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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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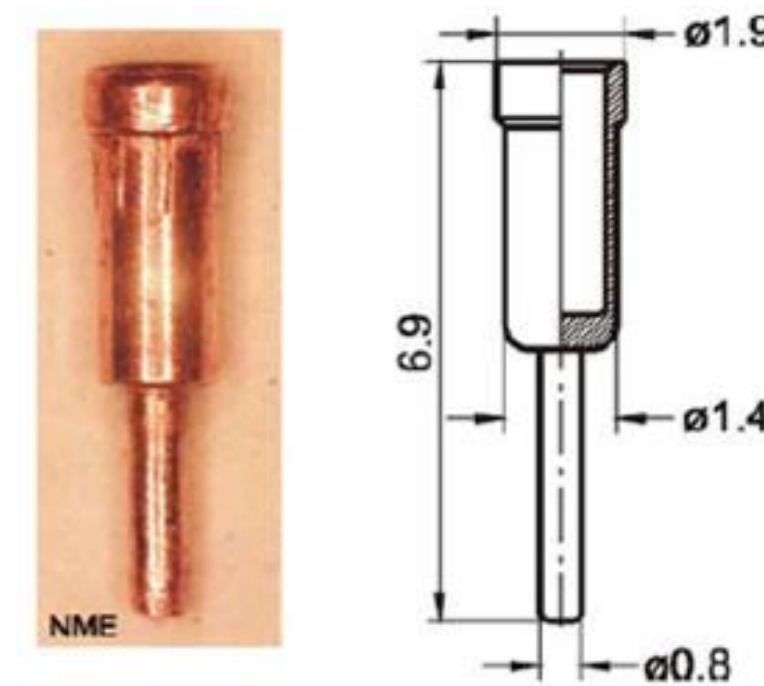


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1- Industrial context

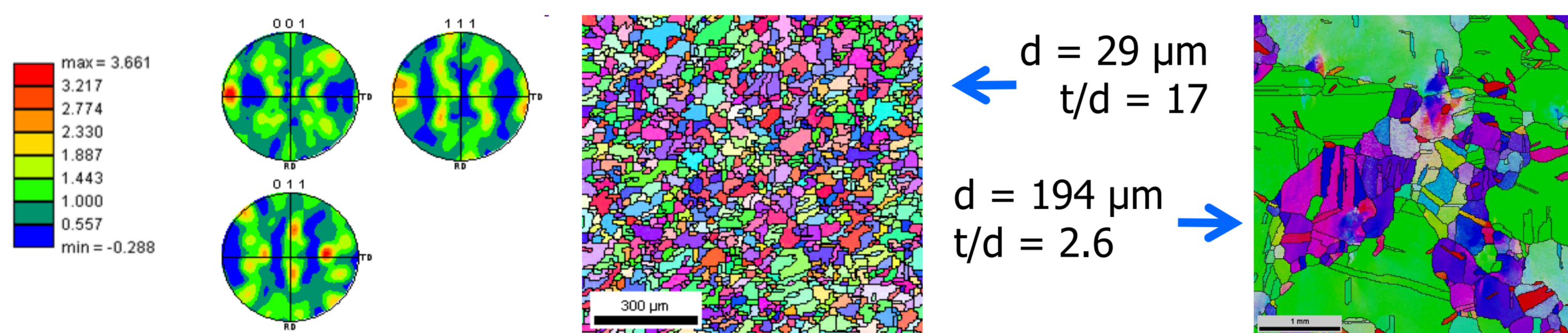


- Miniaturization of technological systems → modification of mechanical behaviour
- size effect parameter : $\frac{t}{d} = \frac{\text{thickness}}{\text{grain size}}$
- Improvement of the microforming processes → temperature dependence of the size effect



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

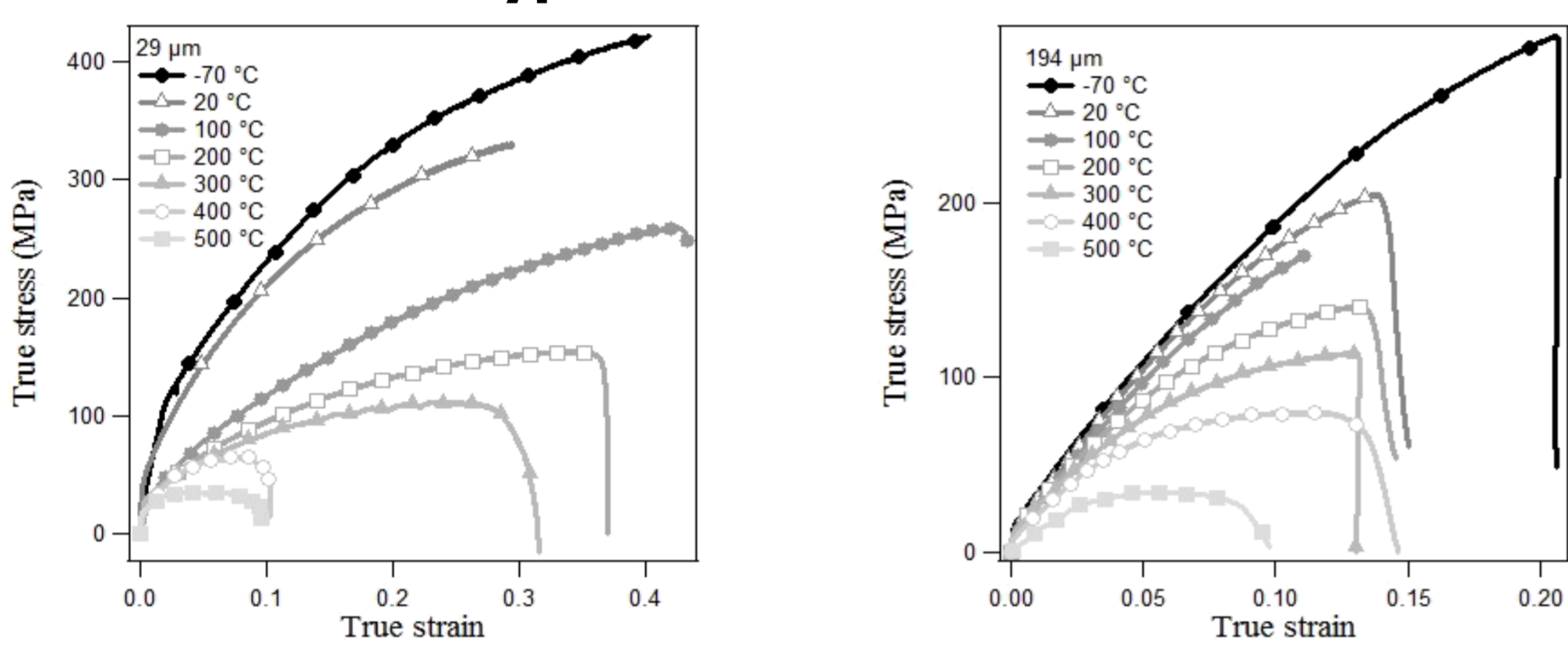
Strain rate : $2 \cdot 10^{-4} \text{ s}^{-1}$ before and after the temperature jump

Unload before the jump to avoid the microstructure changes

Unload in stage II or stage III

4- Mechanical properties

Typical tensile curves



$$\sigma = f(\epsilon)$$

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

Linear stage II of work hardening

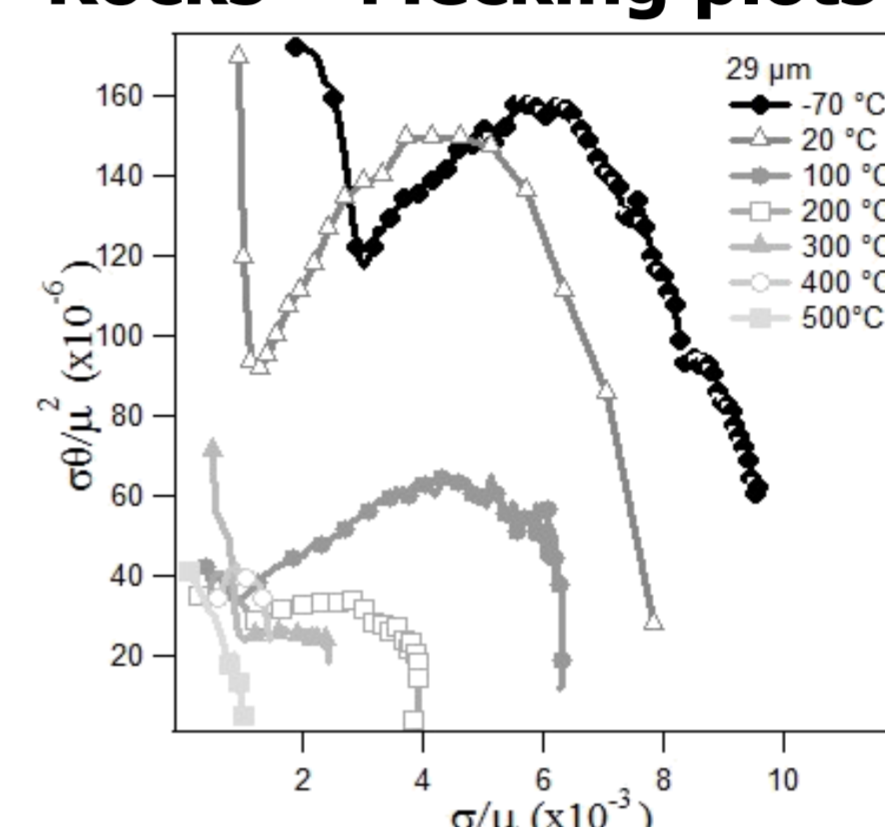
$$\sigma\theta = \Delta_{II} \sigma + (\sigma\theta)_0$$

[Keller, Hug, Feaugas. *International Journal of Plasticity*, 2011]
 [Hug, Keller. *Metallurgical and Materials Transactions A*, 2010]

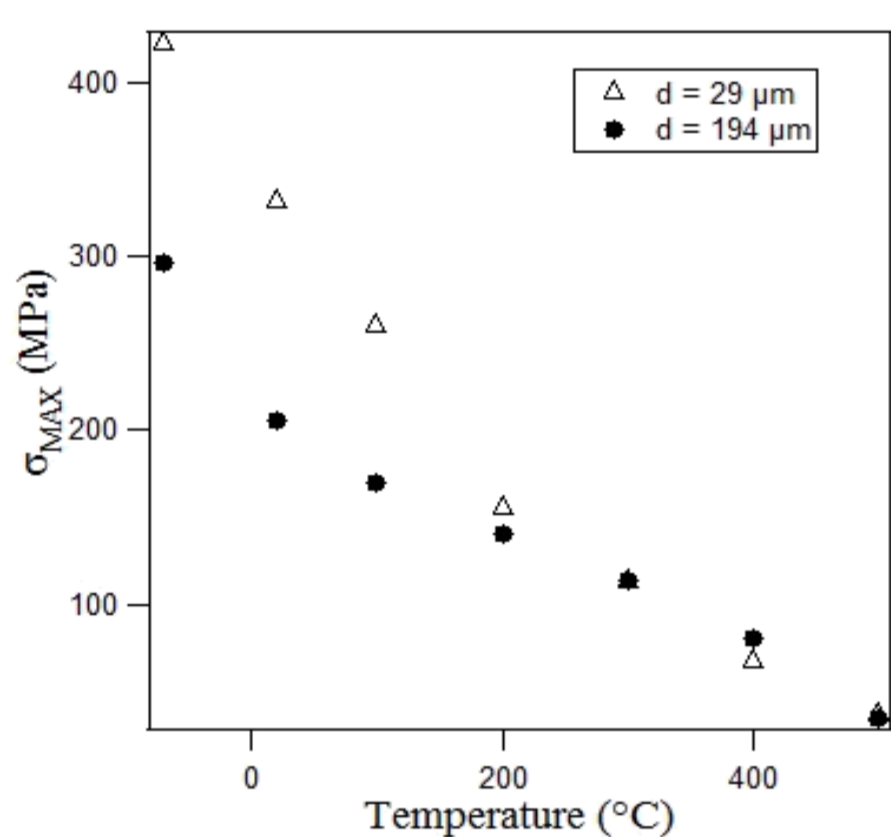
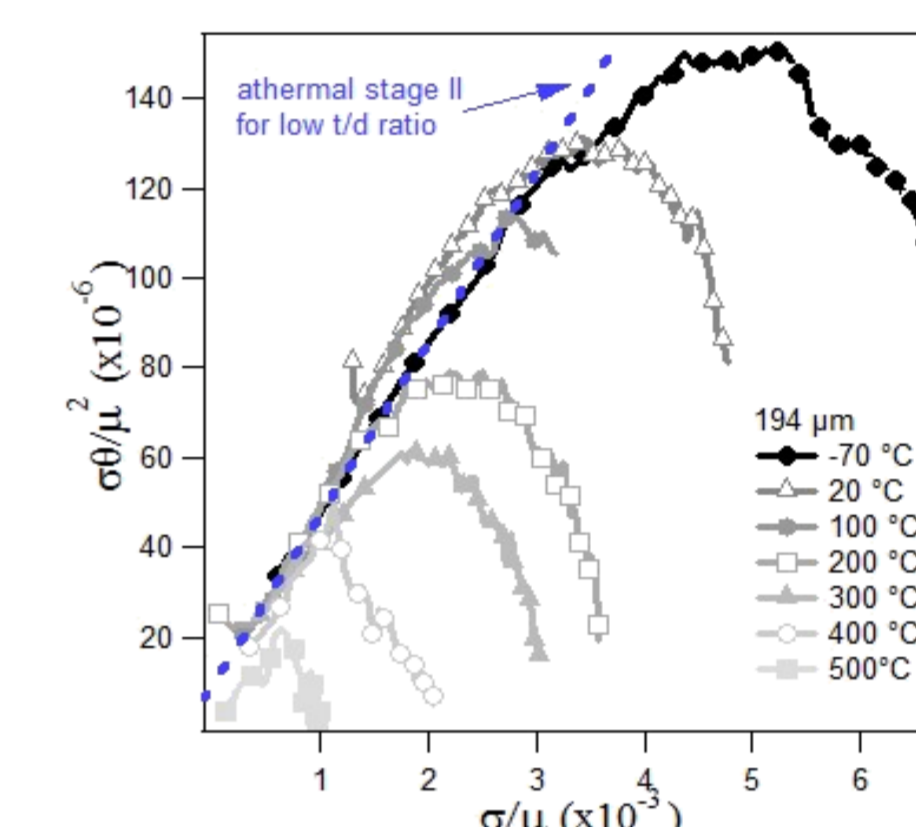
Interactions between dislocations

Grain boundaries contributions

Kocks – Mecking plots

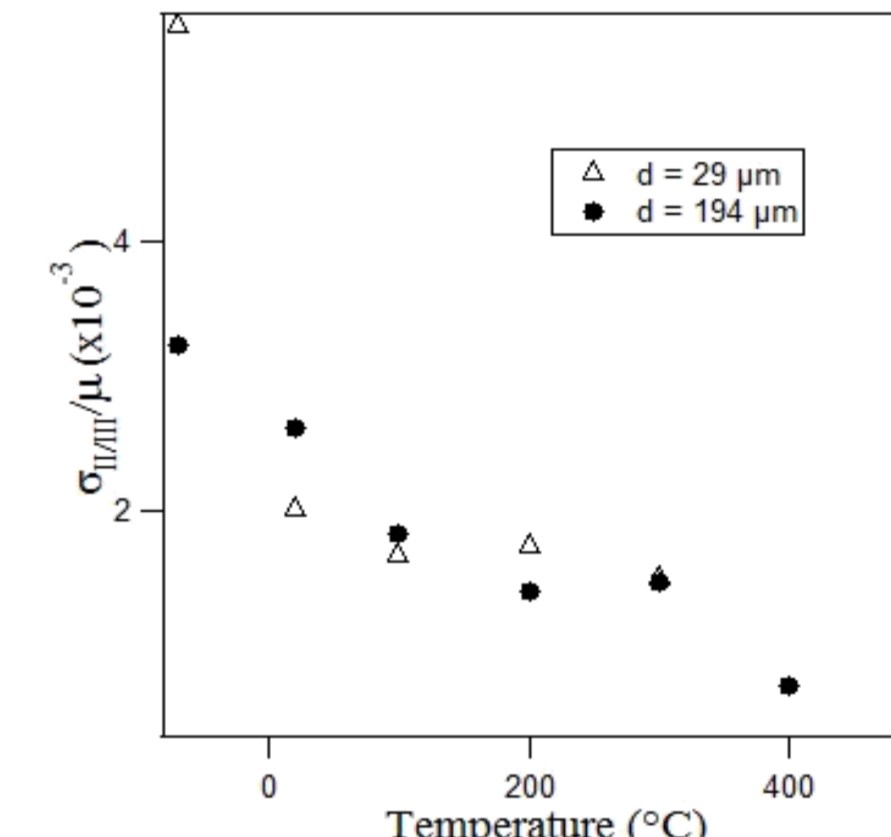
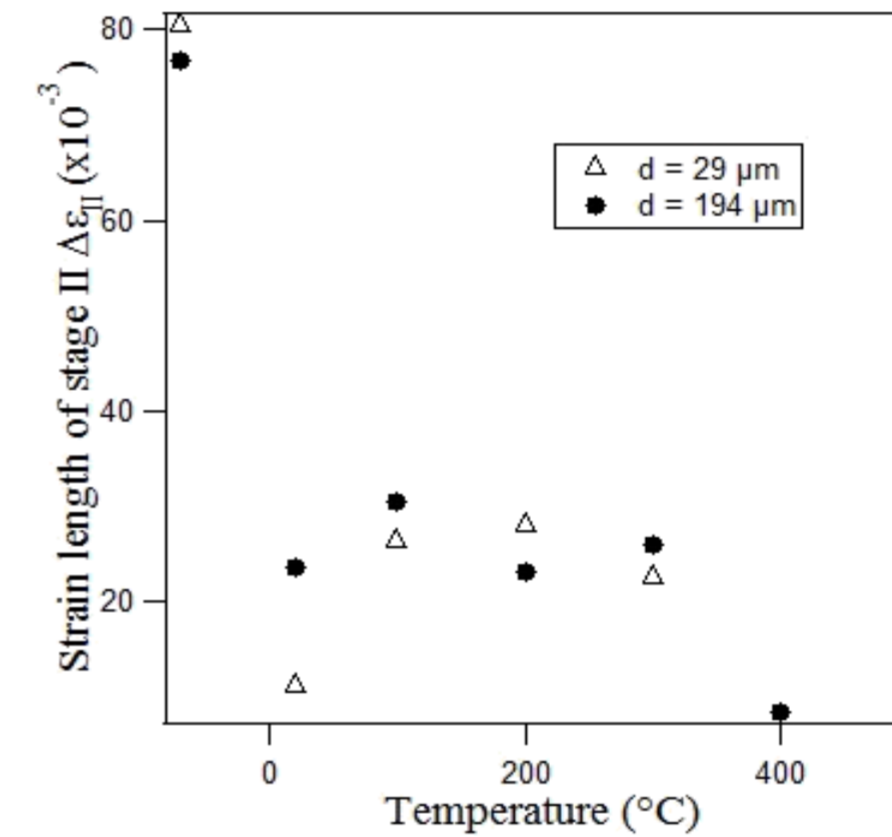


[Kocks, Mecking. *Progress in Materials Science*, 2003]
 [Sevillano. In *Material Sciences and Technology*, 1993]

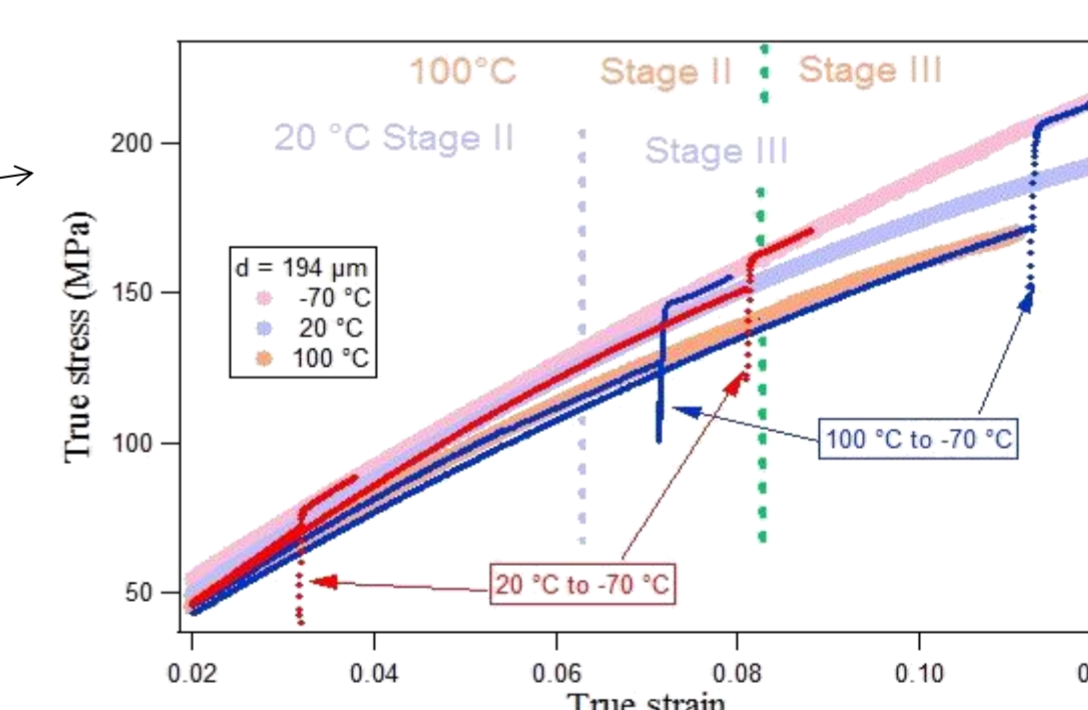
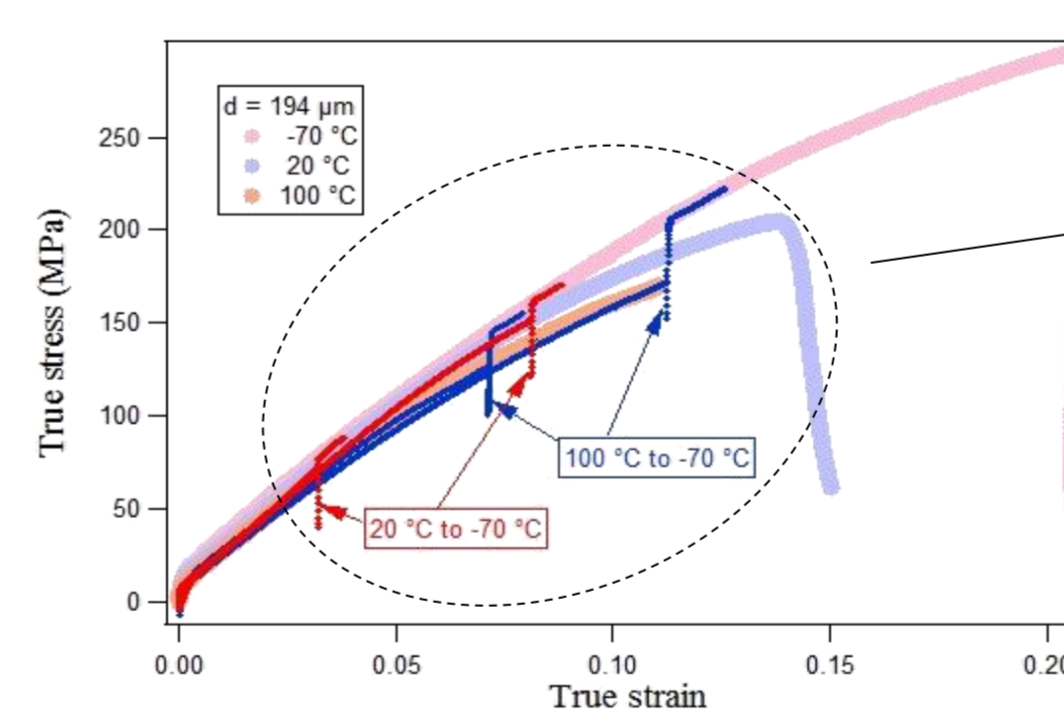
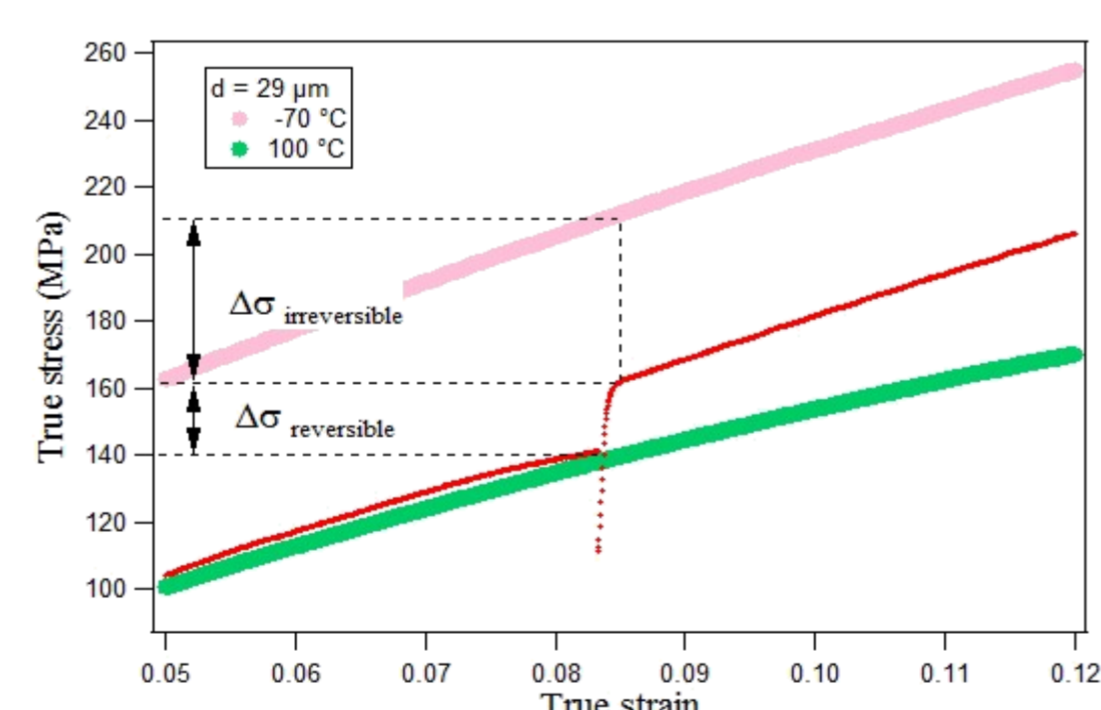
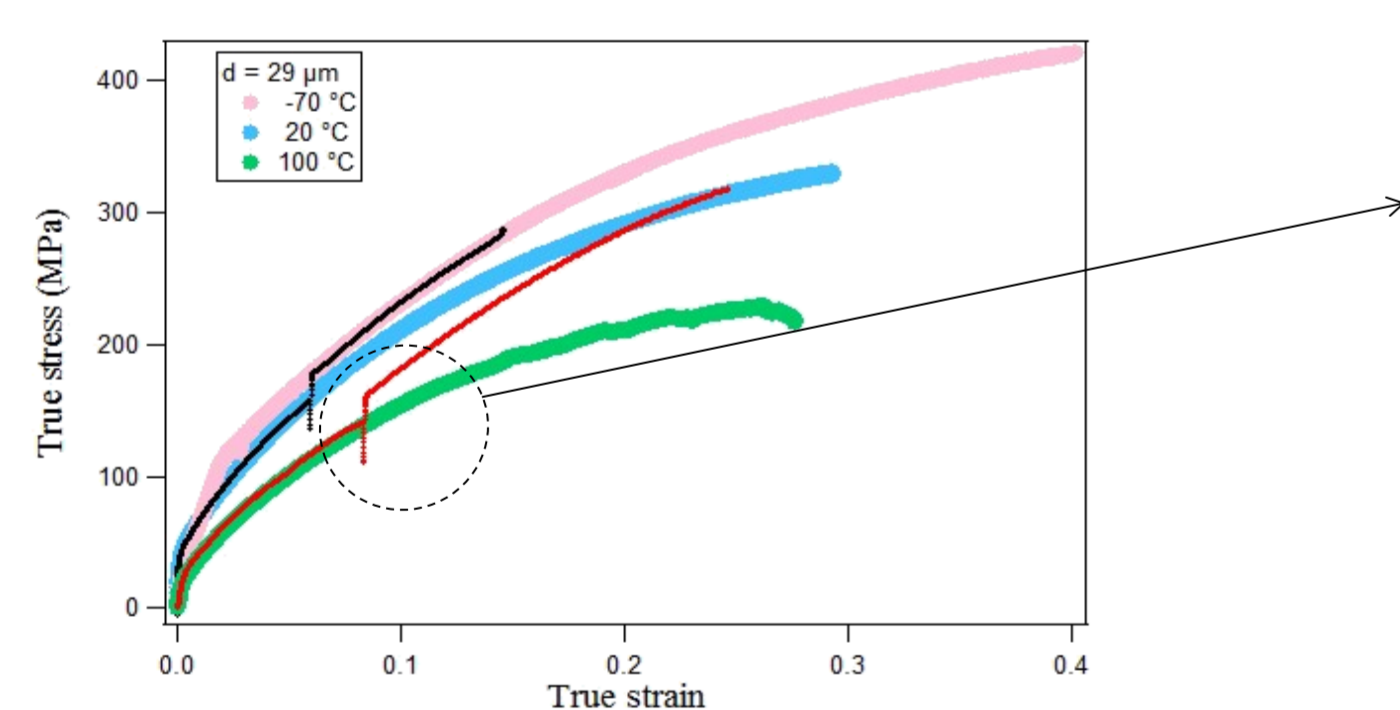


Parameter evolutions with temperature

- The grain size does not affect the ultimate tensile test σ_{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



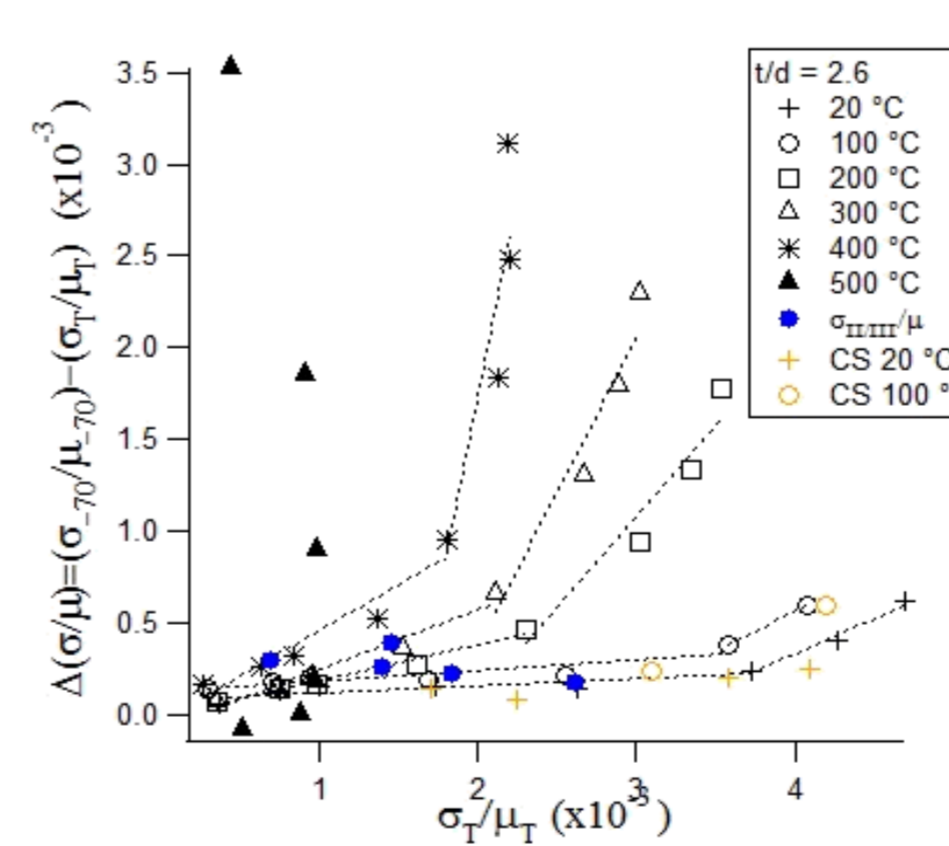
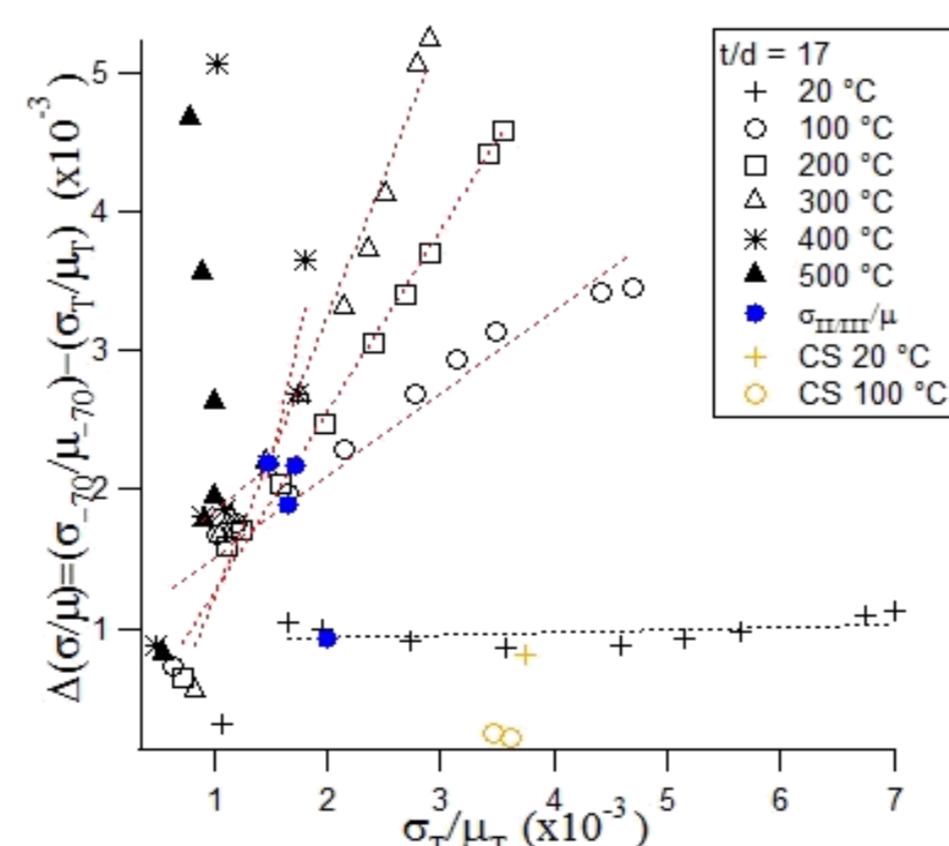
$$\sigma = s(\dot{\epsilon}, T) \hat{\alpha} \mu b \sqrt{\rho} \equiv \alpha \mu b \sqrt{\rho}$$

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 σ_T/μ_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