Fatigue gigacyclique des matériaux métalliques investiguée par des essais ultrasoniques : effets de fréquence, matériaux et mécanismes

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Fatigue gigacyclique
Very High Cycle Fatigue

- **Car engine: (crankshaft, ball bearings, etc.):**

  10^8- 10^9 cycles

- **Wheel of a high speed train:**

  10^9 cycles

- **Large diesel engine for ship:**

  10^9 cycles or more

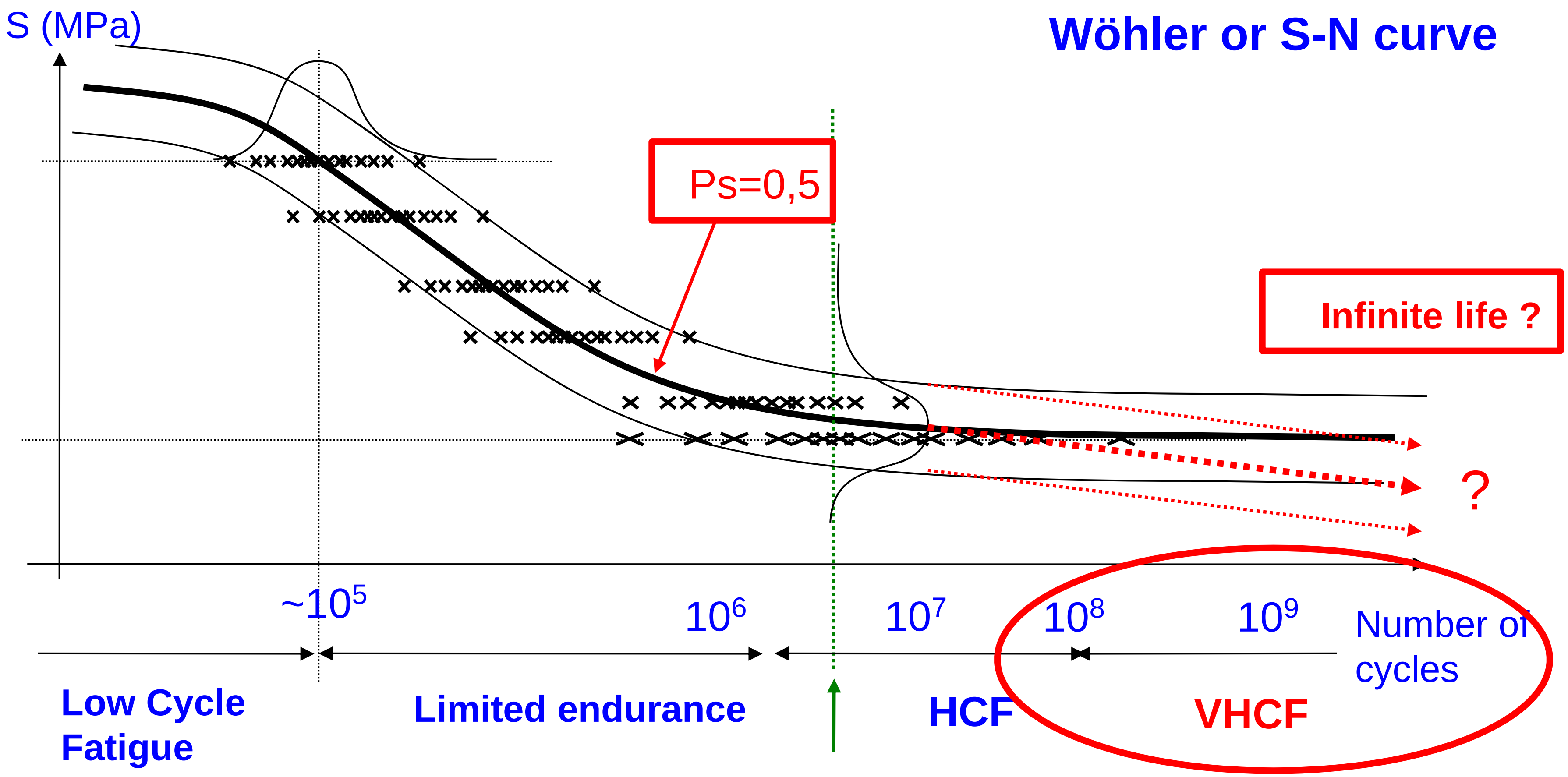
- **Turbine blade under 1 kHz vibration in-service resonance:**

  10^9 cycles after 300 hours only!

Master MAGIS

Cours VHCF:
T. Palin-Luc
V. Favier

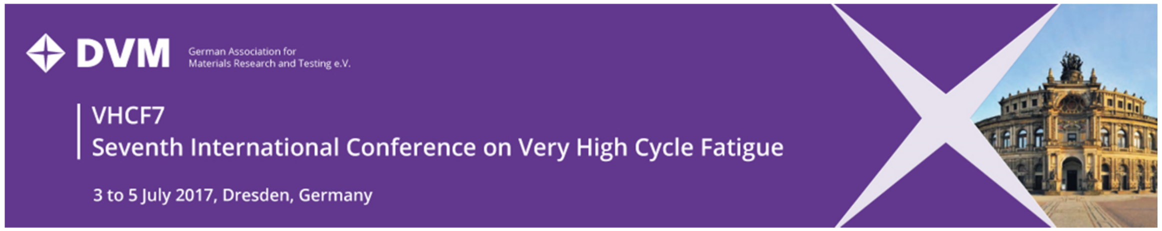
Fatigue gigacyclique
Very High Cycle Fatigue



Motivation
Investigating VHCF

- **Development of ultrasonic fatigue tests at a loading frequency of 20kHz (Stanzl-Tschegg and Bathias research teams)**

	100 Hz	**20 kHz**
10^6 cycles	< 3 h	50 s
10^9 cycles	~ 116 days	~ 14 h

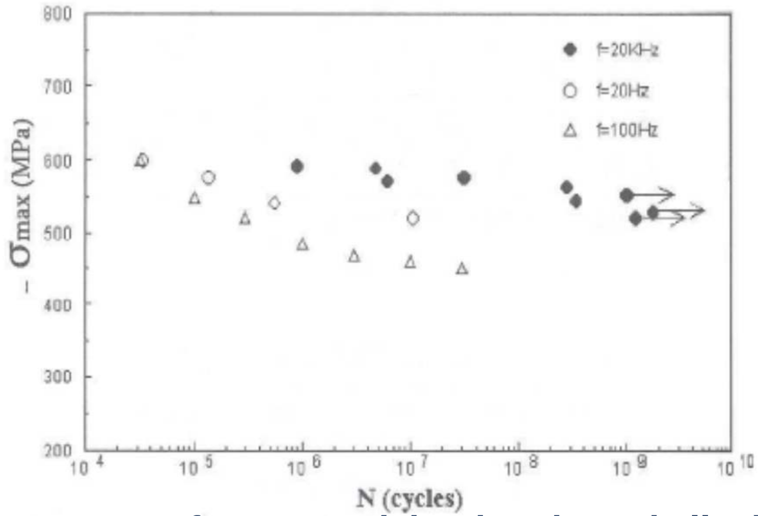


Scientific issue : Frequency effect ?

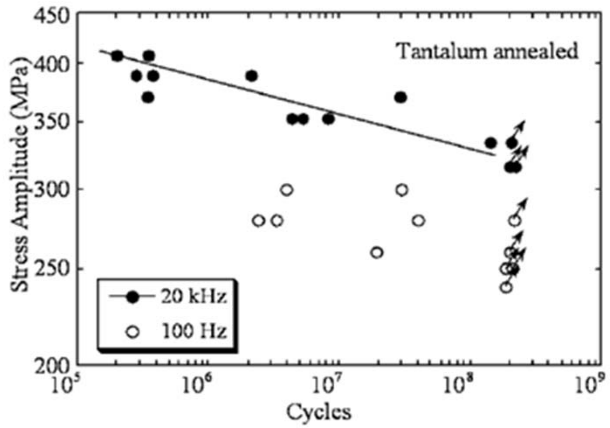
Procédés et Ingénierie en Mécanique et Matériaux

A present debate…

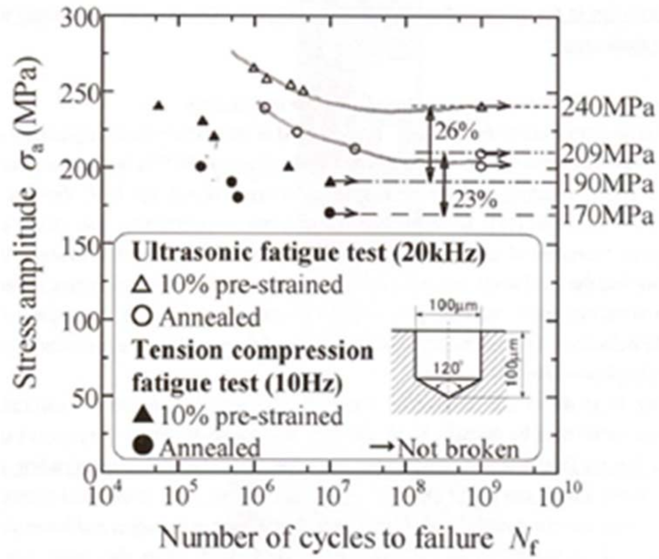
Frequency sensitive fatigue response



SN curve for T6A4V (Titanium based alloy), R=-1, Bathias and Paris (2005)



SN curve for Tantalum annealed (Papakyriacou et al, MSEA, 2001)



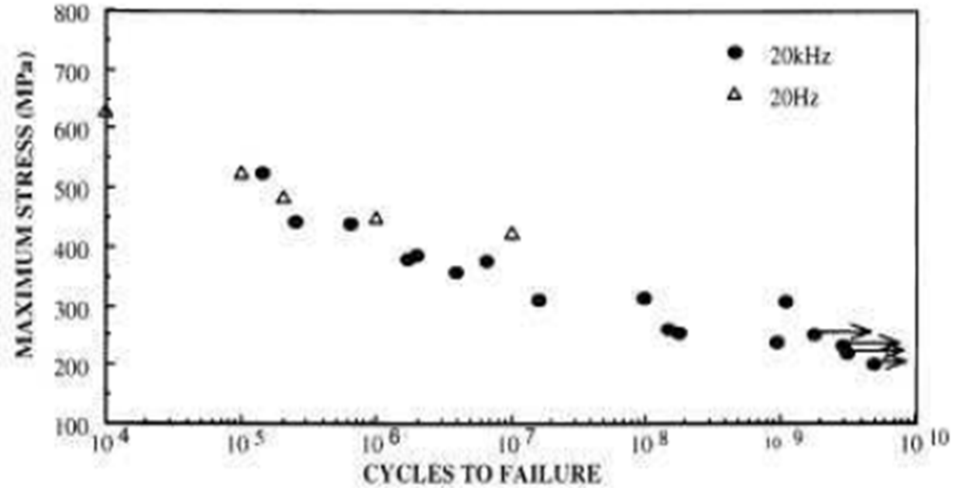
SN curve for low carbon steel (Tsutsumi et al, F&F Eng Mat. Struct., 2009)

Master MAGIS

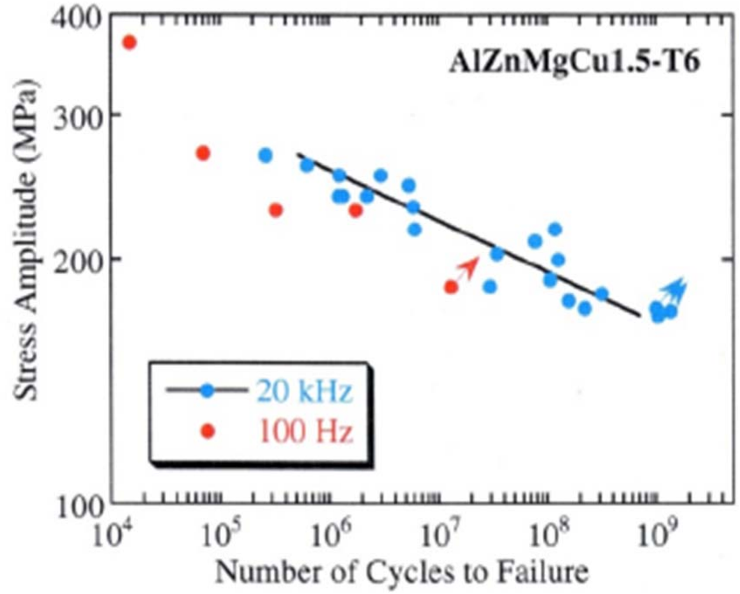
Scientific issue : Frequency effect ?

A present debate…

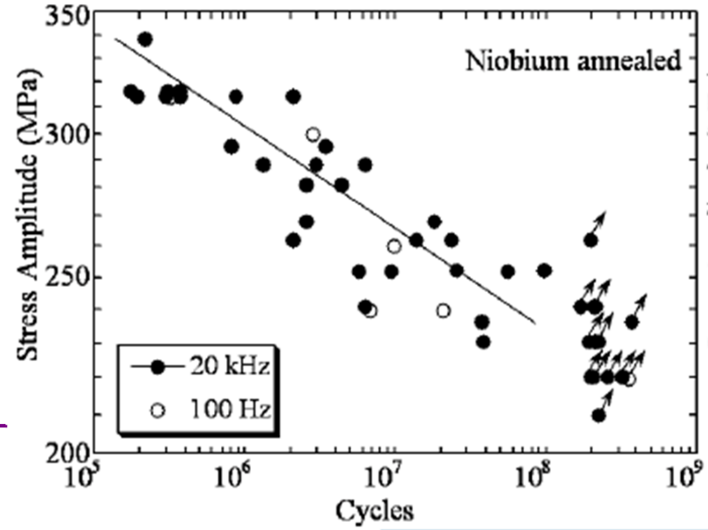
Frequency insensitive fatigue response



SN curve for Udimet 500 (Nickel based alloy), R=-1, Bathias (1999)

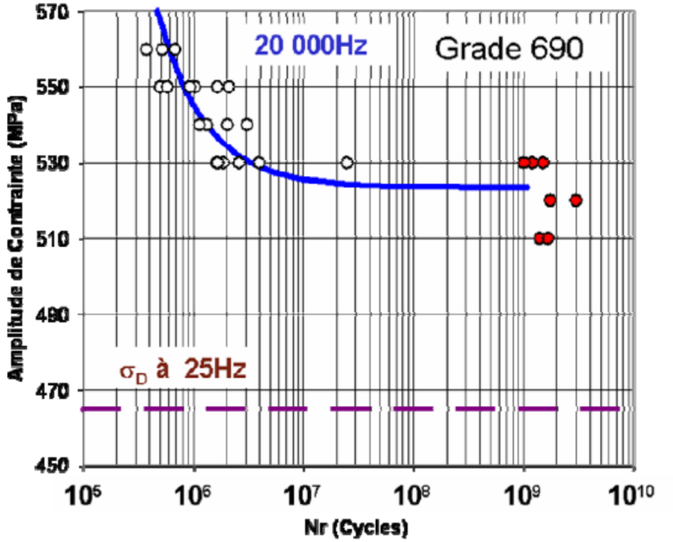


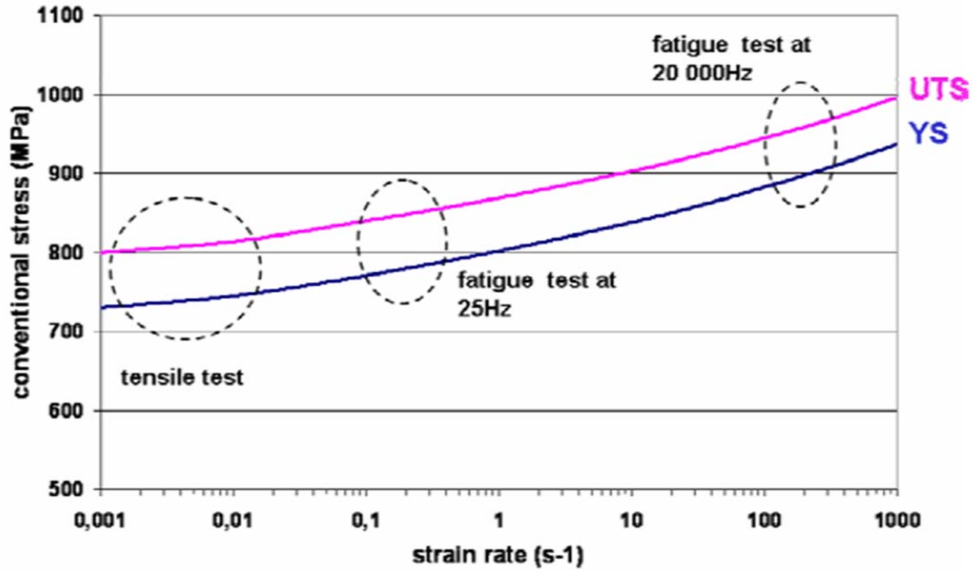
SN curve for AlZnMgCu1.5.T6(Aluminium alloy 7075) (Mayer et al, MSEA, 2001



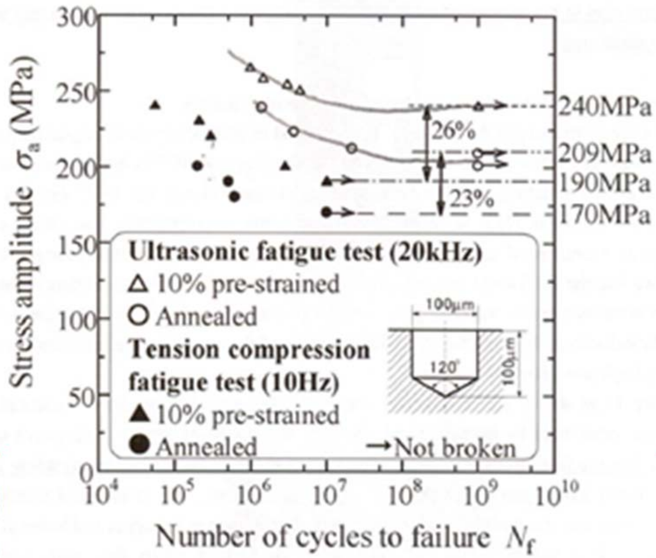
Scientific issue : Frequency effect ?

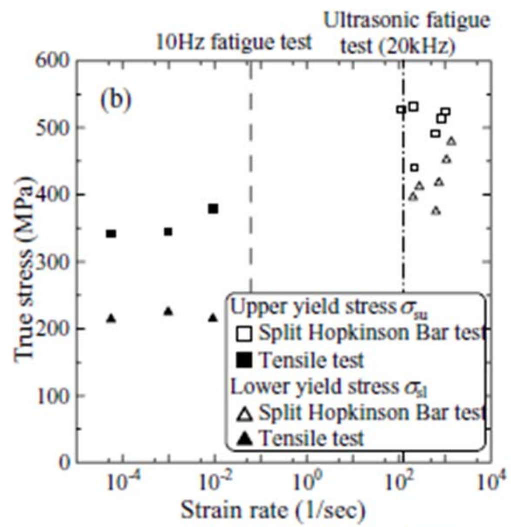
Galtier and Cugy, MECAMAT Aussois, 2007





SN curve for low carbon steel (Tsutsumi et al, F&F Eng Mat. Struct., 2009)

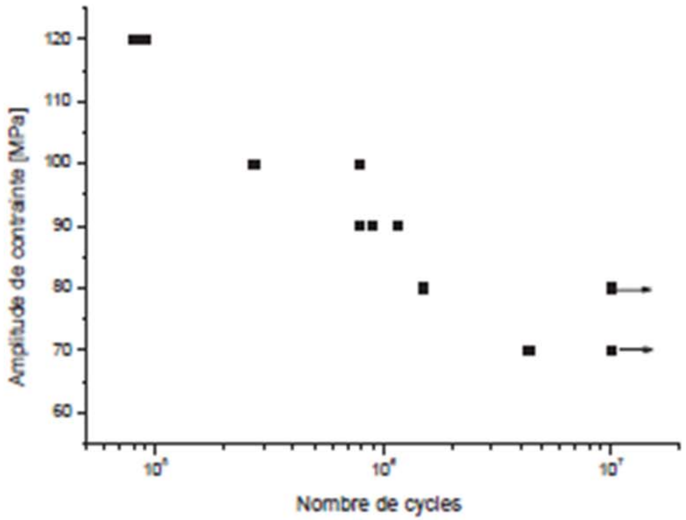




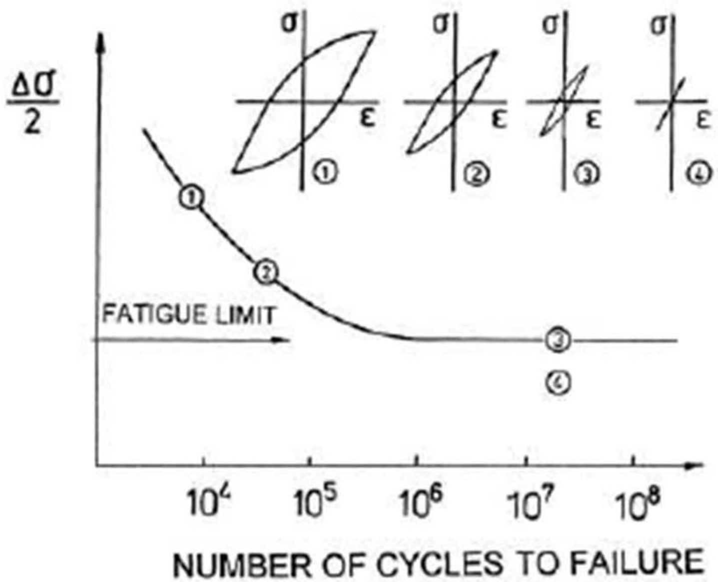
VHCF: Context for mechanisms: Macroscopic behavior

Macroscopic elastic response…but intrinsic dissipation (damping, self-heating)

SN curve for pure copper (Mughrabi, IJF, 2002)



a)

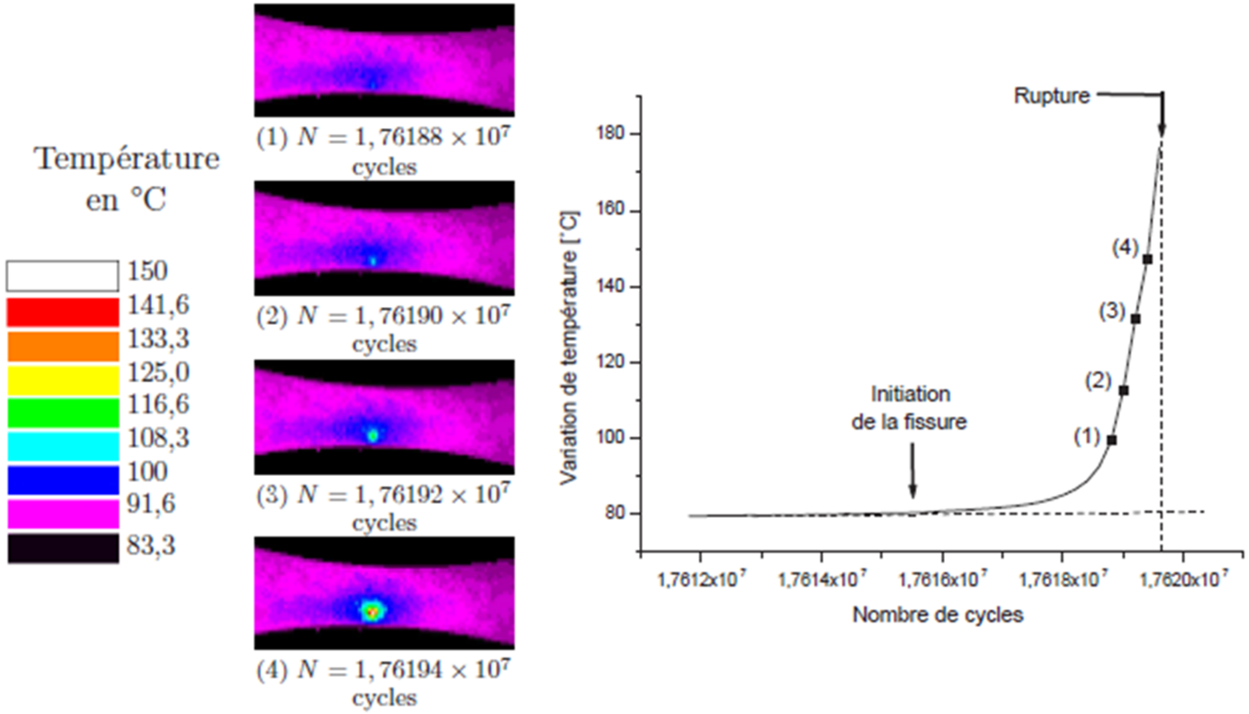


b)

Plastic shear strain amplitude < 10^{-5} →microplasticty

VHCF: Context for mechanisms : crack initiation/crack propagation life

> 95% of the specimen fatigue life is consumed by the crack initiation process initiation stage.



Temperature field on the specimen surface cyclically loaded and just before failure – 42CD4 steel (stress aplitude=345 MPa, NF=1.76107 ctcles)

From (Xue et al, Fatigue Fract. Eng Mater. Struct, 2006) and (Wagner et al, Fatigue Fract. Eng Mater. Struct, 2010

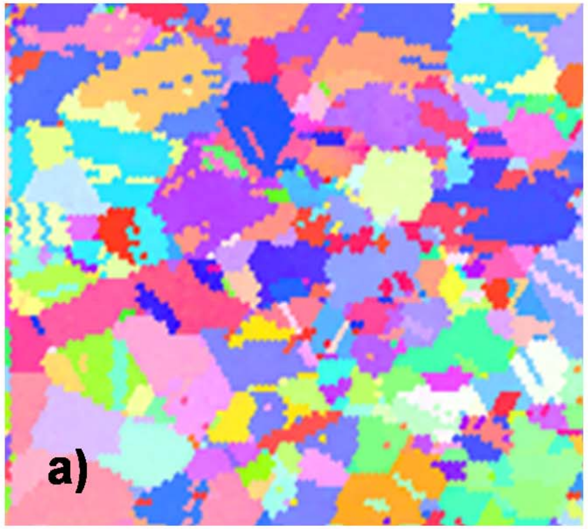
Objectives

- **What are the microplastic mechanisms leading to crack initiation at 20 kHz in the VHCF regime?**
- **Are they similar to the mechanisms involved during fatigue investigated using conventional fatigue machine (<100 Hz)?**
- **Are there differences between f.c.c. and b.c.c metals ?**

Materials

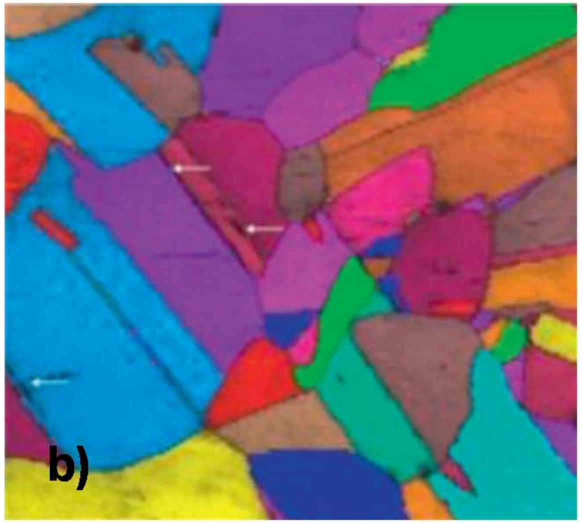
α-brass (15 wt%Zn)
f.c.c.

mean ϕ = 10 μm



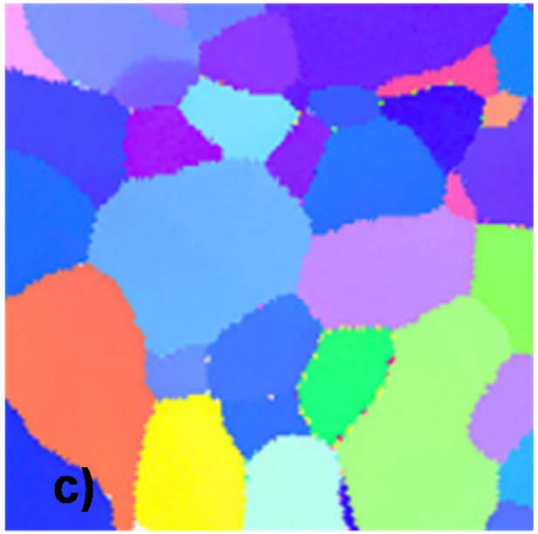
Pure copper
(99.95% purity)
f.c.c.

mean ϕ = 30 μm



α-iron
(80 wt ppm carbon)
b.c.c.

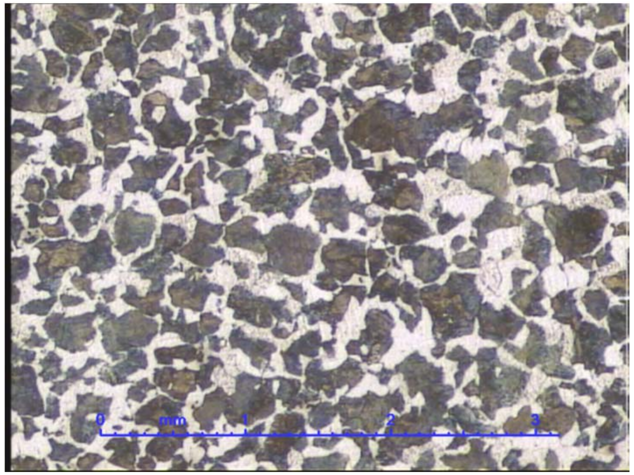
mean ϕ = 30 μm

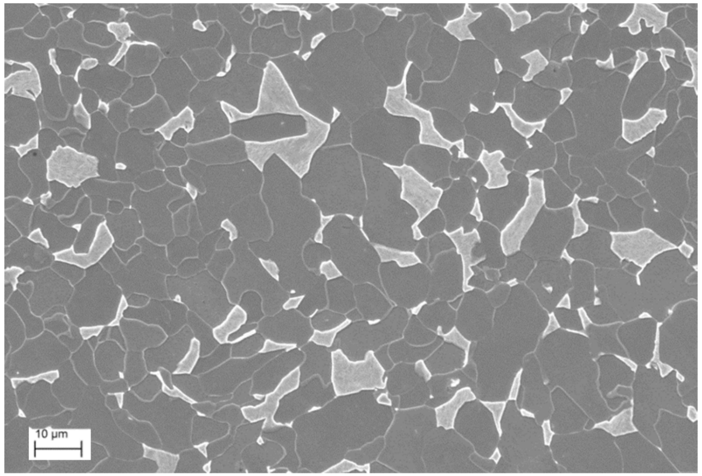


50 μm

Materials

Ferritic-pearlitic steel	Ferritic-martensitic steel
(C45)	(DP600)
b.c.c.	b.c.c.
mean ϕ = 40 µm	mean ϕ = 7 µm





PhD N. Torabian (see poster session)
B. Weber – ArcelorMital

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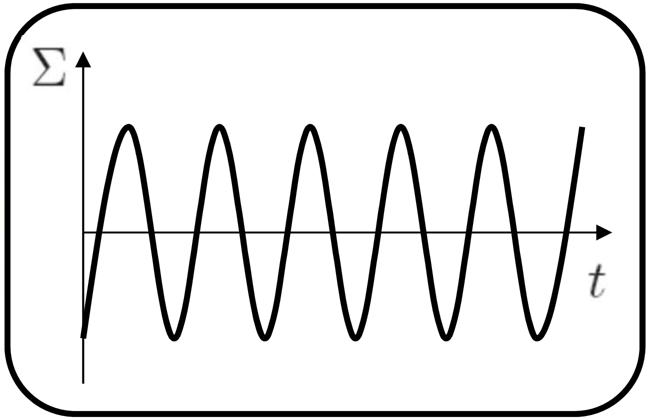
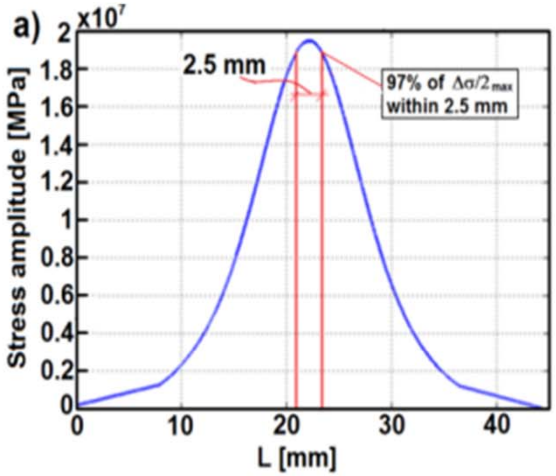
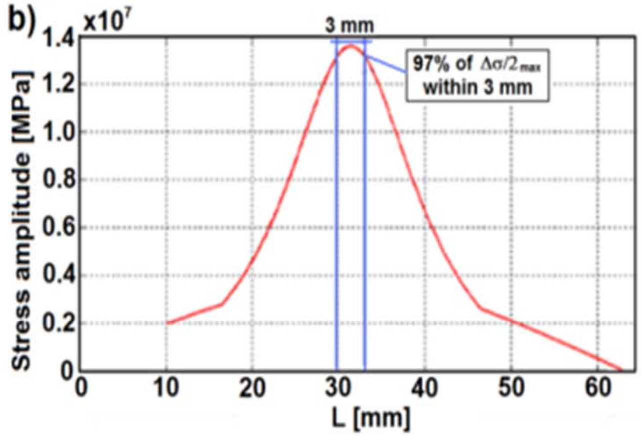
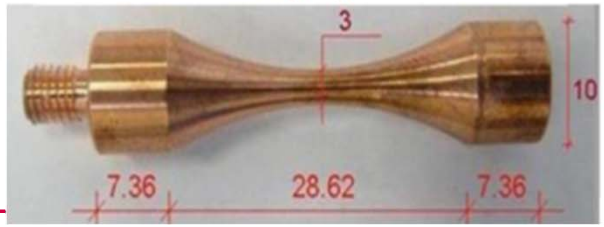
sous l'égide de la Fondation de France

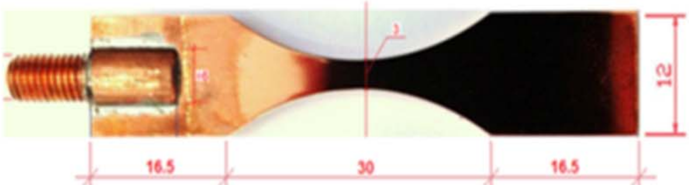
Experimental procedure







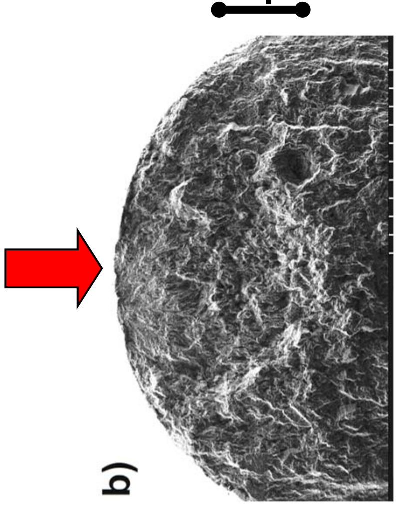




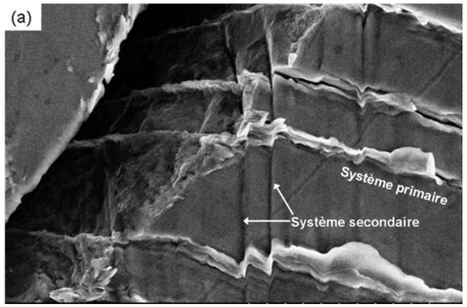
Bathias and Paris (2004)

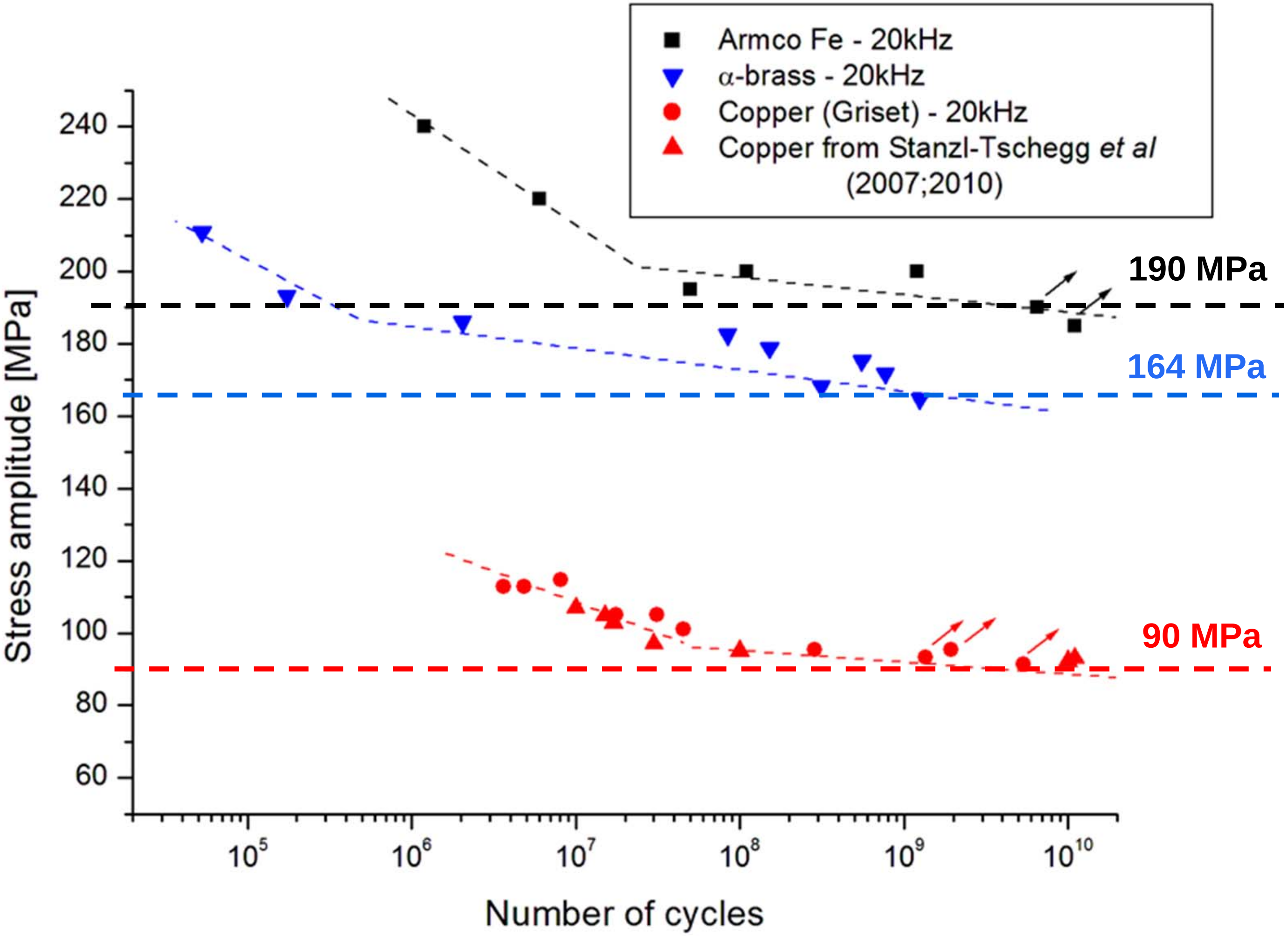
SN Curves

with air cooling conditions



Phung et al, IJF, 2014





Favier et al, Int. J. Fatigue, 2016

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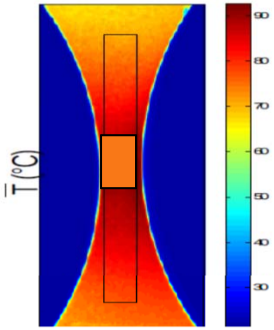
Mechanical properties

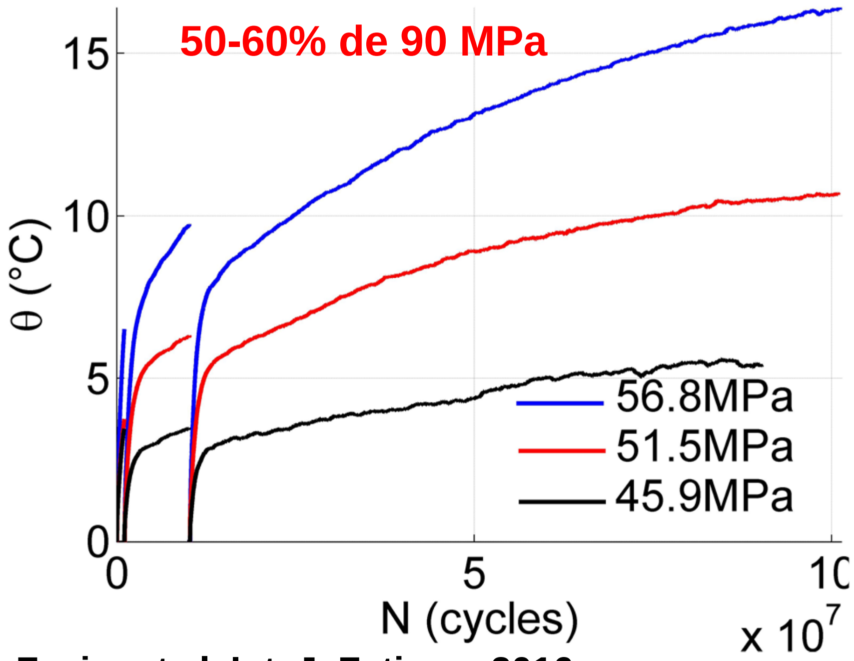
Materials	Elastic anisotropy coefficient	UTS (MPa)	σ_D (MPa) (Fatigue strength at 10^9 cycles)	σ_D/UTS
α-iron	2.4	400	190	0.47
α-brass	8	306	164	0.53
copper	3.3	232	90	0.39

Favier et al, Int. J. Fatigue, 2016

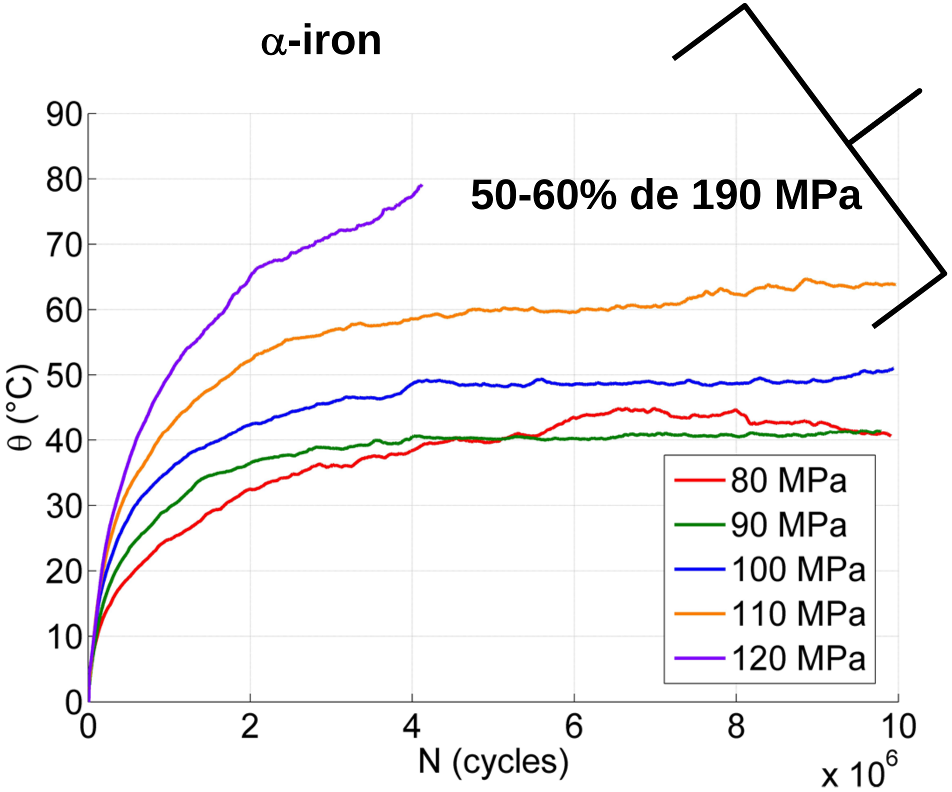
Self heating during cycling



copper



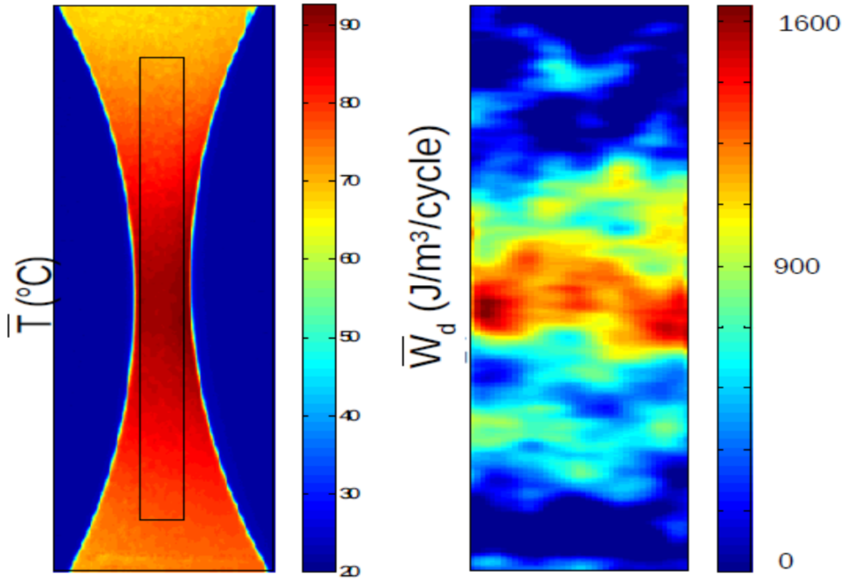
α-iron

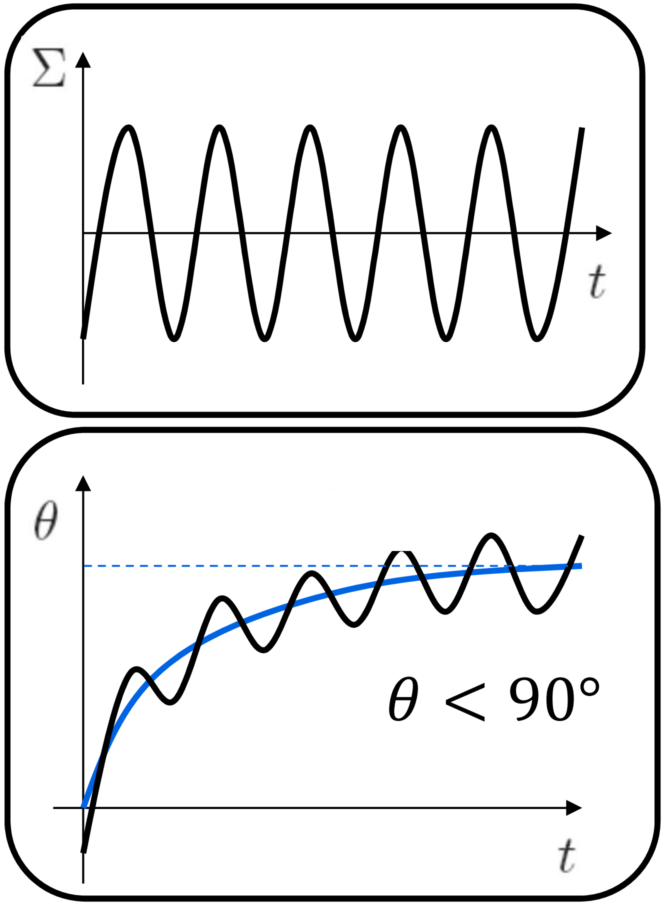


Favier et al, Int. J. Fatigue, 2016

α-brass: θ<90°C

Determination of the dissipated energy

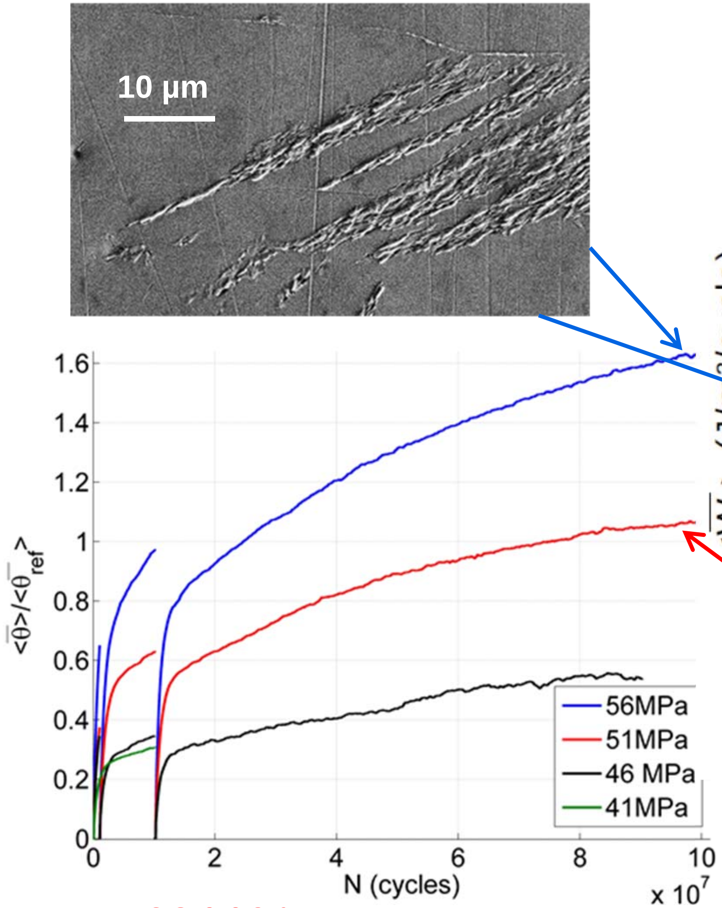


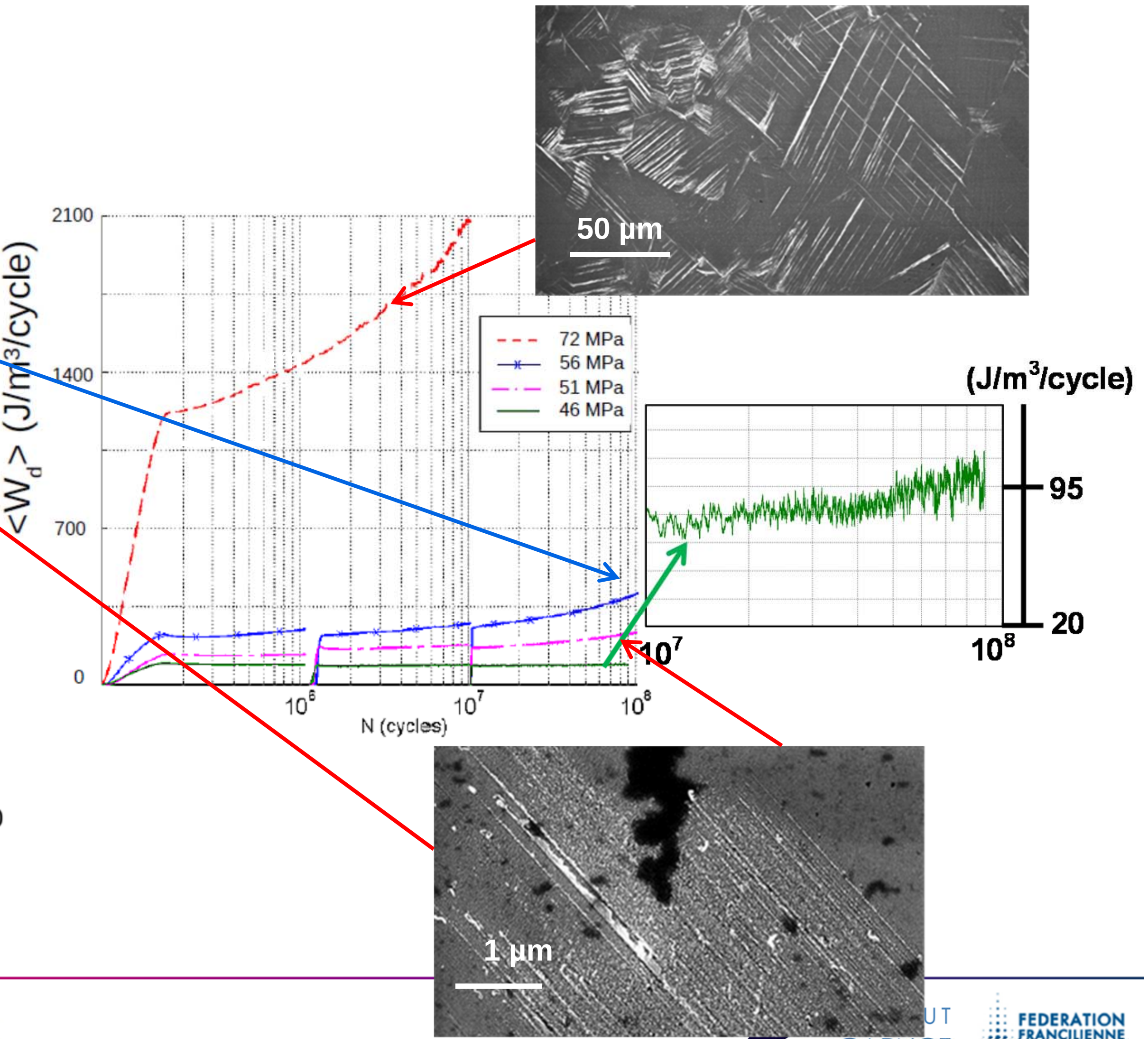


heat diffusion equation

$$\rho C \frac{\partial \theta}{\partial t} - k\Delta\theta = d_1 + s_{the}$$

0D mean dissipated energy per cycle



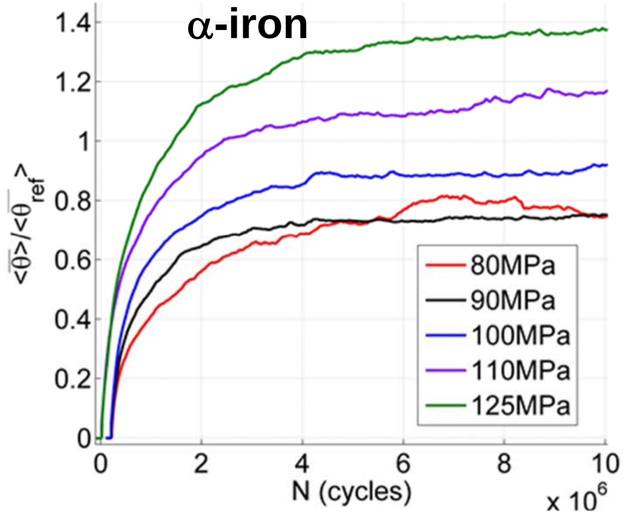


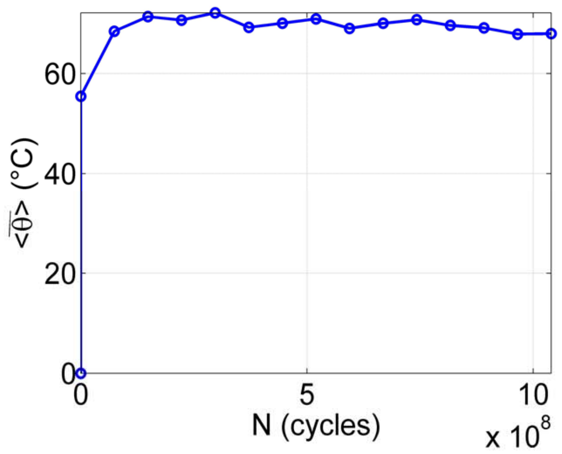
copper

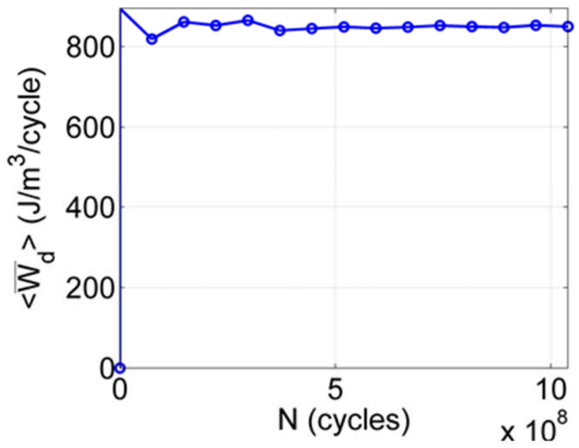
Favier et al, Int. J. Fatigue, 2016

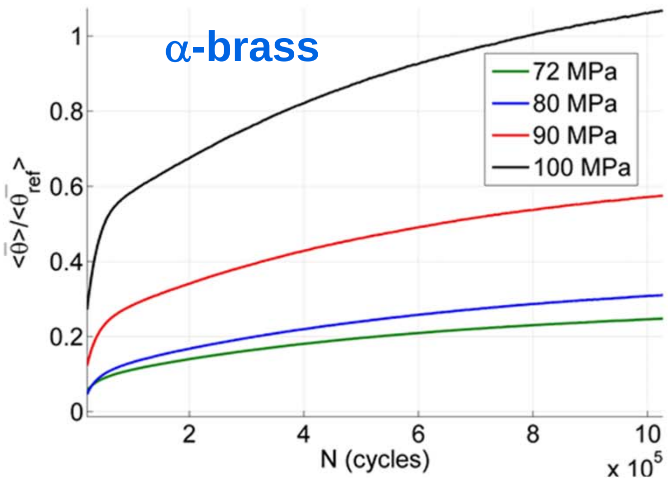
0D Mean dissipated energy per cycle

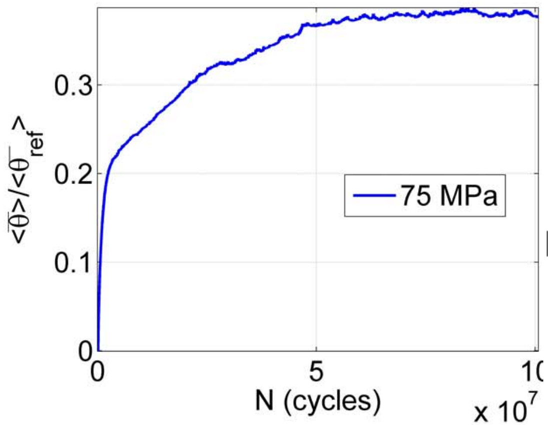
Wang et al, Int. J. Fatigue, 2012

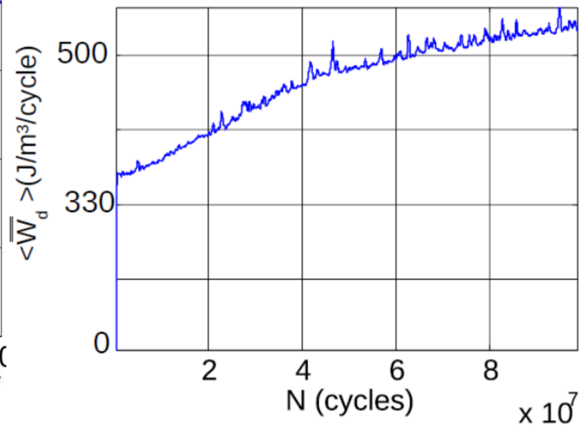








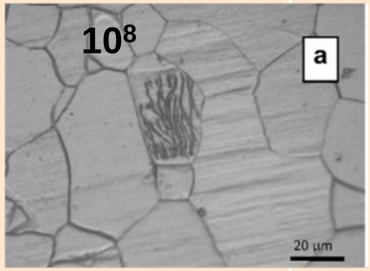
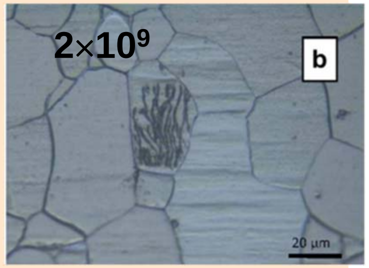
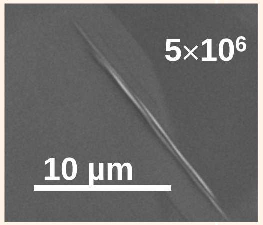
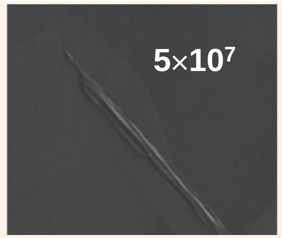
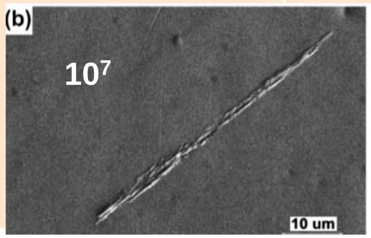
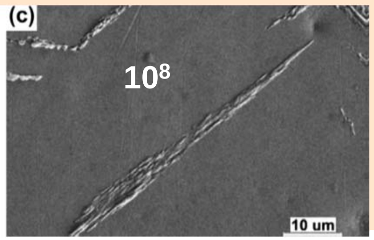




Phung et al, Int. J. Fatigue, 2013 **Favier et al, Int. J. Fatigue, 2016**

Summary

for stress amplitudes of 50-60% of σ_D = 20-30% of UTS

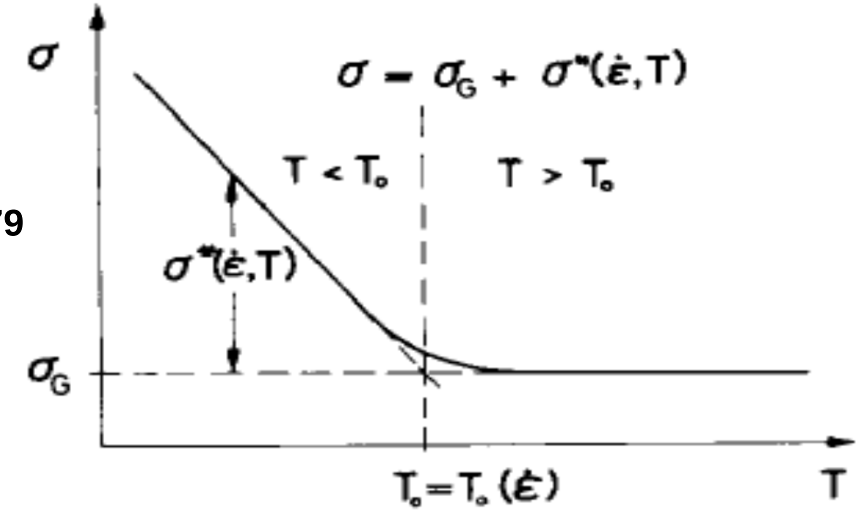
Materials	Evolution of the dissipated energy per cycle during cycling	Evolution of PSMs	
α-iron (b.c.c.)	constant		
α-brass (f.c.c.)	growing		
Copper (f.c.c.)	growing		

Favier et al, Int. J. Fatigue, 2016

Discussion

Dominant deformation mode below 30% of UTS

Mughrabi et al, 1979

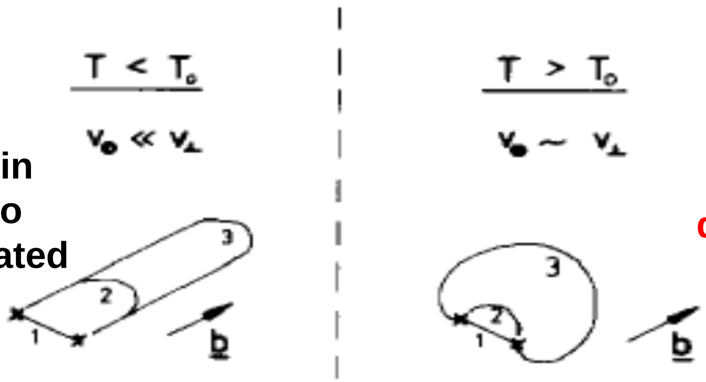


Campbell & Ferguson, 1970

α-iron T_0 (20 kHz) = T_0 (10-100s^{-1}) $\in$ [130° C-400° C]

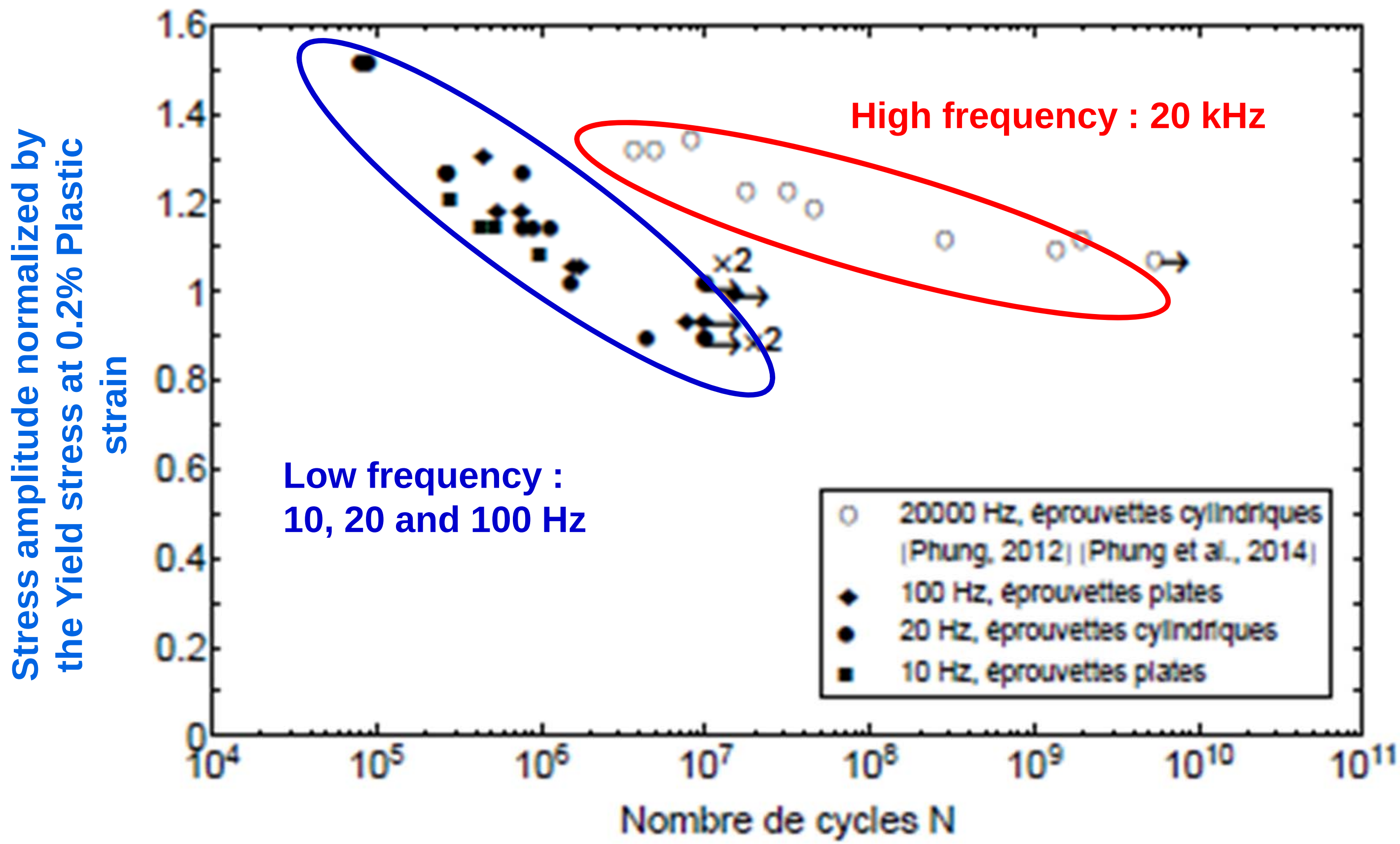
Favier et al, Int. J. Fatigue, 2016

α-iron , no strong change in dislocation structure → no significant change in dissipated energy during cycling



Copper and α-brass , stronger dislocation motion, change in dislocation structure → change in dissipated energy during cycling

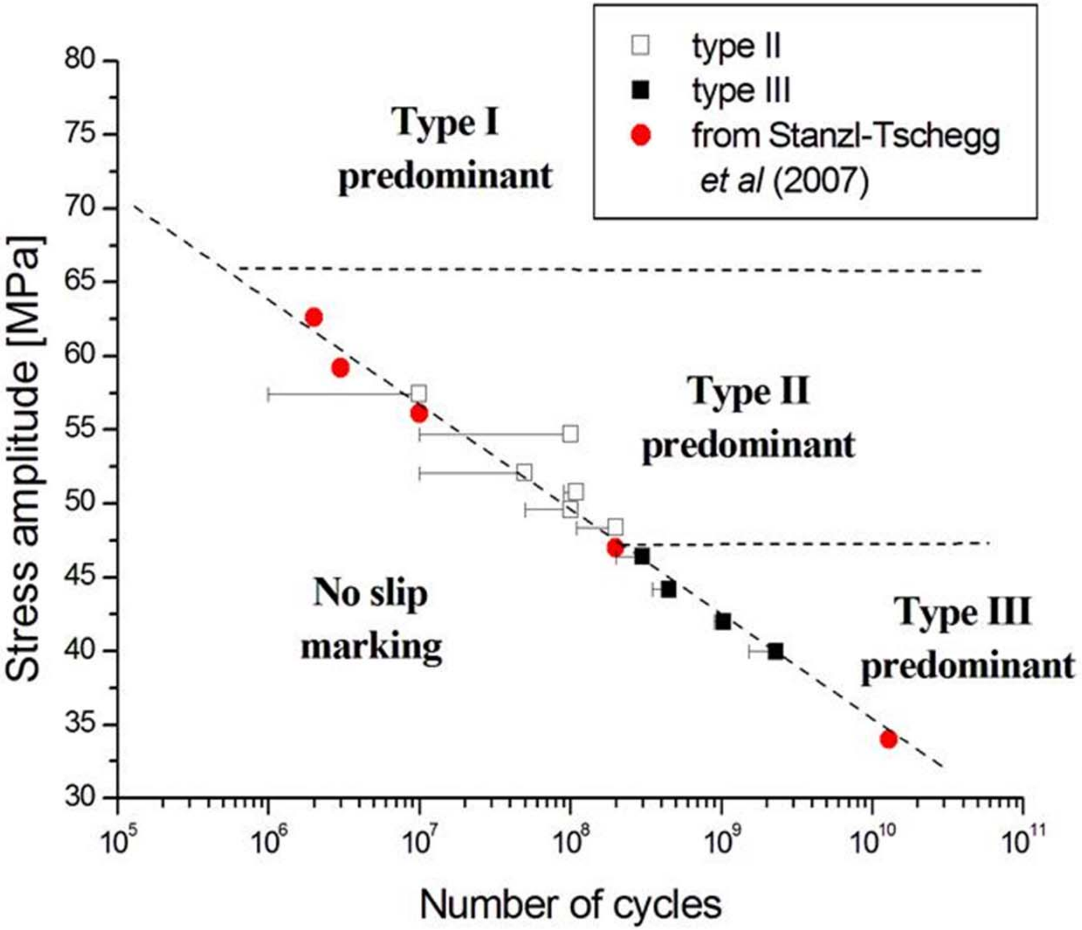
SN Curves
Stress normalized by the flow stress

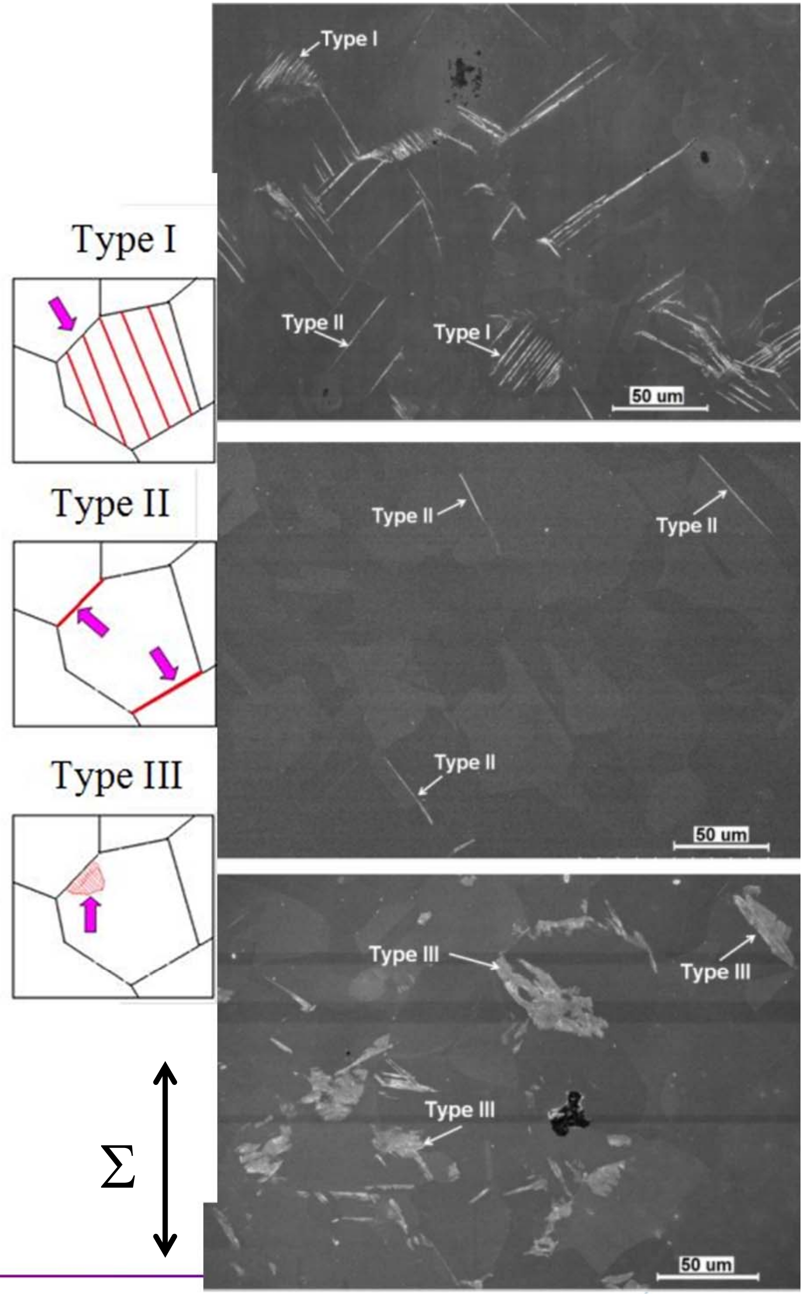


Strain rate sensitivity cannot explain alone the change in SN curves with frequency

Early slip markings

Fatigue strength at 10^9 cycles = ~90 MPa

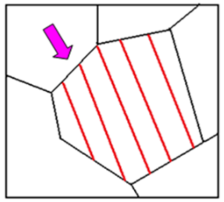
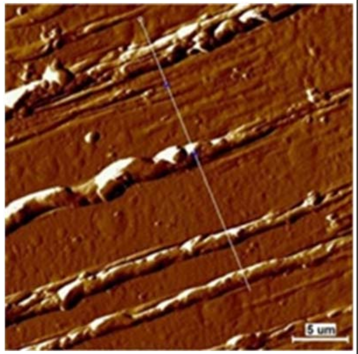


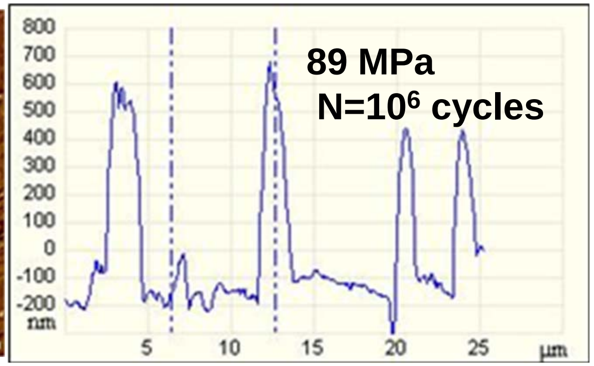


Phung, Favier, Ranc, Vales, Mughrabi, Int.J. Fatigue (2014)

Slip markings morphology

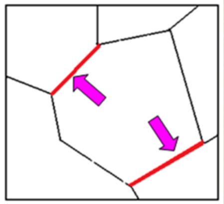
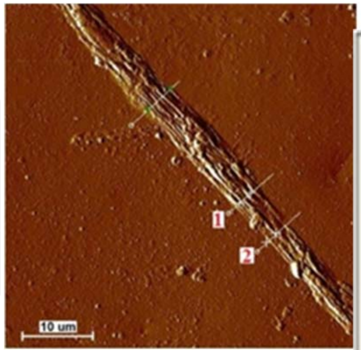
Low frequency ?

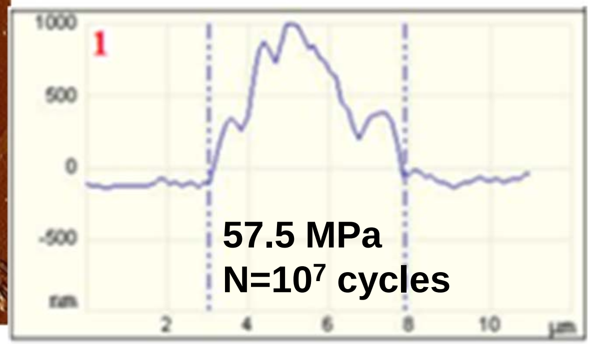





Type I

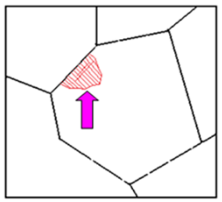
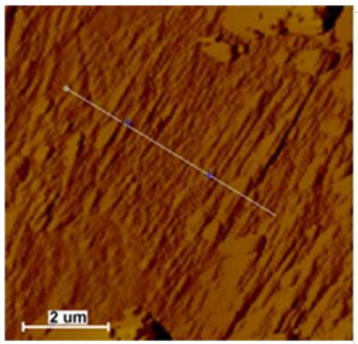
Classically observed : PSBs

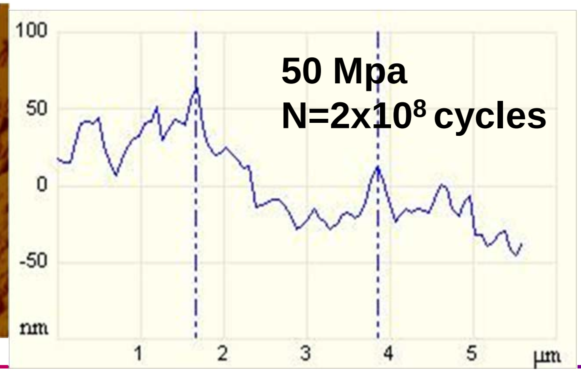





Type II

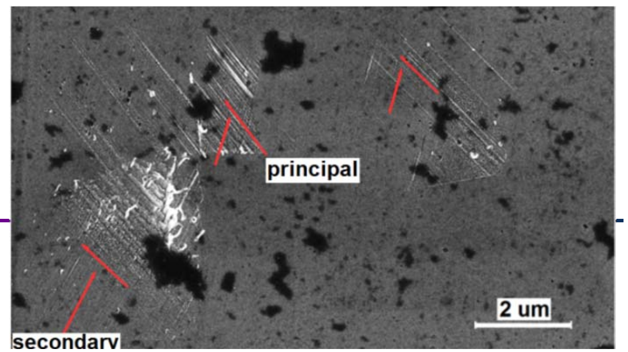
Neumann and Tönnessen (1988),Polak and Vasek (1994), Llanes and Laird (1992), Peralta *et al.* (1999) Small stress ampl.



Type III

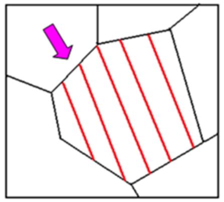
Basinski and Basinski (1969) // N<10 cycles

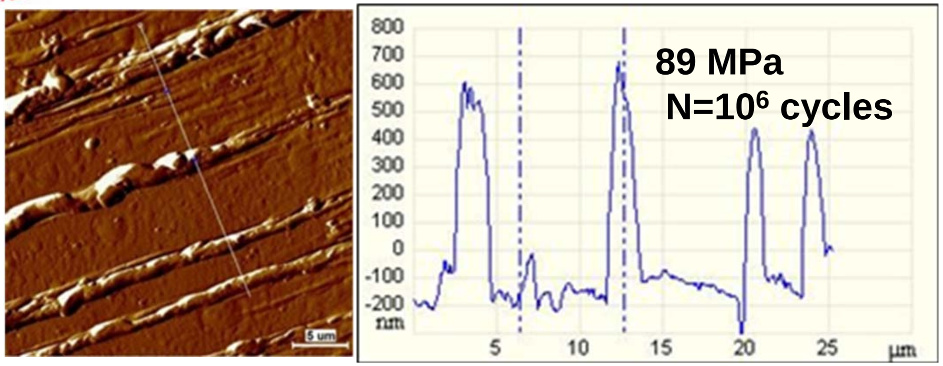


Phung, Favier, Ranc, Vales, Mughrabi, Int.J. Fatigue (2014)

Slip markings morphology

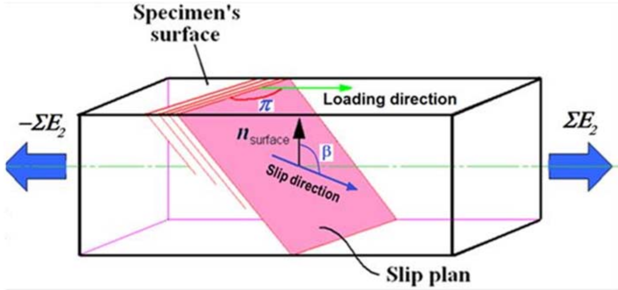
Criterion ?

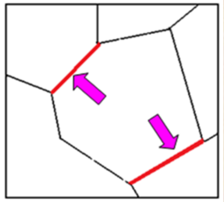


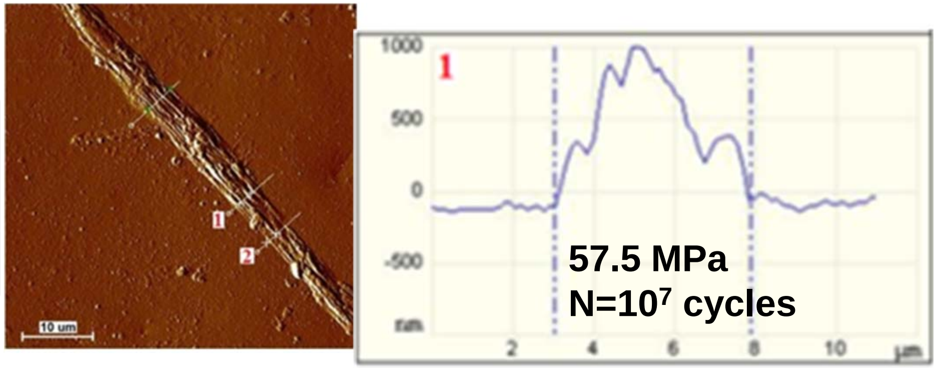


Type I

Predicted by the maximum Schmid factor criterion (El Bartali et al, 2008

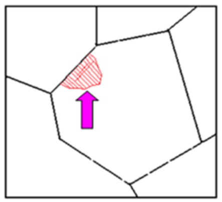


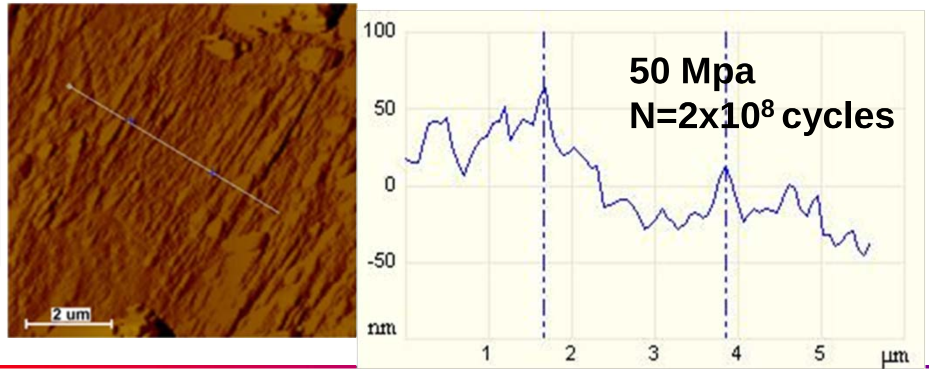




Type II

?

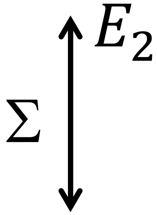




Type III

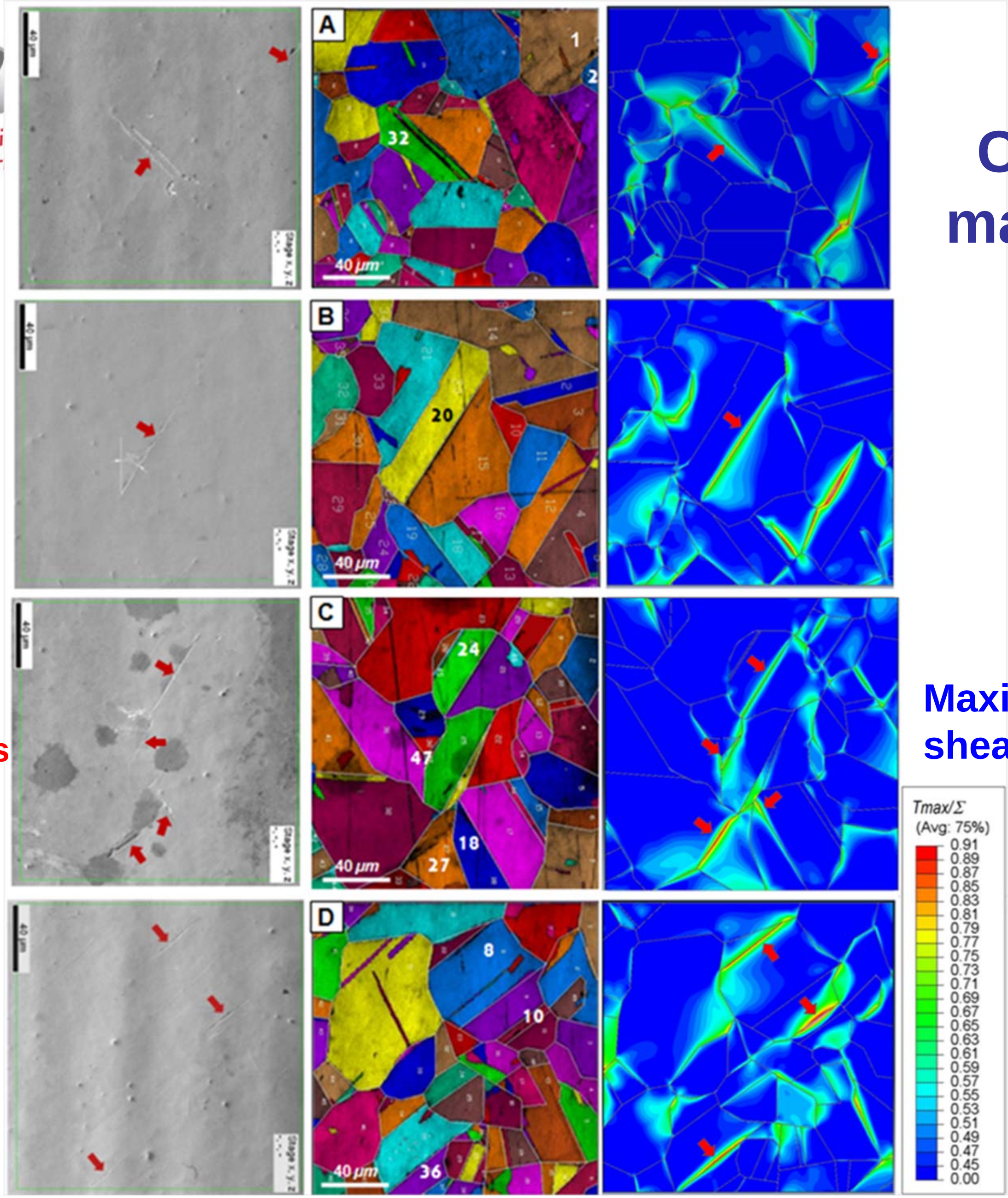
?

Phung, Favier, Ranc, Vales, Mughrabi, Int.J. Fatigue (2014)

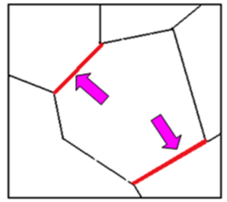


56.4 MPa
10^7 cycles

192 grains
11 slip markings



Criterion for slip markings of type II



Cubic elasticity

$$\tau^s = R^s_{ij}\sigma_{ij}$$

Maximum resolved shear stress

Phung, Favier, Ranc, Int.J. Fatigue (2015)

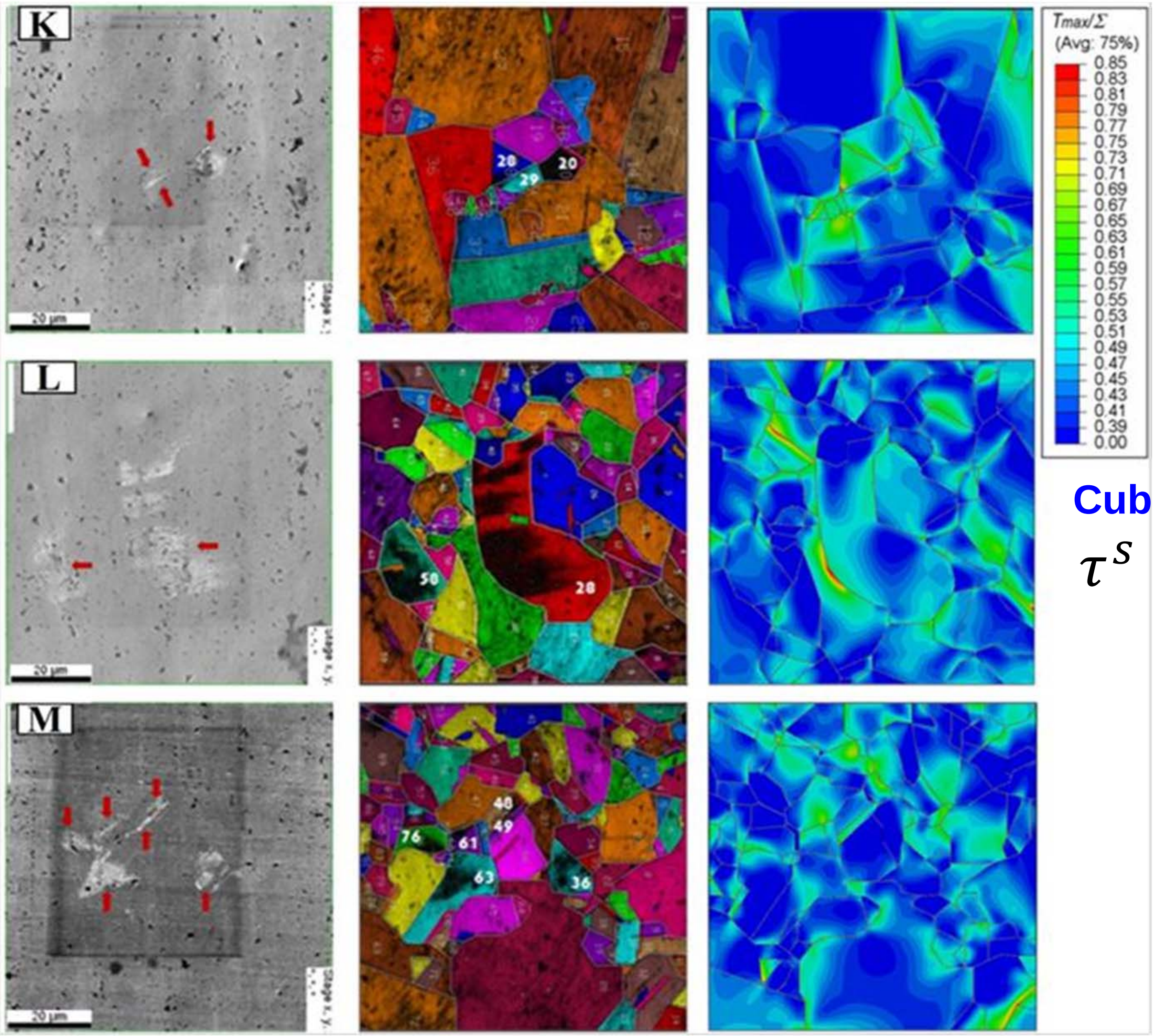
Criterion for slip markings of type III

E_2

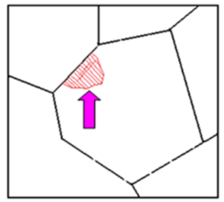
Σ

59.6 MPa
10^8 cycles

204 grains
11 slip markings



Maximum resolved shear stress



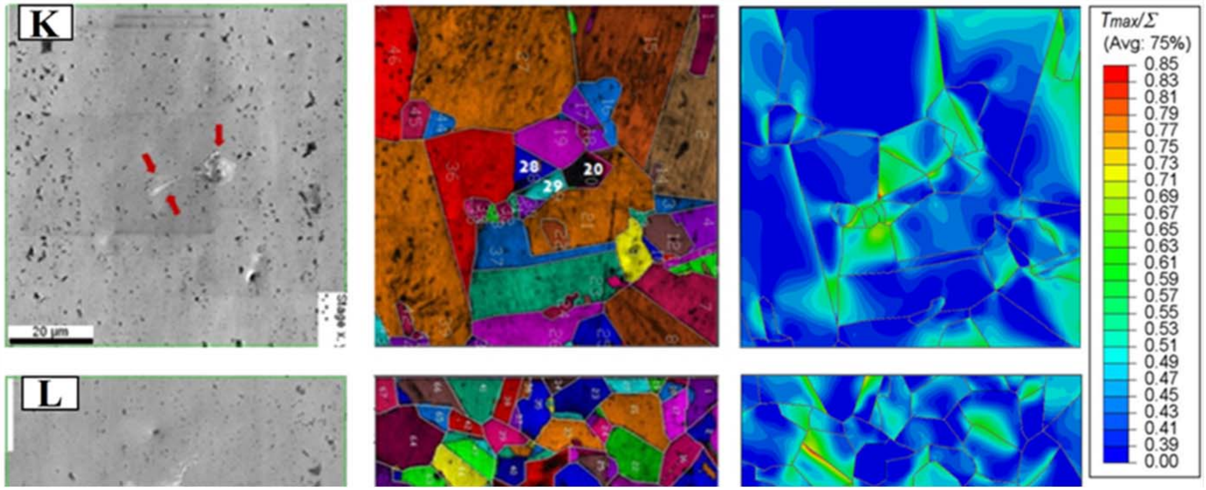
Cubic elasticity

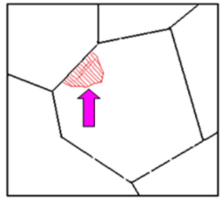
$$\tau^s = R^s_{ij}\sigma_{ij}$$

Phung, Favier, Ranc, Int.J. Fatigue (2015)

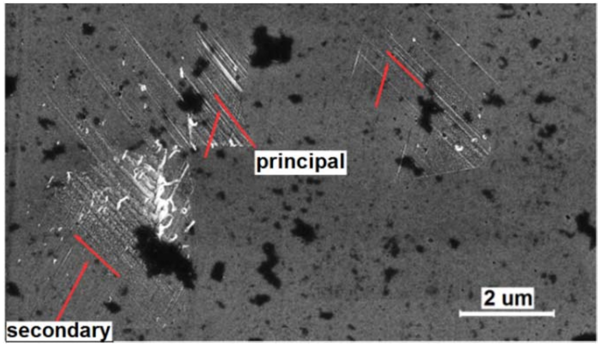
Discussion

49.6 MPa - N=10^8 cycles





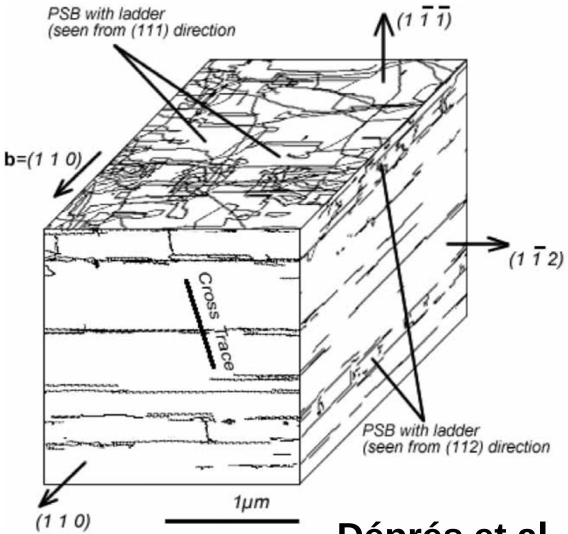
$29\ \mathrm{MPa} \leq \left|\tau_{max}\right| \leq 41\ \mathrm{MPa}$



Cross slip threshold (Cu T=300K)

24.5 MPa

Bonneville et al. (1988)



Déprés et al. (2004)

Key role of cross slip for deformation localisation

(Li & Laird 1994, Peralta et al, 1999)

Slip marking apperance threshold
~Cross slip threshold

Phung, Favier, Ranc, Int.J. Fatigue (2015)

Conclusions

Response in VHCF at 20 kHz is very material-dependent.

Temperature during cycling has to be measured !!

For ductile single phase materials, slip band emergence are responsible for short crack initiation at the surface of the specimen as for LCF and HCF regimes.

Local stress heterogeneities mainly to anisotropic elasticity plays a key role in the slip band sites.

For copper (f.c.c.), frequency effects are attributed to time effect.

For ferrite (b.c.c), frequency effects are attributed to strain rate and temperature effects.

For multiphase materials, crack can initiate at internal defects