



# **Influence of the size effect on the strengthening behaviour of copper : temperature influence**

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## **► To cite this version:**

Pierre-Antoine Dubos, Eric Hug. Influence of the size effect on the strengthening behaviour of copper : temperature influence. EUROMAT 2011, European Congress and Exhibition on Advanced Materials and Processes, Oct 2011, Montpellier, France. 2011. <hal-05227565>

**HAL Id: hal-05227565**

**<https://normandie-univ.hal.science/hal-05227565v1>**

Submitted on 28 Aug 2025

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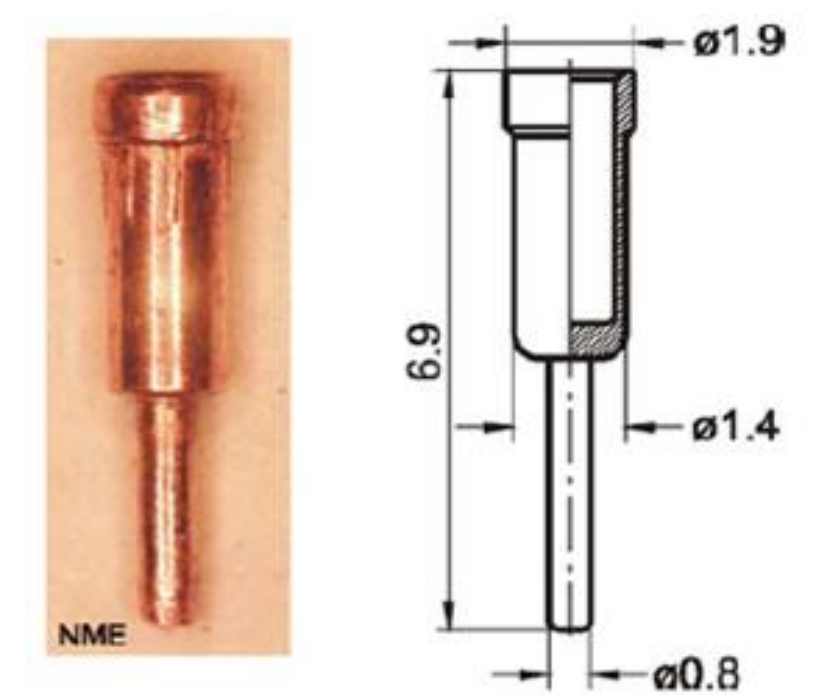
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## 1- Industrial context

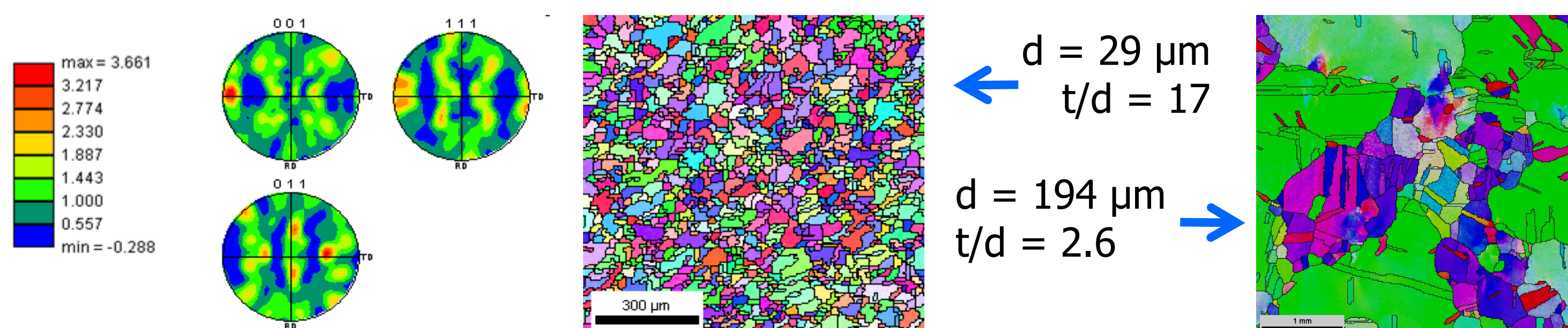


- Miniaturization of technological systems → modification of mechanical behaviour
- size effect parameter :  $\frac{t}{d} = \frac{\text{thickness}}{\text{grain size}}$
- Improvement of the microforming processes → temperature dependence of the size effect



## 2- Material

High purity (99.99 %) polycrystalline copper  
 $t = 500 \mu\text{m}$   $t/d = 2.6$  and  $17$   $(t/d)_c = 6$   
 Specimens annealed in secondary vacuum ( $P_{\text{oxygen}} = 2.10^{-11}$  bar) and then air cooled



## 3-Tensile tests

### Uniaxial tensile test

-70 °C < T < 500 °C  
 Strain rate :  $2 \cdot 10^{-4} \text{ s}^{-1}$

Elongations measured with an extensometer with the gauge length of 12.5 mm

### Tensile test with a temperature jump

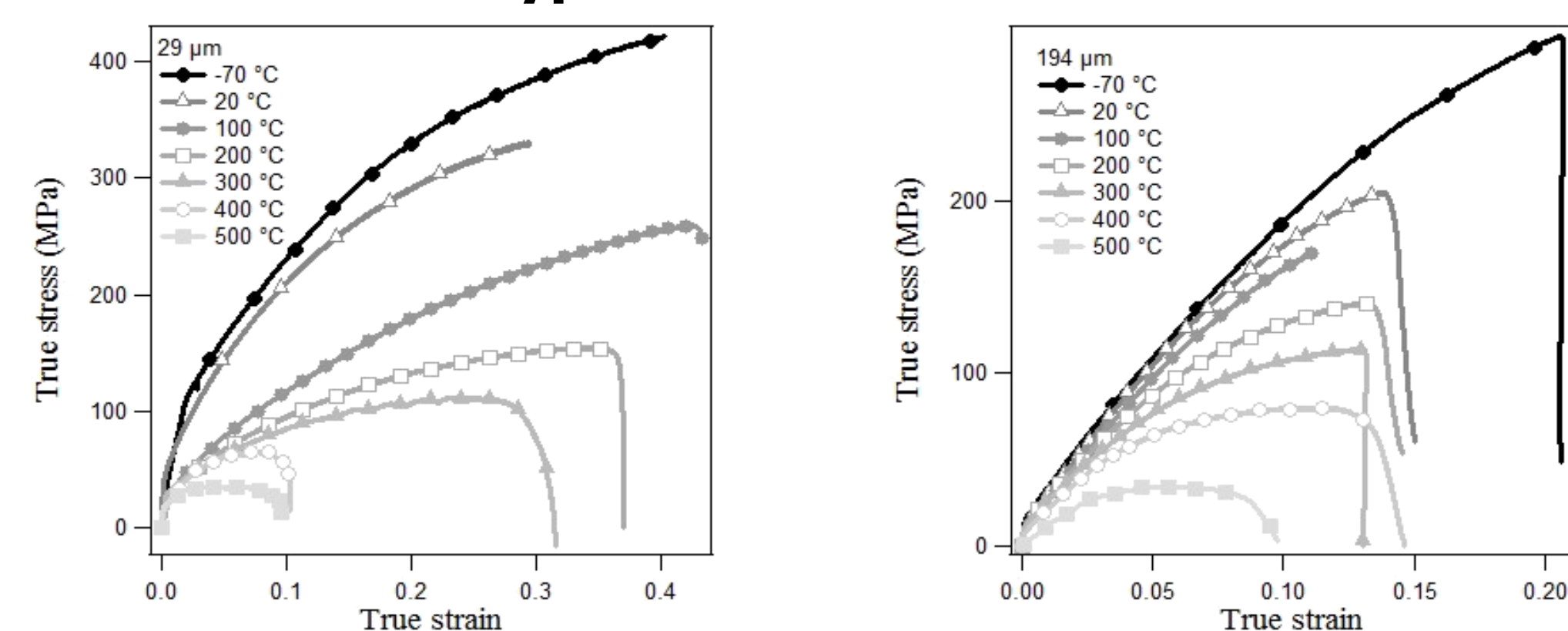
20 °C to -70 °C  
 100 °C to -70 °C  
 Strain rate :  $2 \cdot 10^{-4} \text{ s}^{-1}$  before and after the temperature jump

Unload before the jump to avoid the microstructure changes

Unload in stage II or stage III

## 4- Mechanical properties

### Typical tensile curves



$$\sigma = f(\varepsilon)$$

$$\sigma\theta = f(\sigma) \text{ with } \theta = \frac{d\sigma}{d\varepsilon}$$

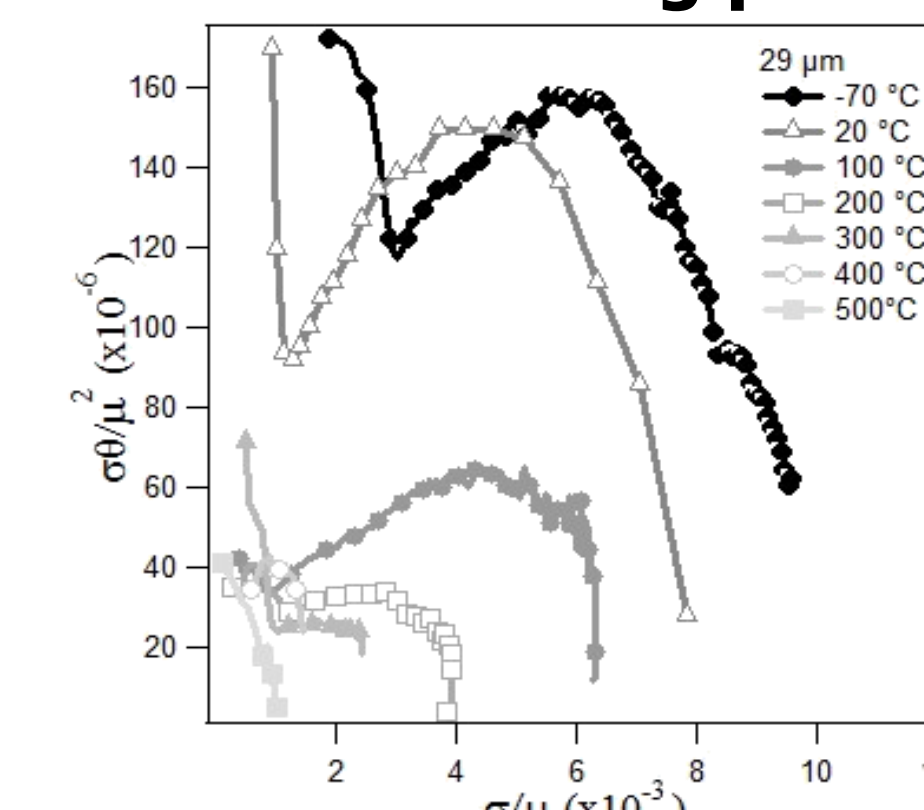
Linear stage II of work hardening

$$\sigma\theta = \Delta_{II} \sigma + (\sigma\theta)_0$$

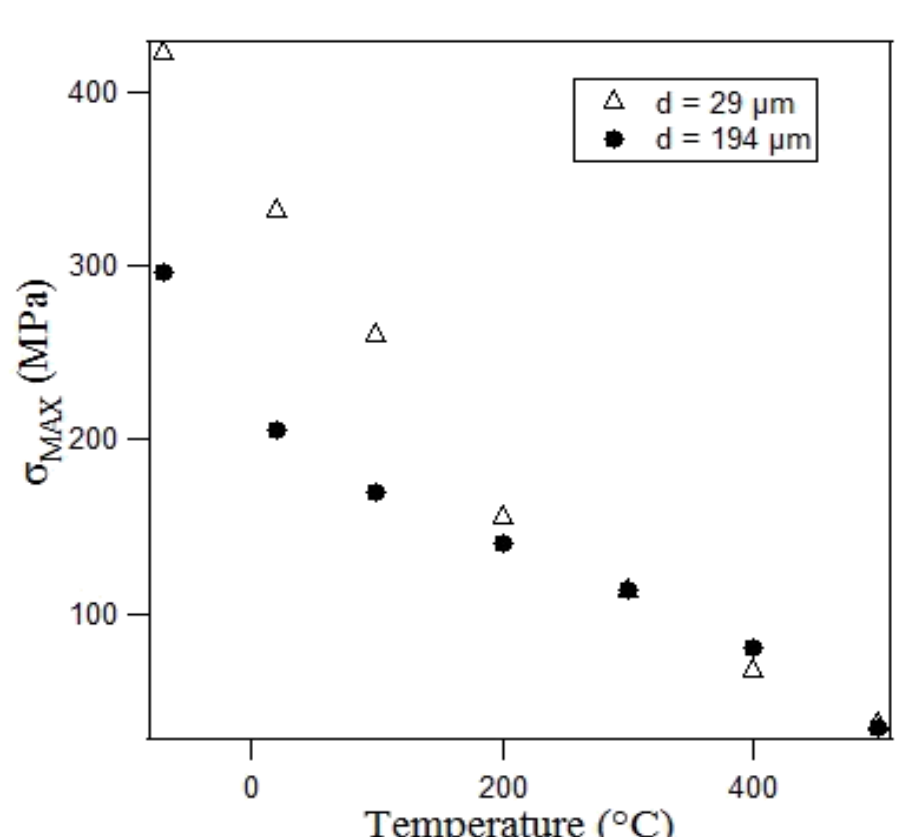
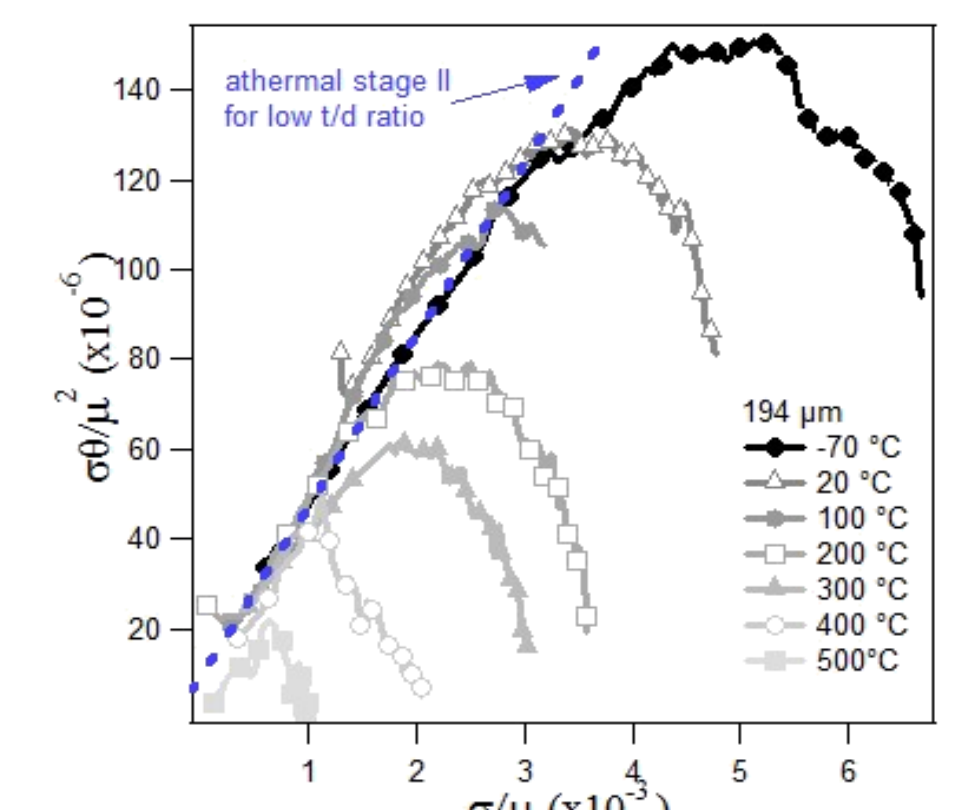
Interactions between dislocations

Grain boundaries contributions

### Kocks – Mecking plots

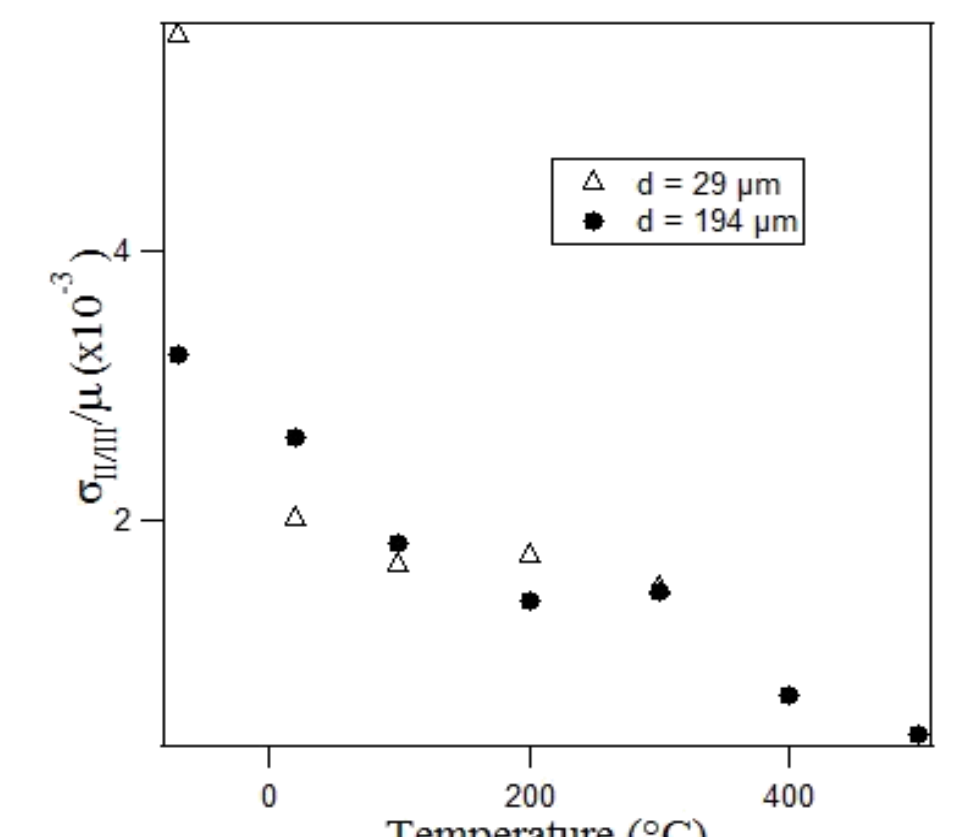
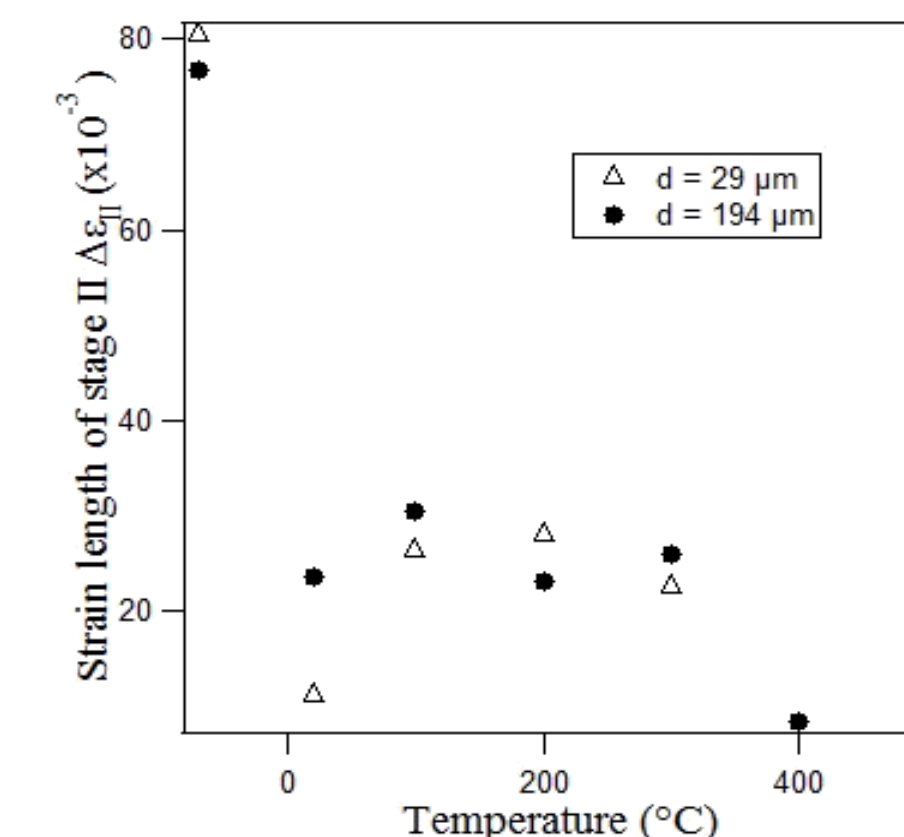


[Kocks, Mecking. *Progress in Materials Science*. 2003]  
 [Sevillano. In *Material Sciences and Technology*. 1993]

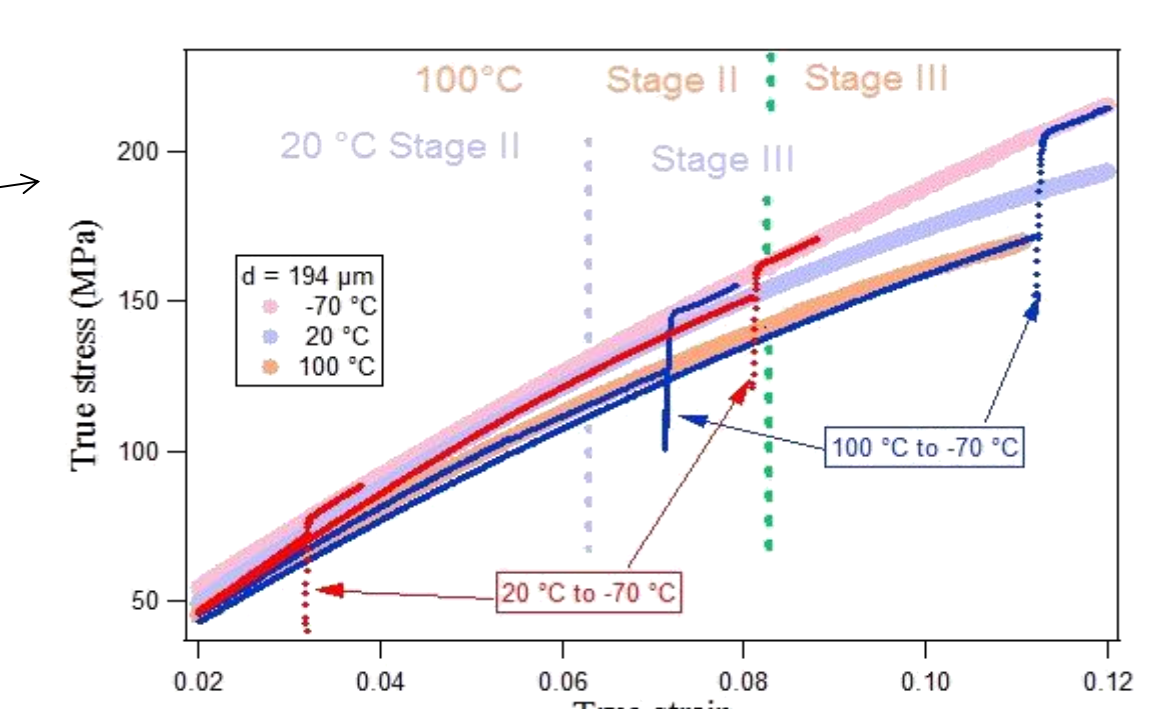
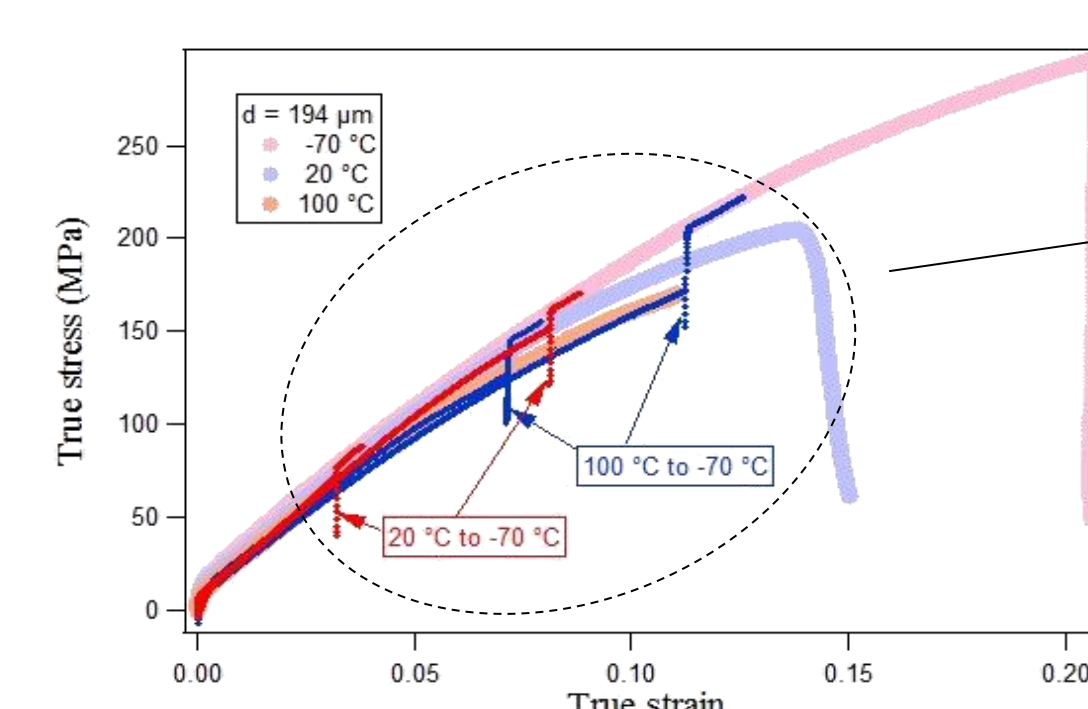
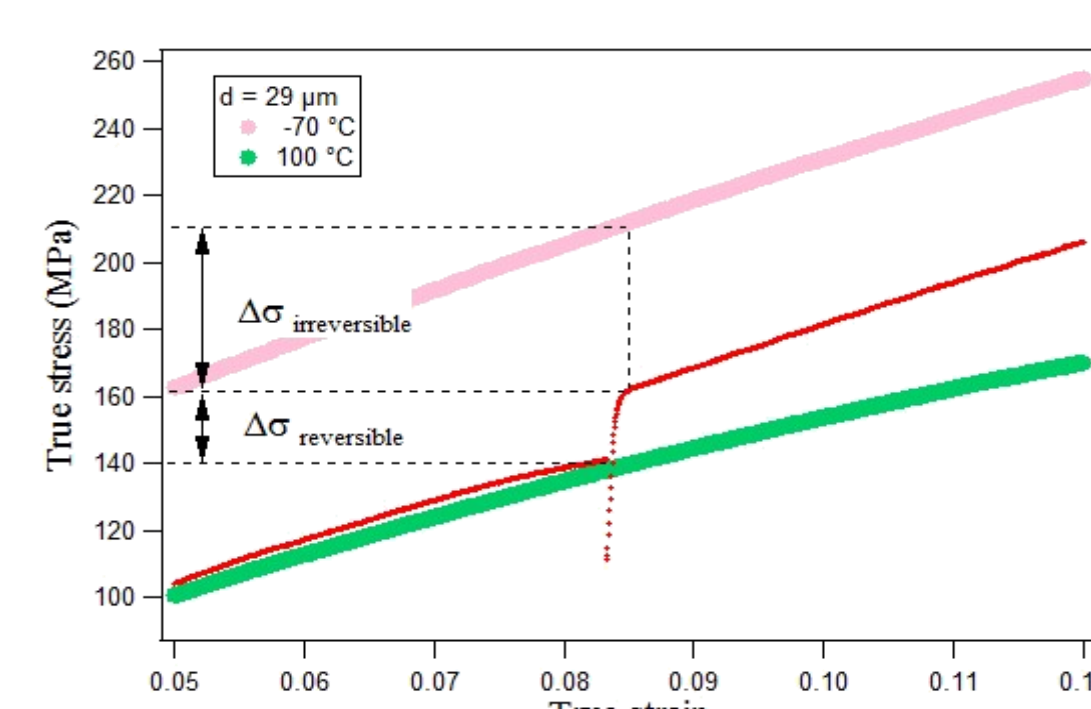
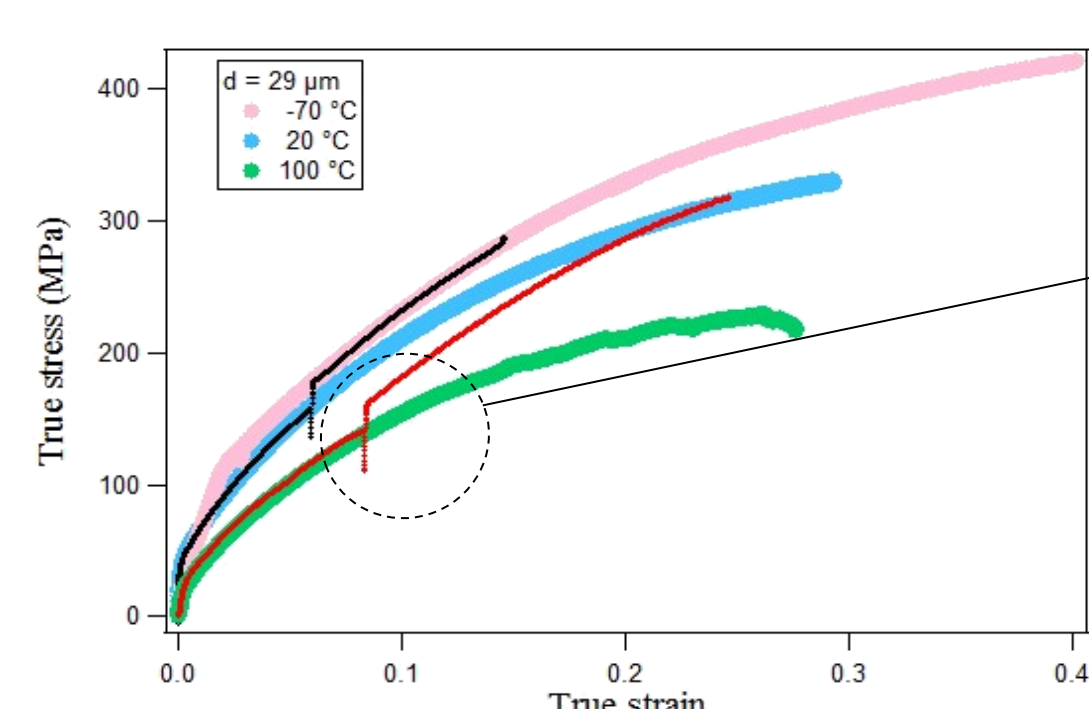


### Parameter evolutions with temperature

- The grain size does not affect the ultimate tensile test  $\sigma_{\text{MAX}}$  from 200 °C
- T increases the dislocation mobility and decreases dense structures, delaying the entry to stage II and decreasing the strain length of stage II
- Thermic activation of stage III, generalization of cross slip, dynamic recovery → Work hardening decreases



## 5- Origin of work hardening mechanisms with temperature



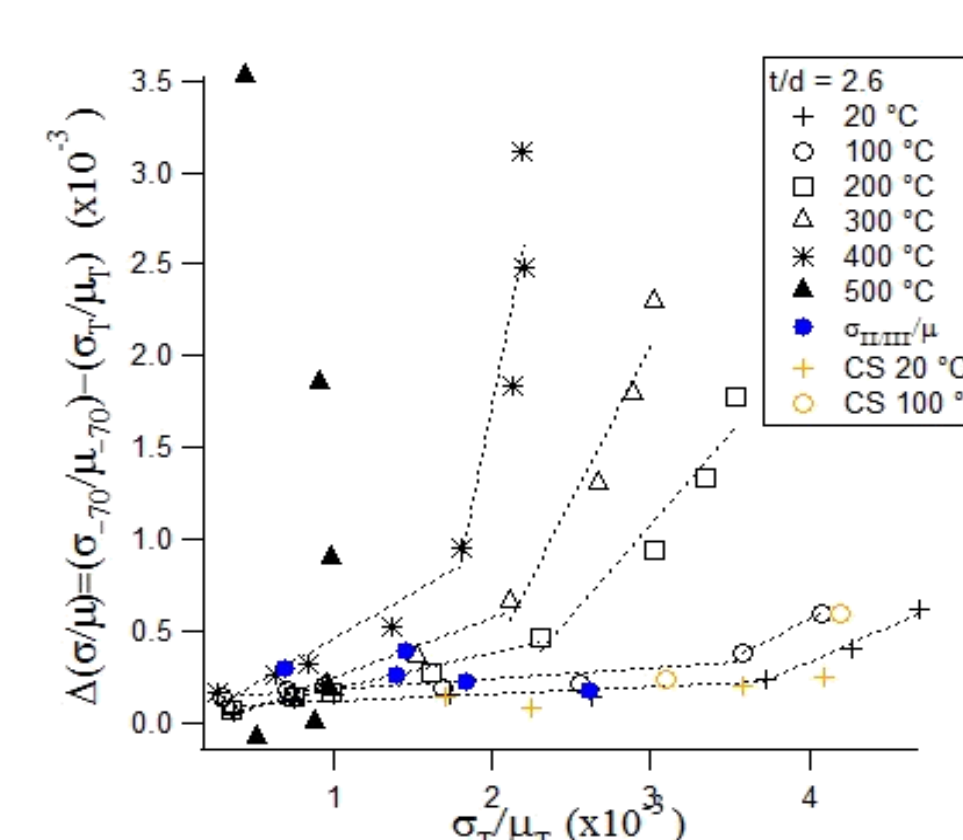
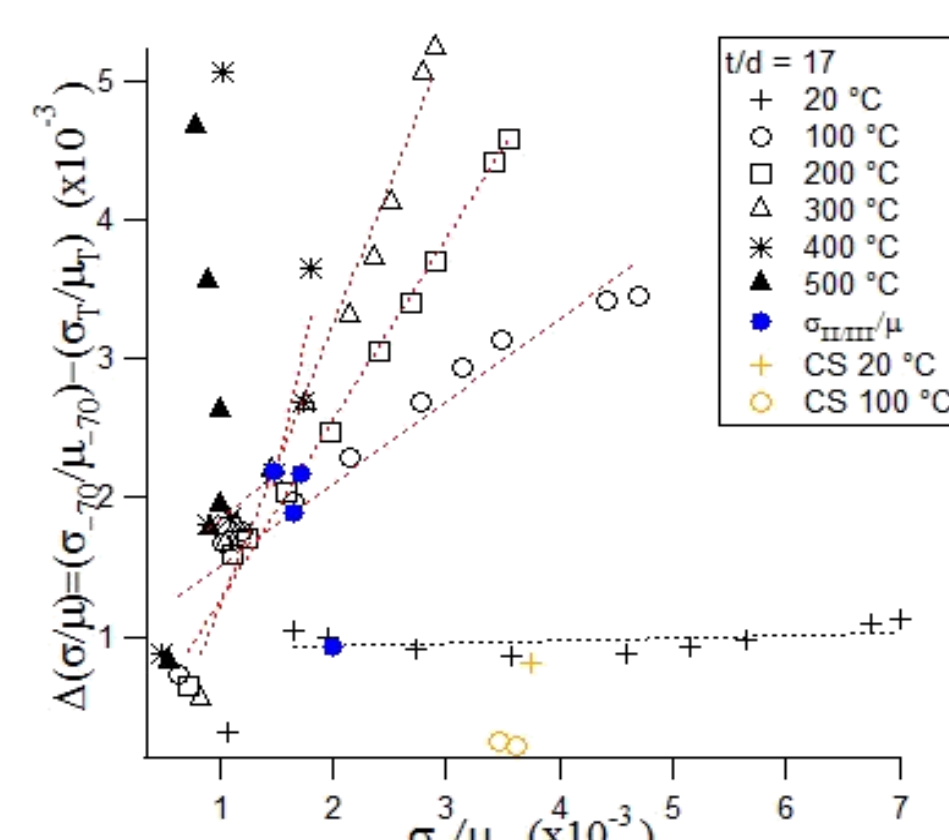
$$\sigma = s(\dot{\varepsilon}, T) \hat{\alpha} \mu b \sqrt{\rho} \equiv \alpha \mu b \sqrt{\rho}$$

### Taylor's equation

$$\Delta \frac{\sigma}{\mu} = \frac{\sigma_{T_{ref}}}{\mu_{T_{ref}}} - \frac{\sigma_T}{\mu_T} = \left( \frac{s_{T_{ref}}}{s_T} - 1 \right) \frac{\sigma_T}{\mu_T}$$

### Cottrell – Stokes (CS) law

[Cottrell, Stokes. *Proceedings of the Royal Society of London*. 1955]  
 [Mecking, Kocks. *Acta Metallurgica*. 1981]



### Cottrell – Stokes law with temperature tests

#### Influence of size effect parameter on work hardening mechanisms

- $t/d = 17$  → CS law respected (linear behaviour between  $\Delta(\sigma/\mu)$  and  $\sigma_T/\mu_T$ )
- $t/d = 2.6$  → Two trends → change of dislocations structures, through the parameter s, from a certain work hardening level

### Cottrell – Stokes law with « jump temperature » tests

$t/d = 17$

- After the temperature jump, same behaviour than tensile test at a given temperature
- Possibility of a CS study without jump

$t/d = 2.6$

- Same behaviour for 20 °C to -70 °C jump
- Irreversible and reversible parts for 100 °C to -70 °C jump

## 6- Conclusion

- Disappearance of stage II for the low t/d ratio can be lie to the dislocation structures change
- Work hardening decreases with T, improvement of the micro-forming behaviour for thin copper sheets with low grain number in the thickness