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

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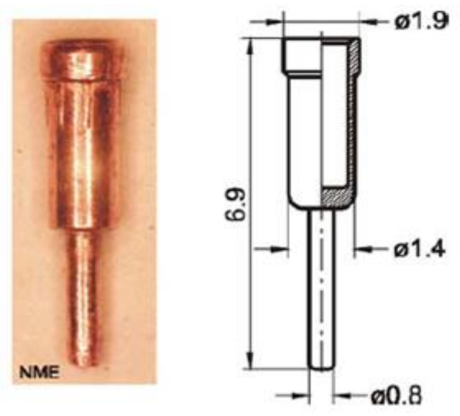
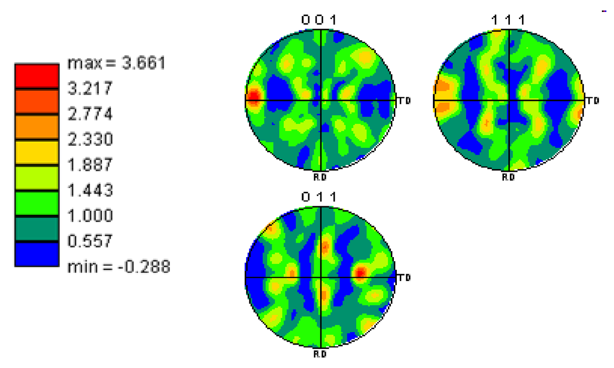
1- Industrial context

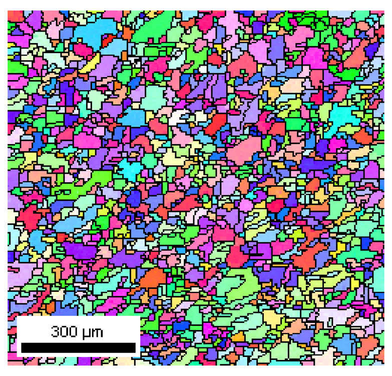
- Miniaturization of technological systems → modification of mechanical behaviour
- size effect parameter : $\frac{t}{d} = \frac{\text{thickness}}{\text{grain size}}$
- Improvement of the microforming processes → temperature dependence of the size effect



2- Material

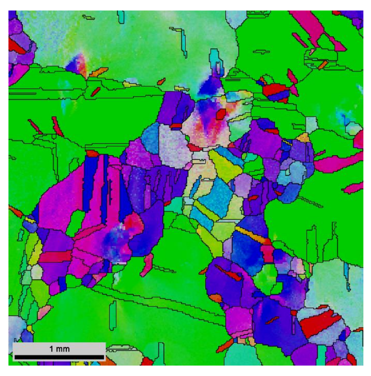
High purity (99.99 %) polycrystalline copper
t = 500 µm   t/d = 2.6 and 17 $(t/d)_c = 6$
Specimens annealed in secondary vacuum ($P_{(oxygen)} = 2.10^{-11}$ bar) and then air cooled





d = 29 µm
t/d = 17

d = 194 µm
t/d = 2.6



3-Tensile tests

Uniaxial tensile test

-70 °C < T < 500 °C
Strain rate : 2.10^{-4} s^{-1}

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

Tensile test with a temperature jump

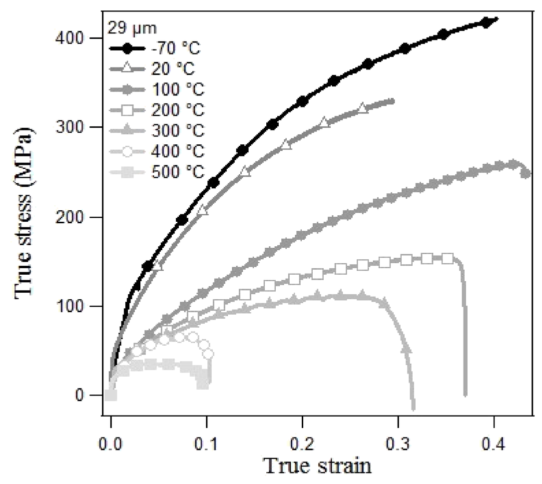
20 °C to -70 °C
100 °C to -70 °C
Strain rate : 2.10^{-4} s^{-1} before and after the temperature jump

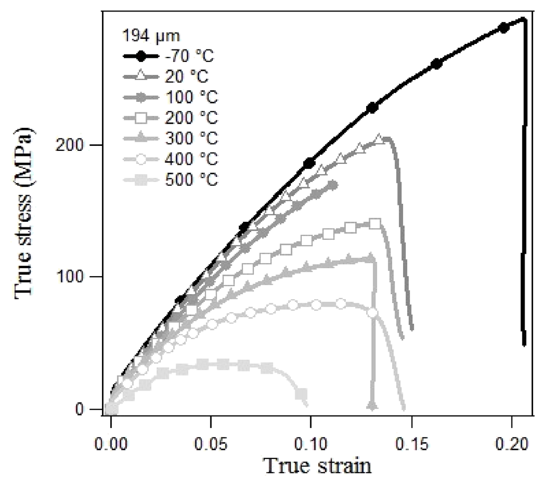
Unload before the jump to avoid the microstructure changes

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

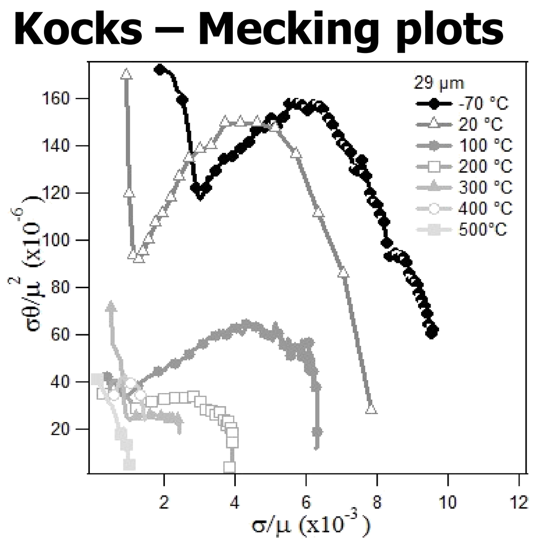
$$\sigma\theta = \Delta_{II}\,\sigma + (\sigma\theta)_0$$

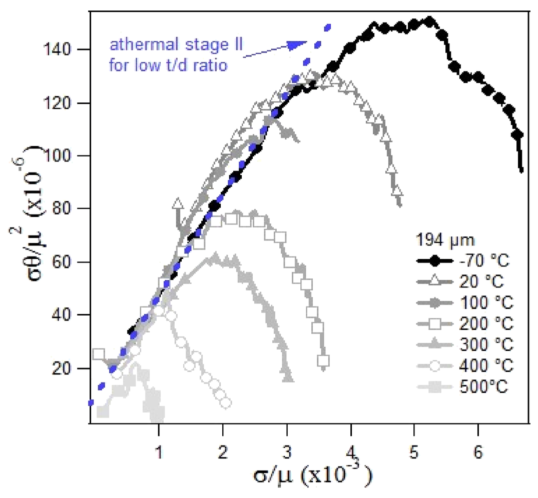
[Keller, Hug, Feaugas. *International Journal of Plasticity*. 2011]
[Hug, Keller. *Metallurgical and Materials Transactions A*. 2010]

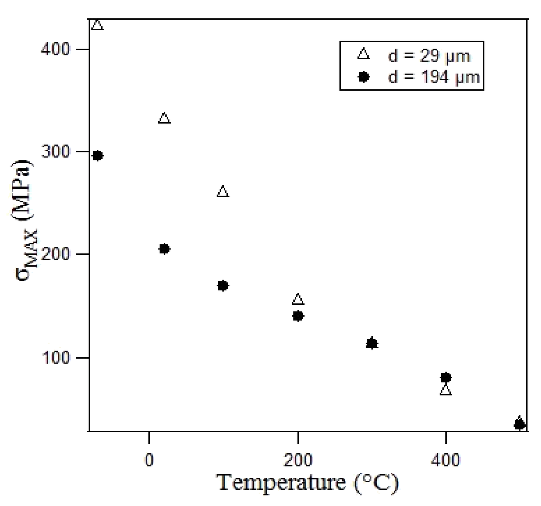
Interactions between dislocations   Grain boundaries contributions

Kocks – Mecking plots

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

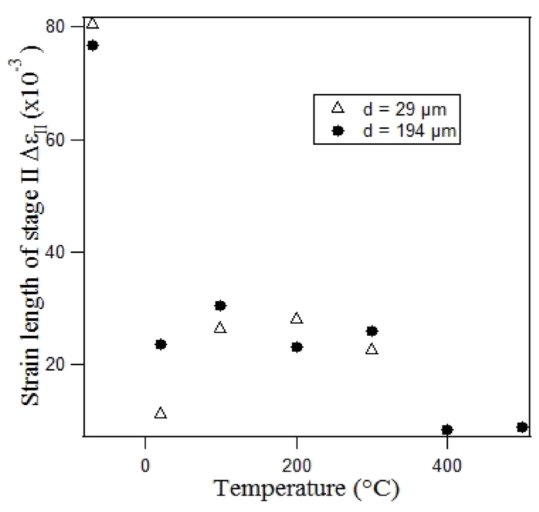


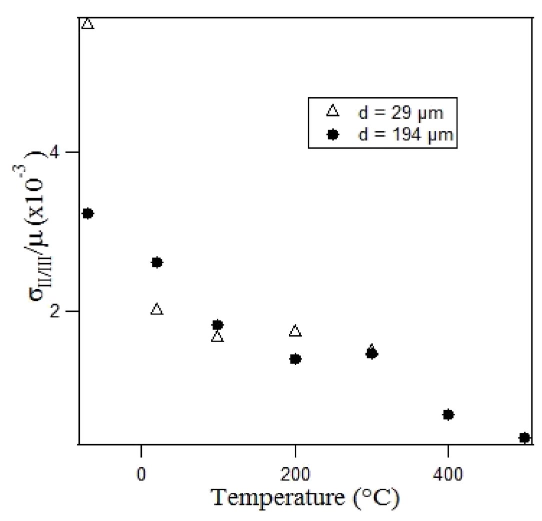




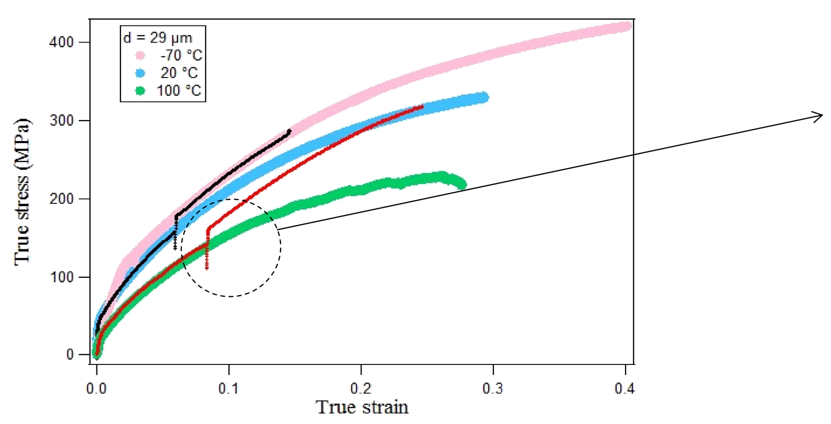
Parameter evolutions with temperature

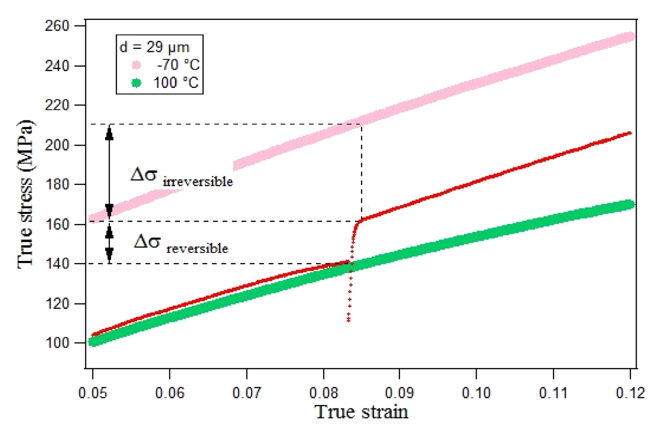
- The grain size does not affect the ultimate tensile test σ_{MAX} from 200 °C
- T increases the dislocation mobility and decreases dense structures, delaying the entry to stage II and decreasing the strain length of stage II
- Thermic activation of stage III, generalization of cross slip, dynamic recovery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





5- Origin of work hardening mechanisms with temperature





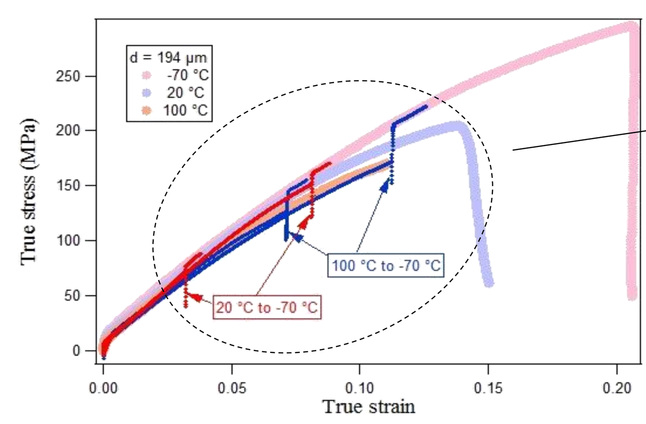
$$\sigma = s(\dot{\varepsilon},T)\hat{\alpha}\mu b\sqrt{\rho} \equiv \alpha\mu b\sqrt{\rho}$$

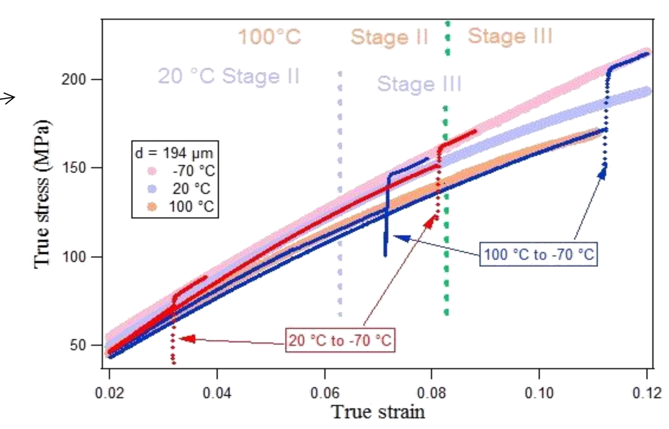
Taylor's equation

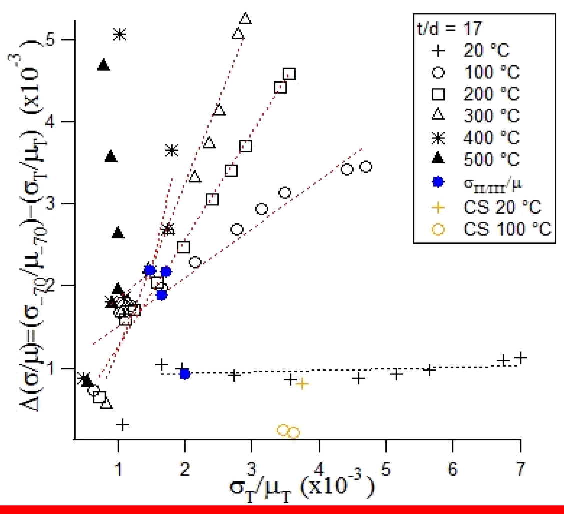
$$\Delta\frac{\sigma}{\mu} = \frac{\sigma_{T_{réf}}}{\mu_{T_{réf}}} - \frac{\sigma_T}{\mu_T} = \left(\frac{s_{T_{réf}}}{s_T} - 1\right)\frac{\sigma_T}{\mu_T}$$

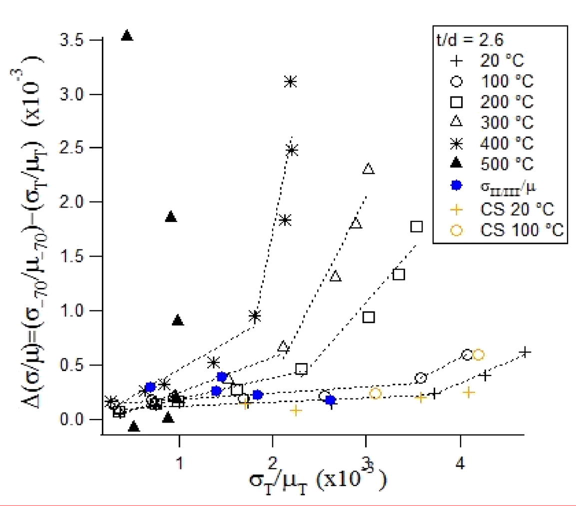
Cottrell – Stokes (CS) law

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









Cottrell – Stokes law with « 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

Cottrell – Stokes law with temparature 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

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