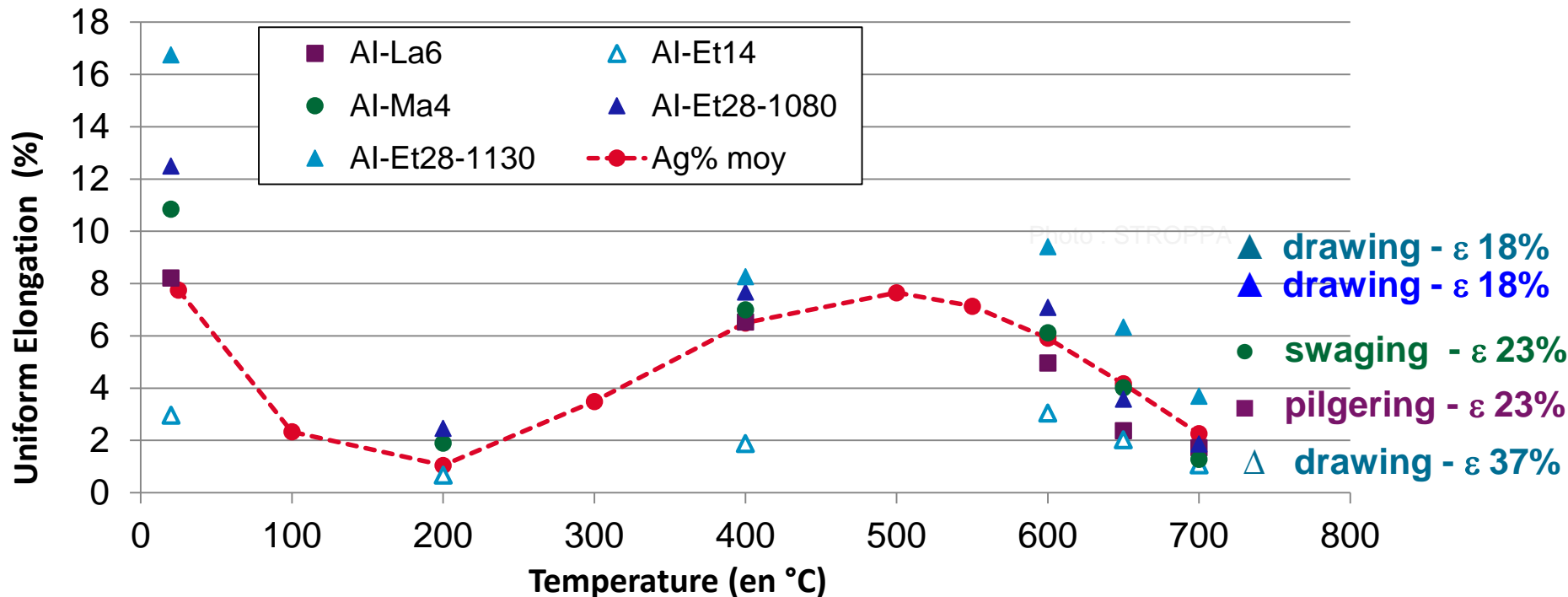
Influence of the cold process and the % of cold work on the YS values



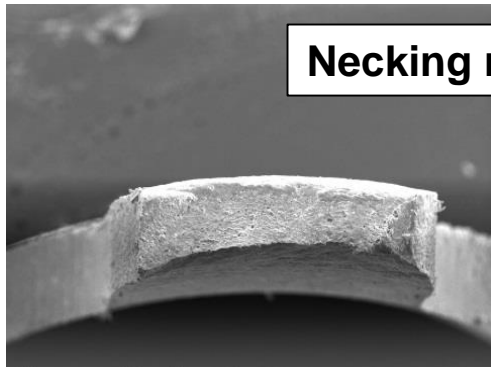
- ✓ The Yield Strength (YS) decreases linearly from 560-750 MPa below to 380-500 MPa by raising the temperature from 20°C to 700°C
- ✓ For the same CW level ( $\epsilon = 23\%$ ) the YS values are quite similar
- ✓  $\hookrightarrow$  ( $\epsilon = 17\%$ ) the lowest the grain size the highest the YS values

=> Hall Petch Effect

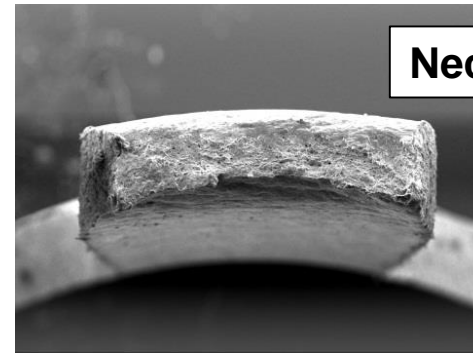
## Influence of the cold process and the % of cold work on the uniform elongation (UE)



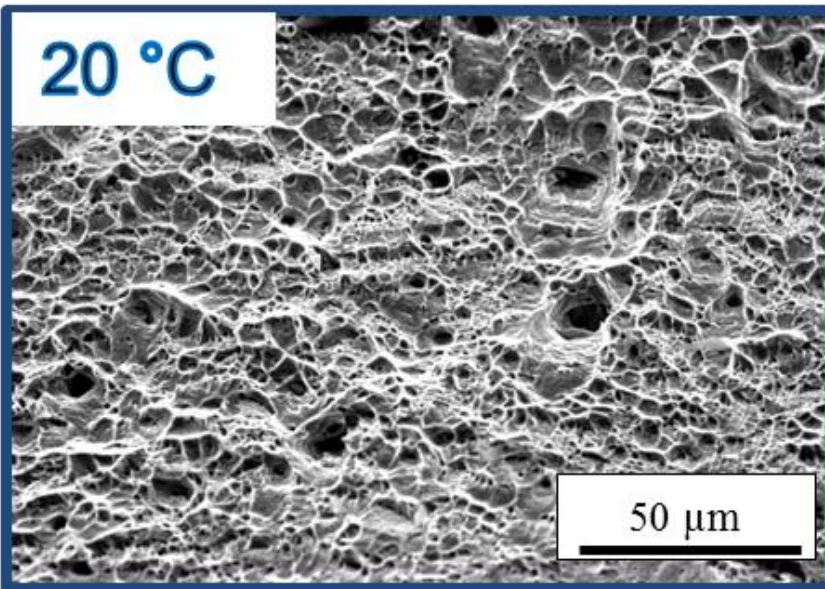
- ✓ The highest the % of cold work the lowest the UE over the temperature range
- ✓ The effect of T°C on ductility is not monotonous, with UE decreasing between 20°C and 200°C, increasing up to 500-600°C and finally decreasing above 600°C
- ✓ Very low UE is measured at 200°C (UE ~ 1 - 2%)

Fracture surfaces for Al-Ma-4 (cold swaging  $\epsilon 23\%$ ) tested at 20°C and 200°C

Necking rate : 53%



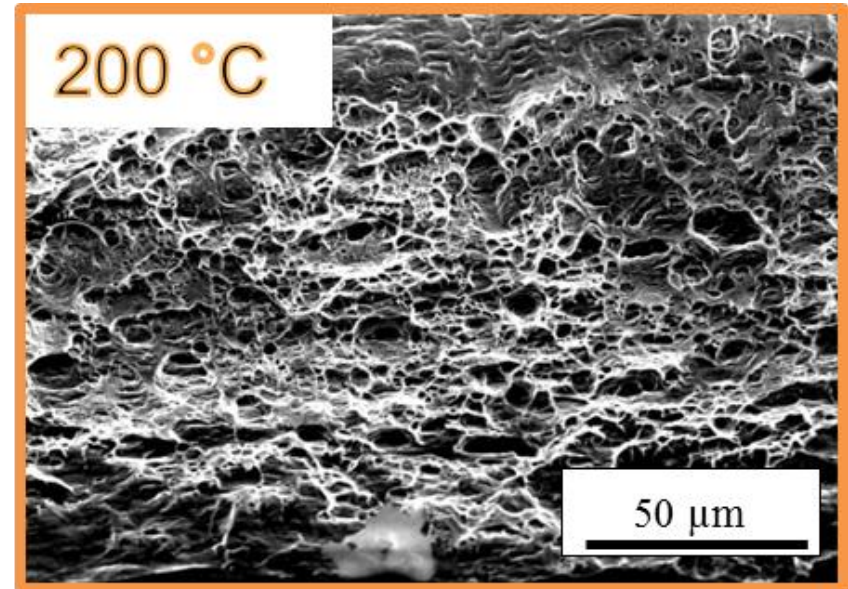
Necking rate : 21%

Necking rate  
 $Z = (S_0 - S) / S_0$ 

20 °C

50 μm

Ductile fracture with fine dimples



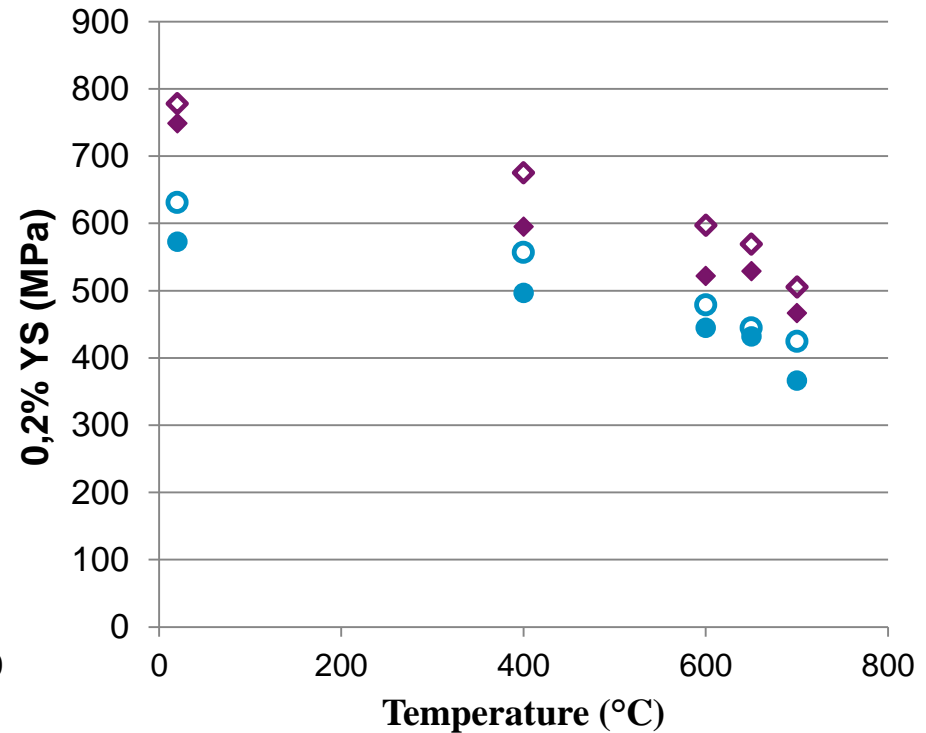
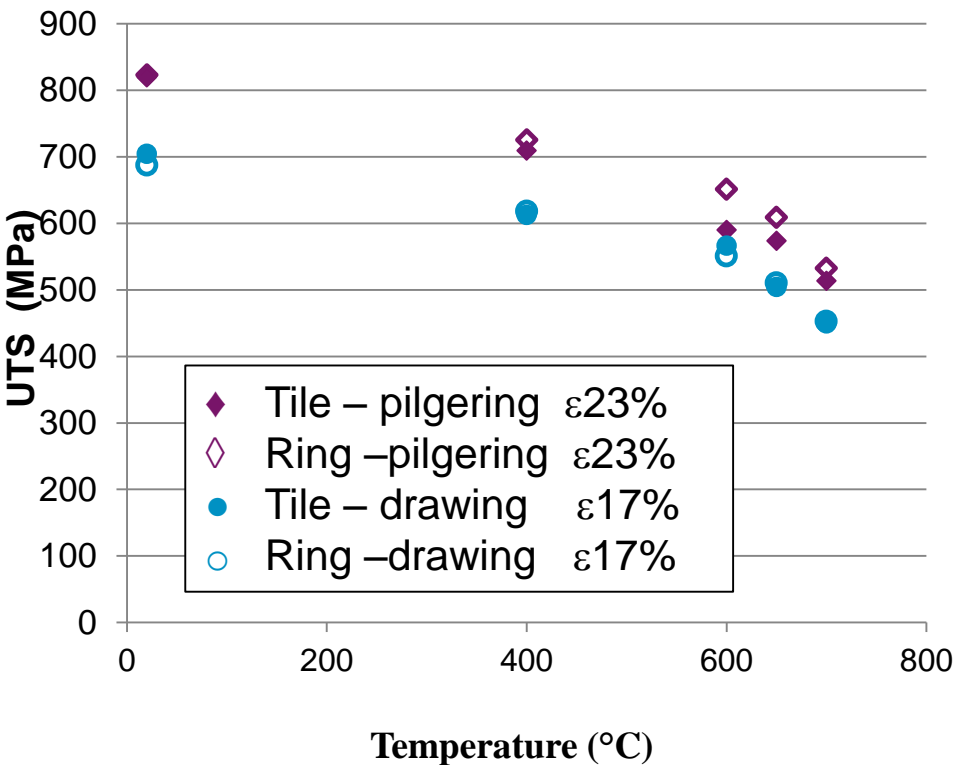
200 °C

50 μm

Ductile fracture with elongated dimples



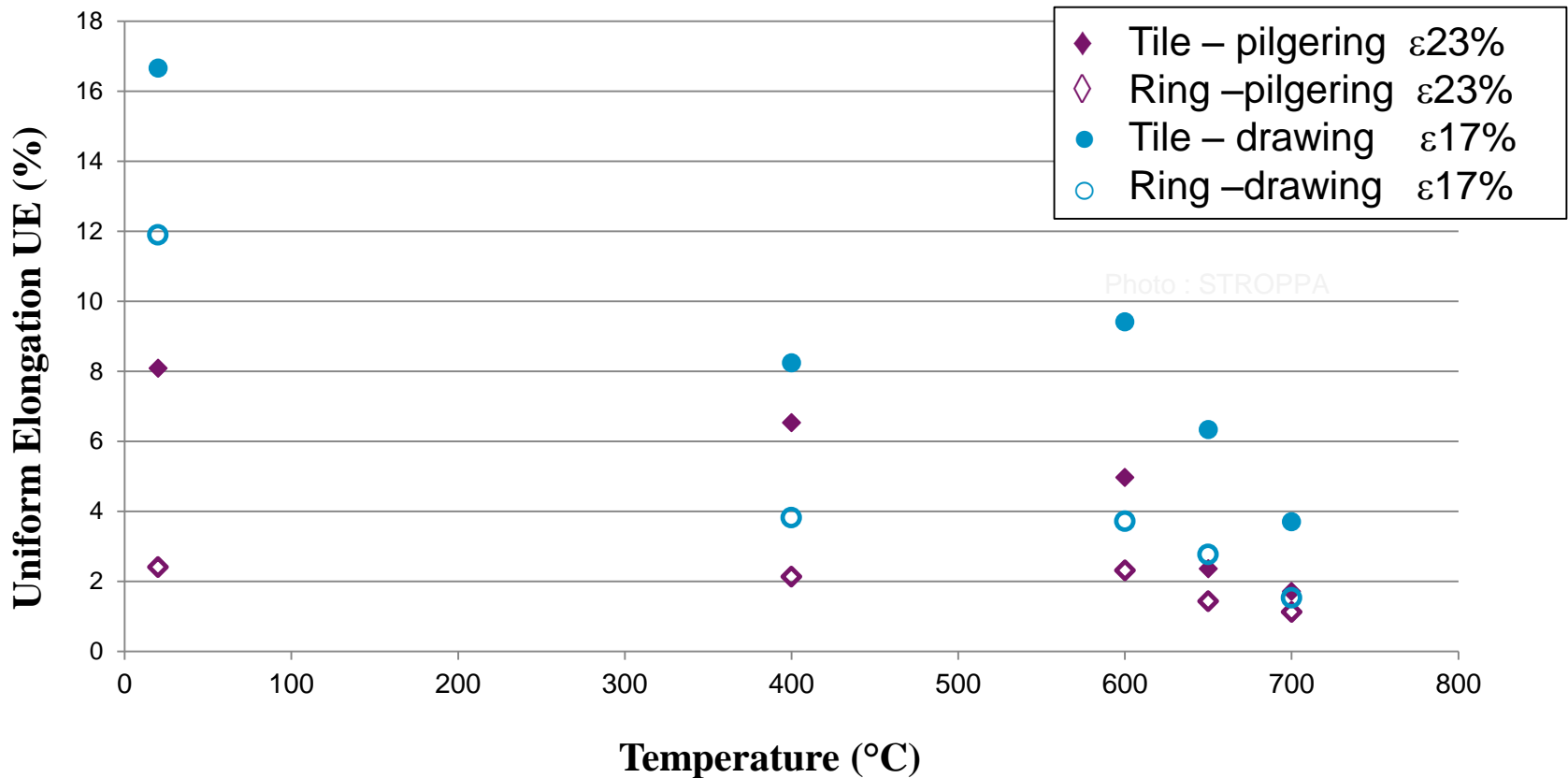
## Comparison : ring ↔ tile tests



The levels of strength (UTS, YS), are slightly higher in the circumferential direction (ring sp.) than those measured in the longitudinal direction (tile sp.)



### Comparison : ring tests ↔ tile tests



The UE are weaker in the circumferential direction (ring p.) than those measured in the longitudinal direction (tile sp.).



## Tensile behaviour of austenitic 15-15Ti $\epsilon$ SS :

- ✓ The stress-strain curves show strong temperature dependencies of strength and ductility.
- ✓ Both YS and UTS decrease linearly as test temperature raising from 20°C to 700°C.
- ✓ For the same level of cold work, no effect of the cold processes could be highlighted. However, the higher the amount of cold work ( $\epsilon \sim 37\%$ ), the higher the YS and the UTS and the lower the UE.
- ✓ In the circumferential direction, the levels of strength are slightly higher and the UE are weaker than those measured in the longitudinal direction, suggesting a low degree of anisotropy.
- ✓ The effect of temperature on ductility is not monotonous, with UE decreasing between 20°C and 200°C, increasing up to 500-600°C and finally decreasing above 600°C.  
Very low UE is thus measured at 200°C.

Why such low levels of ductility are measured at  $\sim 200^\circ\text{C}$  (and at a lesser degree at  $400^\circ\text{C}$ ) ?

→ It could be a consequence of a localization of the deformation which would result in a very limited plastic flow until necking

For 316 austentic SS :

The strong temperature dependence of the stress to activate twinning implies that it is not possible to induce twinning during plastic deformation at about  $200^\circ\text{C}$  and above. This limits plastic deformation to lower levels of UE

⇒ *Wu and al, JNM, 356 (2006) 70–77*

Or *Byun and al, Acta Mat., 52 (2004), 3889-3899*

For 15-15Ti $\epsilon$  SS : the origin of this singularity of behaviour is being studied at CEA in the course of the PhD work of Emilien Curtet

Thanks for your attention

Questions ?

