INTRODUCTION TO MATERIAL VARIABILITY OF MECHANICAL PROPERTIES AND LENGTH SCALES

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I - INTRODUCTION - CASE STUDIES

II - ELASTICITY

III - PLASTICITY

IV - FRACTURE : 2 Case Studies
- **Duplex Stainless Steels**
- **Welds**

V - A SIMPLE MODEL BASED ON WEAKEST LINK THEORY

VI - CONCLUSIONS

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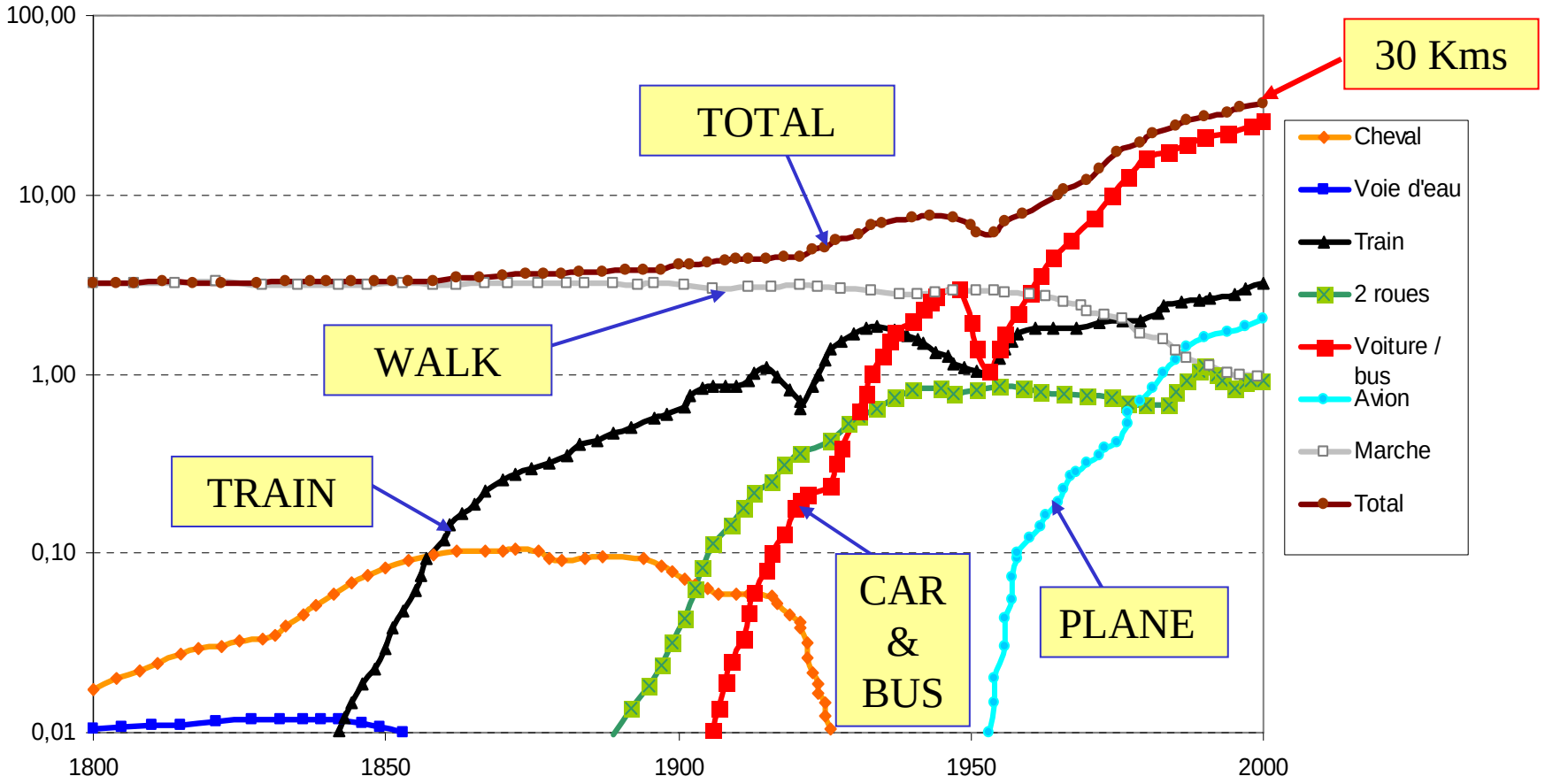
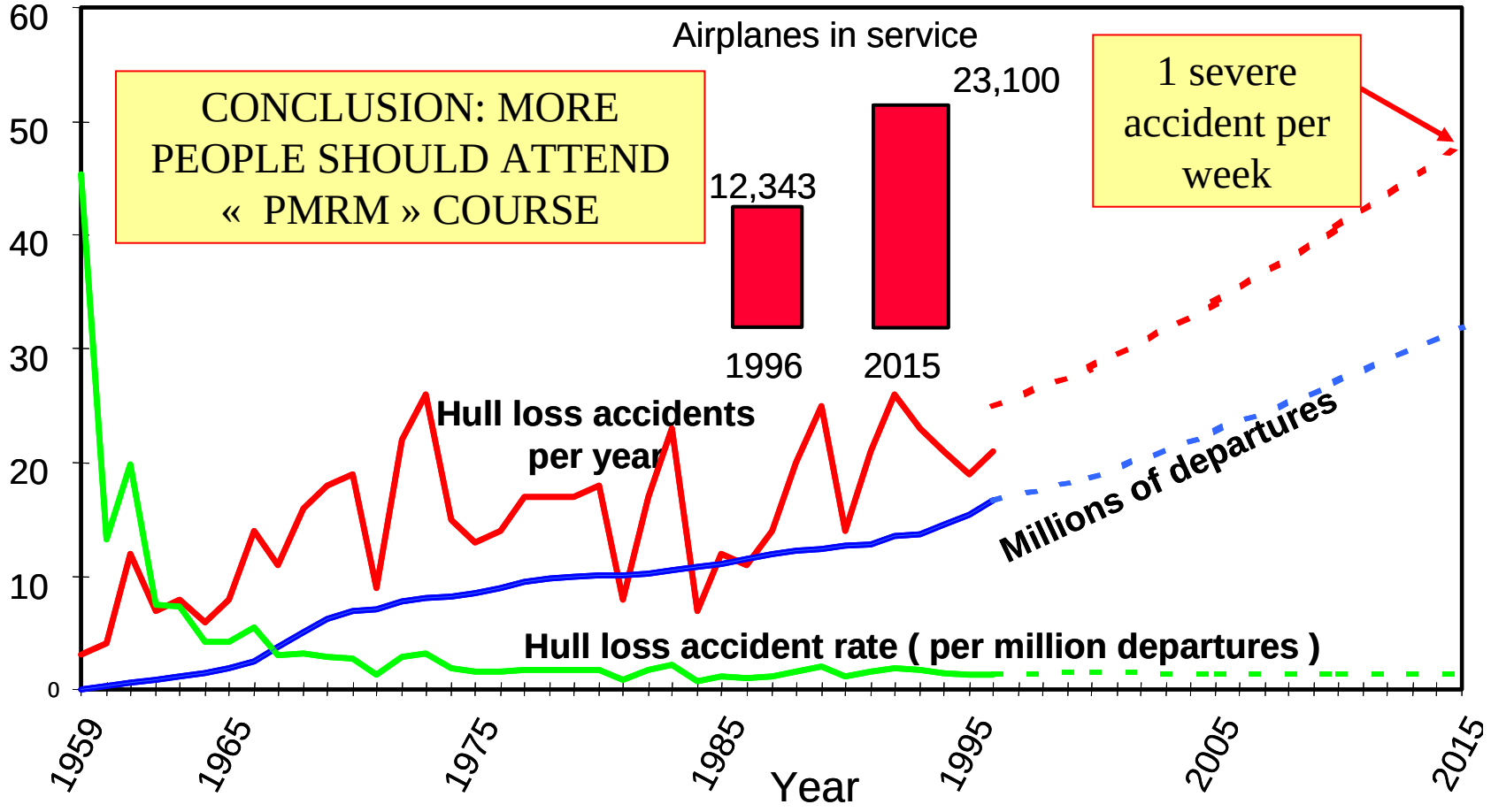
TRANSPORTATION : FARTHER , FASTER , EASIER and CHEAPER

Evolution of the distances (Km) covered per person and per day in France since 1800

- *Grübler et Nakicenovic, 1991, Estimations de Francis Papon pour la marche*
- *Jean-Marc Jancovici – Mines ParisTech mai-juin 2010- www.manicore.com*



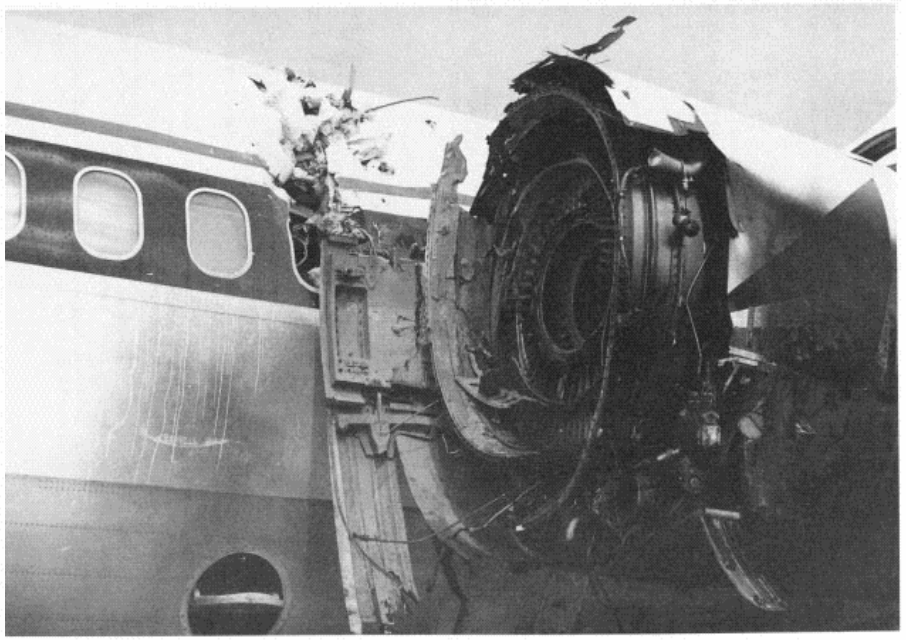


Etude statistique sur l'évolution du trafic aérien et du nombre d'accidents (source MANHIRP, 2001)

Introduction

Moteur CFM56 (source Snecma)

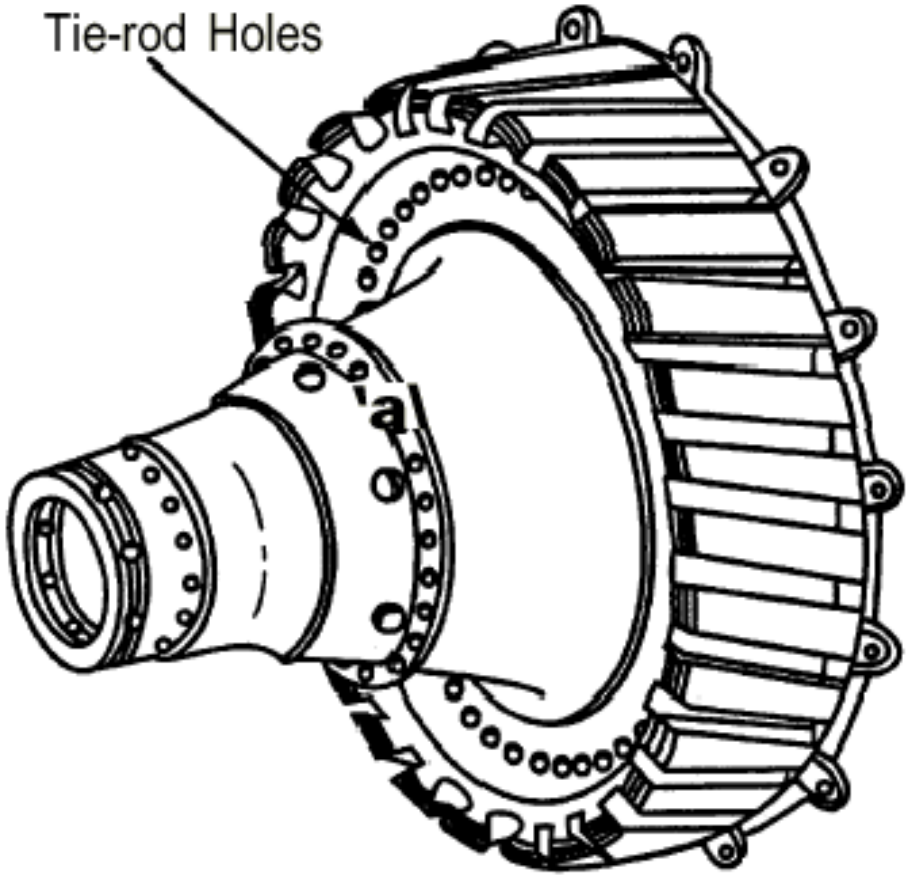
TA6V. Défaut de perçage. Rupture disque fan.



Accident Pensacola, Floride, U.S.A., 06 juillet 1996

Eclatement d'un disque de MD88 Delta Air Lines, Moteur P & W JT8D

Introduction



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Aloha, 28 avril 1988

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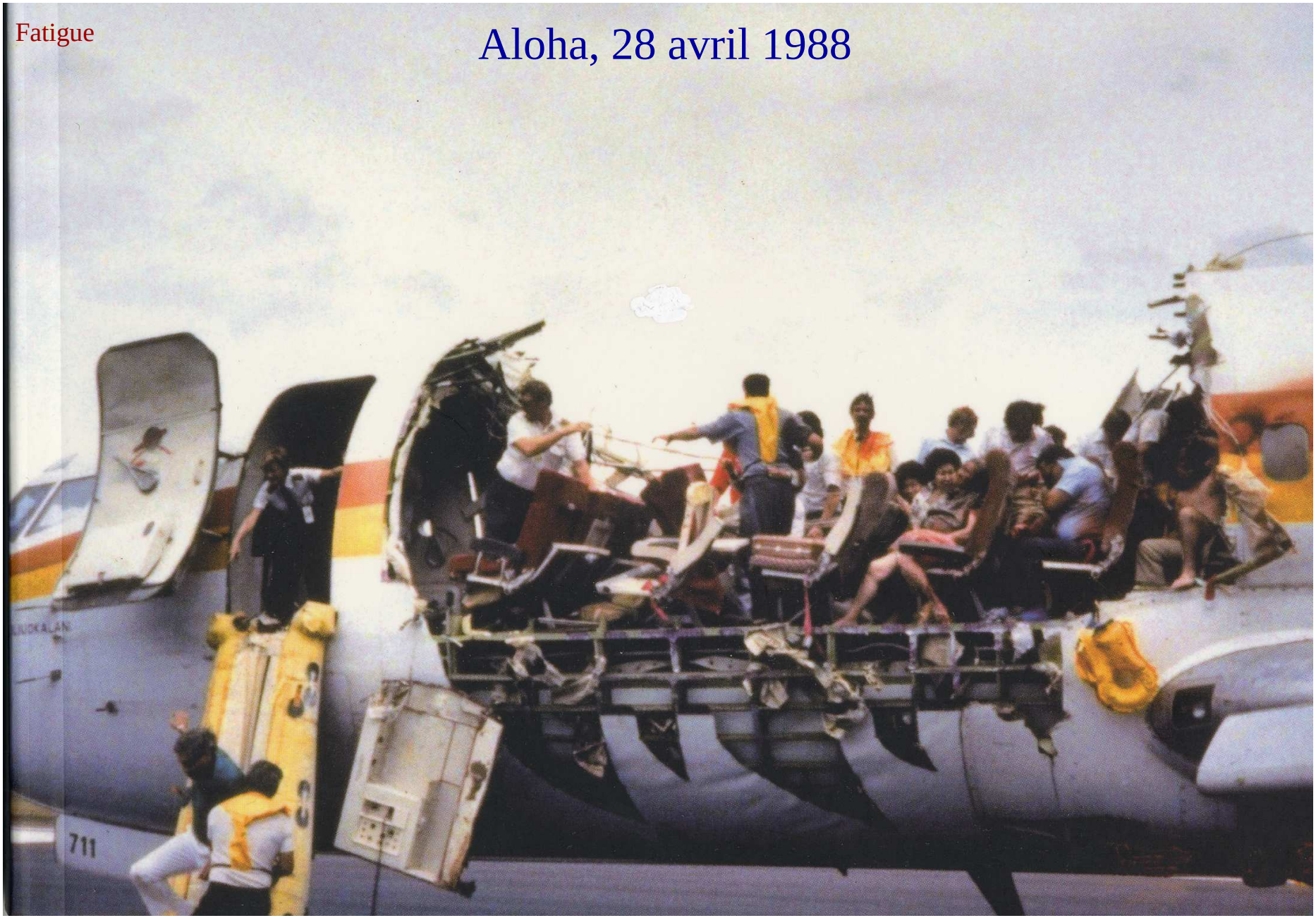

Boeing 767 Los Angeles, 02 juin 2006

engine type : GE CF6-80A2

Boeing 767 Los Angeles, 02 juin 2006
engine type : GE CF6-80A2

Boeing 767 Los Angeles, 02 juin 2006

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engine type : GE CF6-80A2

Boeing 767 Los Angeles, 02 juin 2006

engine type : GE CF6-80A2

ATTERRISSAGE D'URGENCE
Un Airbus A380 de la compagnie Qantas transportant 459 personnes à son bord a effectué un atterrissage d'urgence jeudi à Singapour en raison de l'avarie d'un de ses quatre réacteurs
MALAISIE
3H45 GMT
L'avion revient se poser à Singapour
SINGAPOUR
Londres
INDONÉSIE
Batam
20 km
Singapour
Le vol QF32 de Qantas devait rallier Sydney après une escale à Singapour
AUS
Sydney
Vers 1h15 GMT
Une explosion est signalée alors que l'avion survole l'île de Batam
Réacteur n°2 endommagé
Airbus A380
QANTAS
Des passagers déclarent avoir entendu une explosion et vu des pièces se détacher d'un des réacteurs après le décollage
Incidents sur l'A380
Avril 2010 - Deux pneus d'un A380 de Qantas explosent à l'atterrissage sur l'aéroport de Sydney
Sep. 2009 - Un A380 de Singapore Airlines est obligé de faire demi-tour vers Paris après la défaillance d'un de ses réacteurs
Caractéristiques de l'A380
Capacité 555 passagers
Poids max. 560 tonnes
Rayon d'action 15 000 km
Prix catalogue 260 millions de $ (indicatif)
Source : Airbus
Infographie : Chris Inton
REUTERS

ASTB- Qantas Airbus A 380 inflight engine failure- Batam Island Indonesia – 04 November 2010

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BOUCHARD (N.H.), 1978, R..M. Pelloux

BOUCHARD (N.H.), 1978,
R..M. Pelloux

Erika, 12/12/1999

Erika, 12/12/1999

Erika, 12/12/1999

Provence-Alpes-Côte d'Azur

Après la rupture d'un oléoduc dans les Bouches-du-Rhône

- *9 000 tonnes de pétrole se sont échappées*
- *La solidité des tuyaux est mise en cause*

Marseille. — Ce sont 8 000 à 9 000 tonnes de pétrole brut — et non 2 000 tonnes comme on l'avait dit — qui se sont échappées d'un oléoduc dans la nuit du 9 au 10 août dernier (voir *le Monde* des 12 et 13 août) à Paluds-de-Noves, entre Châteaurenard et Saint-Rémy-de-Provence (Bouches-du-Rhône).

Et l'on commence à peine à dresser le bilan des dégâts. Grâce à la rapidité d'intervention des techniciens de la Société du pipe-line européen (S.P.L.S.E.), les vannes ont été fermées en quelques minutes et une partie du pétrole a pu être aspirée aussitôt en amont de la fuite — et, à l'ampleur des moyens mis en œuvre par la sécurité civile, la pollution a pu être circonscrite.

Sur le lieu même de l'accident, 2 à 3 hectares de vergers ont été contaminés par les hydrocarbures qui se sont infiltrés à une profondeur variant entre 20 et 30 centimètres et plus de 2 mètres. Des drains et des puisards ont été creusés pour assainir le terrain. Une partie des terres et des végétaux devra sans doute être incinérée. Le flot de pétrole a, d'autre part, souillé la rivière l'Aiguillon sur 7 kilomètres et a gagné la Durance, où il s'est répandu sur près de 1 kilomètre avant d'être stoppé par des barrages flottants. Les dégâts causés à la faune n'ont pas pu encore être évalués. Selon les responsables de la S.P.L.S.E., de 80 à 90 % du volume des hydrocarbures échappés à l'oléoduc seront, en définitive, récupérés par pompage.

Les opérations de nettoyage, qui ont été confiées à des sociétés privées après le dégagement, lundi 18 août, des militaires, se poursuivront encore pendant plusieurs semaines. Il conviendra ensuite de tirer tous les enseignements de cet accident,

De notre correspondant régional

qui aurait pu prendre des allures de catastrophe, en particulier pour les six cents exploitants agricoles de la région utilisant l'eau de la Durance et de l'Aiguillon. Tous les frais engendrés par le sinistre et notamment les indemnités aux agriculteurs lésés seront pris en charge par la société exploitant l'oléoduc.

A plus long terme, on s'interroge sur les causes de l'accident et sur la solidité de l'oléoduc. En effet, c'est la deuxième fois qu'un accident de ce type survient en moins de deux ans sur les installations de la société du pipe-line européen. Or, comme en novembre 1978 à Saint-Martin-de-Crau, c'est une soudure longitudinale qui s'est rompue.

Il semble donc, dans un cas comme dans l'autre, que la qualité du matériel livré par les constructeurs puisse être incriminée. Les fuites se sont produites sur deux canalisations de calibres et d'âges différents : celle de 24 pouces installée en 1962 à Saint-Martin-de-Crau, et celle de 40 pouces datant de 1972 à Paluds-de-Noves. Elles n'ont pas été construites par les mêmes sociétés et, selon la société d'exploitation, ces ouvrages avaient été testés de façon concluante avant leur mise en service. La canalisation endommagée de Saint-Martin-de-Crau ne présentait sans doute pas toutes les garanties de solidité puisqu'au lendemain de l'accident la S.P.L.S.E. n'avait pas hésité à remplacer 12 kilomètres de lignes « pour éviter de prendre des risques supplémentaires »... Il est vrai qu'une première fuite, aux conséquences limitées, et que l'on a apprise récemment, avait déjà été constatée dans le même secteur en septembre 1976. Pourtant, le remplacement des tuyaux sur une grande longueur — mesure draconienne et coûteuse — n'est pas envisagée pour l'instant à Paluds-de-Noves.

GUY PORTE.

Ile-de-France

La construction de l'Institut du monde arabe

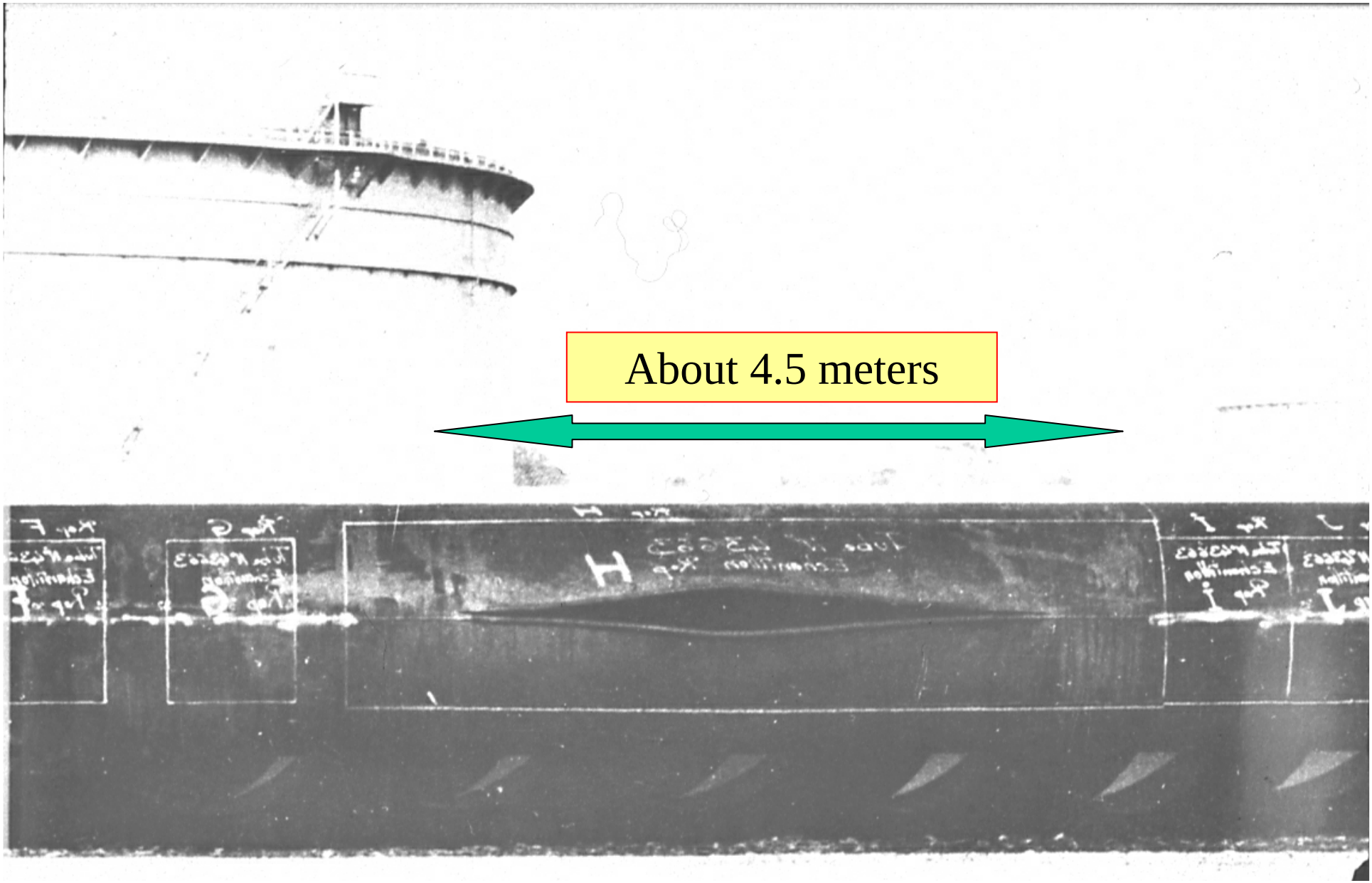
NOUVELLES PROPOSITIONS DE LA MAIRIE DE PARIS

M. Jacques Chirac a proposé le lundi 8 septembre au ministère des affaires étrangères sept terrains de remplacement pour l'implantation de l'Institut du monde arabe ailleurs que rue de la Fédération dans le quinzième arrondissement.

Les deux premiers terrains proposés par la mairie sont respectivement situés près de la Porte Champerret (17e arrondissement) et sur les terrains Citroën (15e). Les cinq autres propositions sont les suivantes : le terrain Peugeot (16e), à Bercy (12e), Citroën (15e), le palais du Bardo dans le parc Montsouris (14e), et en bordure de la place d'Italie (13e), là où devait se dresser la tour « Apogée ».

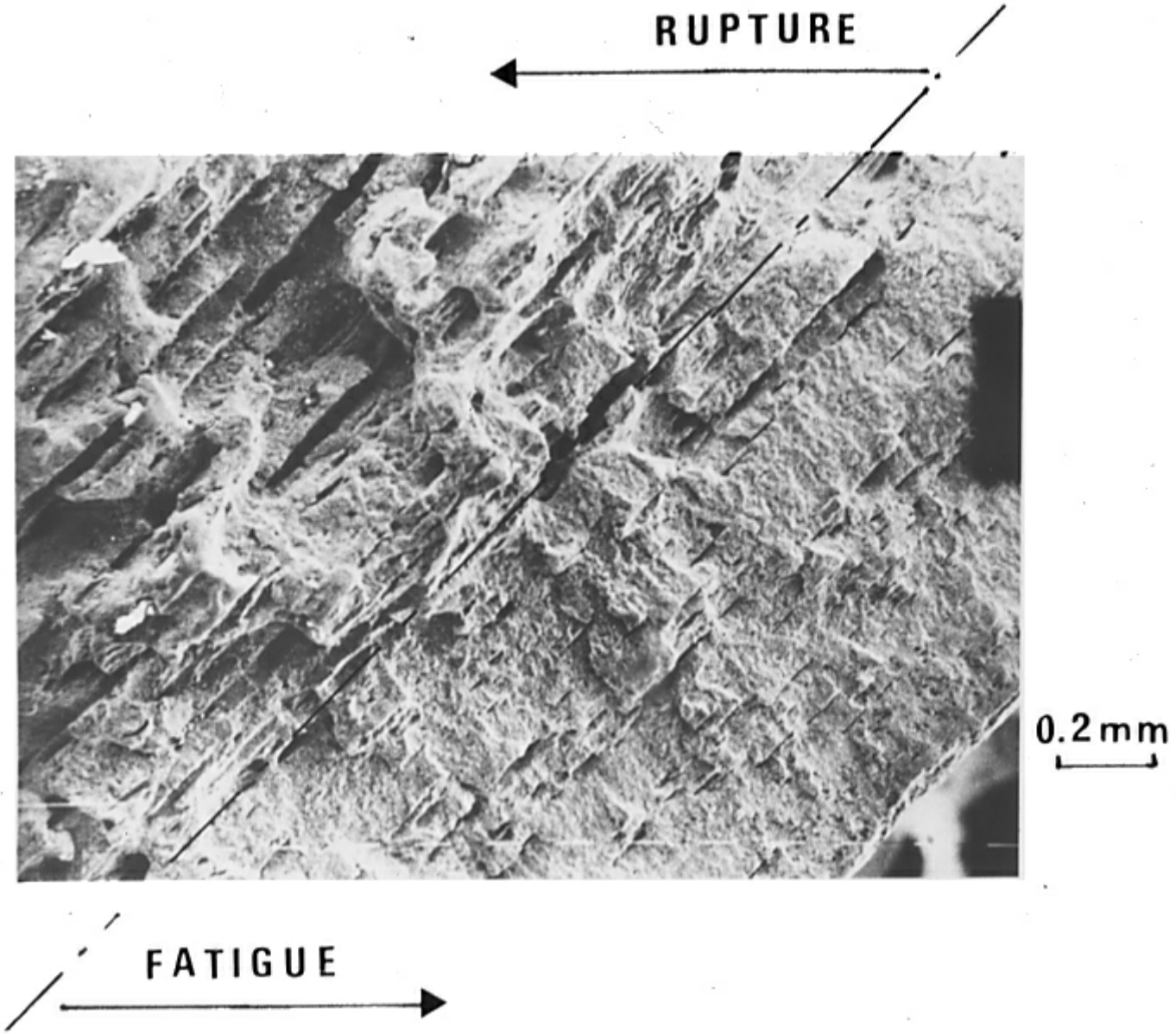
Pour M. Philippe Ardant, coresponsable de l'Institut du monde arabe, « *les propositions de la mairie de Paris ne remettent pas en cause le choix du terrain de la rue de la Fédération. Car ces terrains ont déjà été refusés ou ne sont pas utilisables immédiatement* ».

☸ Fracture
09 august 1980
between St Rémy
de Provence and
Paluds-de-Nove

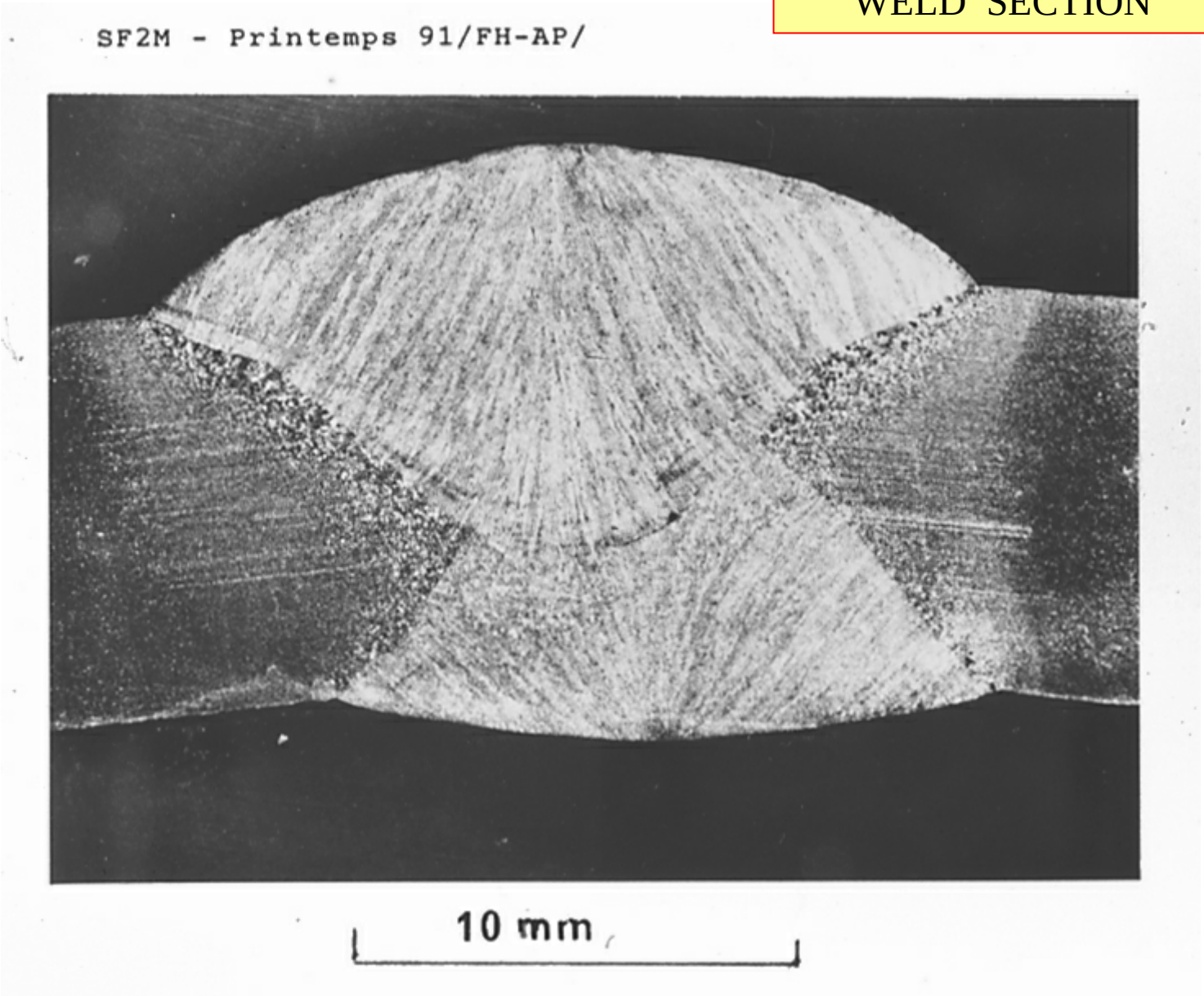

About 4.5 meters

SF2M - Printemps 91/FH-AP/

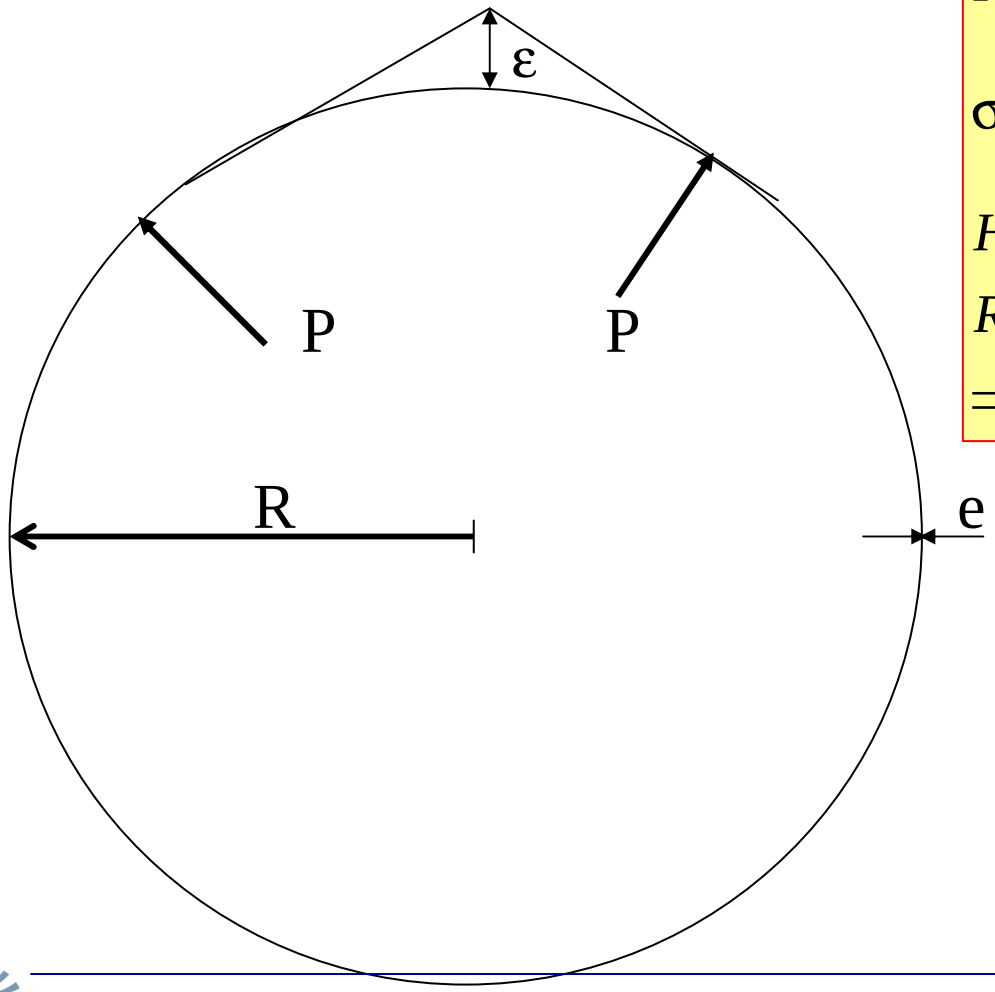
FRACTURE SURFACE OBSERVATION



WELD SECTION



ROOF EFFECT



$$\sigma_{nom} = \frac{PR}{e}$$

Roof Effect (ε)

$$\sigma = \sigma_{nom}\left[1 + \frac{6\varepsilon}{e}\right]$$

Hyp : *Small Displacement*

$R = 500\ mm; \quad \varepsilon = 5\ mm; \quad e = 10\ mm$

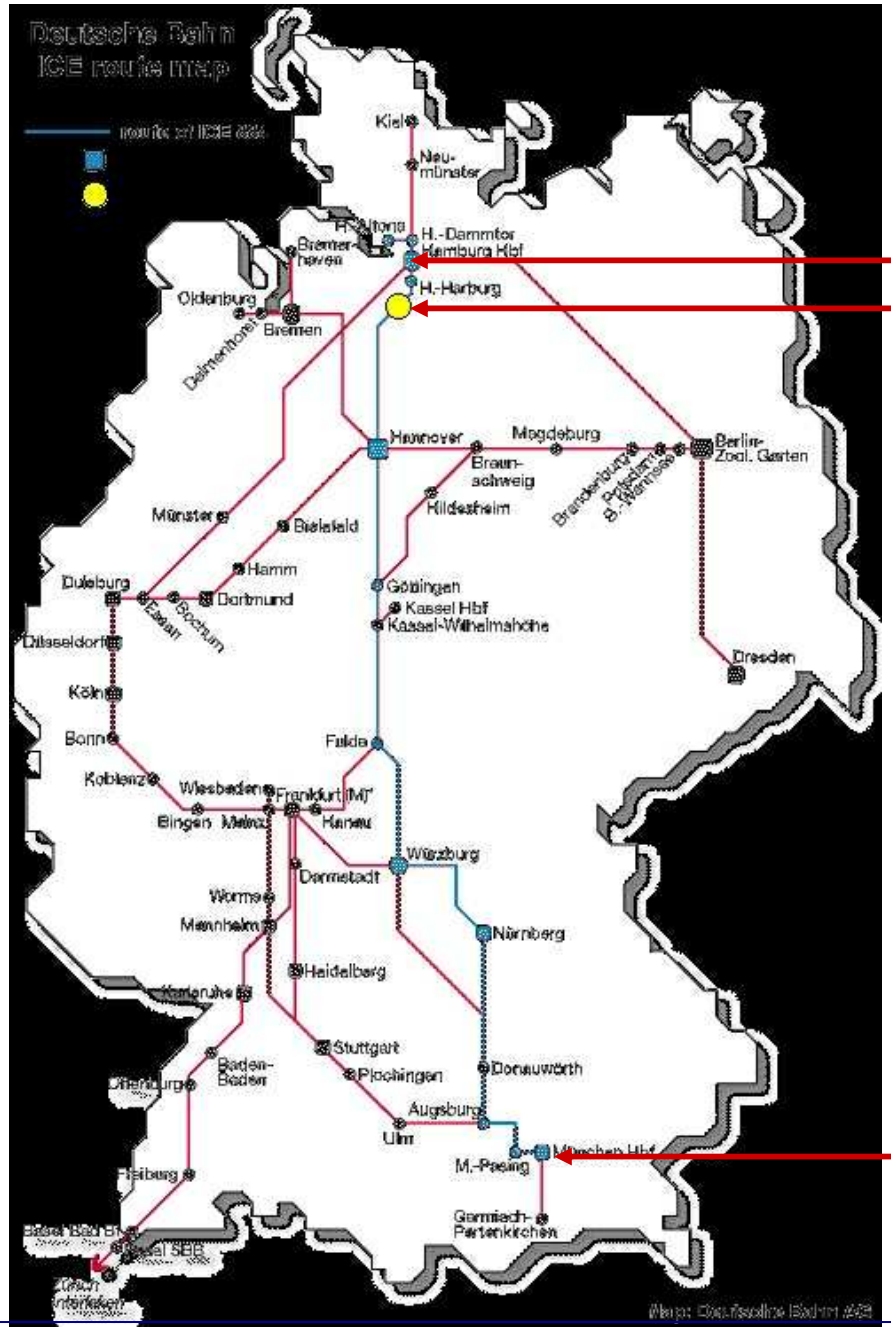
$\Rightarrow \quad \sigma = 4\sigma_{nom}$!

BUT ACCIDENTS ARE STILL POSSIBLE !

Publiée par laprovence
le 07/08/2009 à 17:02:35
3000 mètres cubes de pétrole brut déversés.

100 people died

Münich/Hambourg
round trip ➡
1million cycles



HAMBOURG
ESCHEDE

MÜNICH

ICE ACCIDENT ESCHEDE (03 juin 1998)

ICE ACCIDENT ESCHEDE (03 juin 1998)

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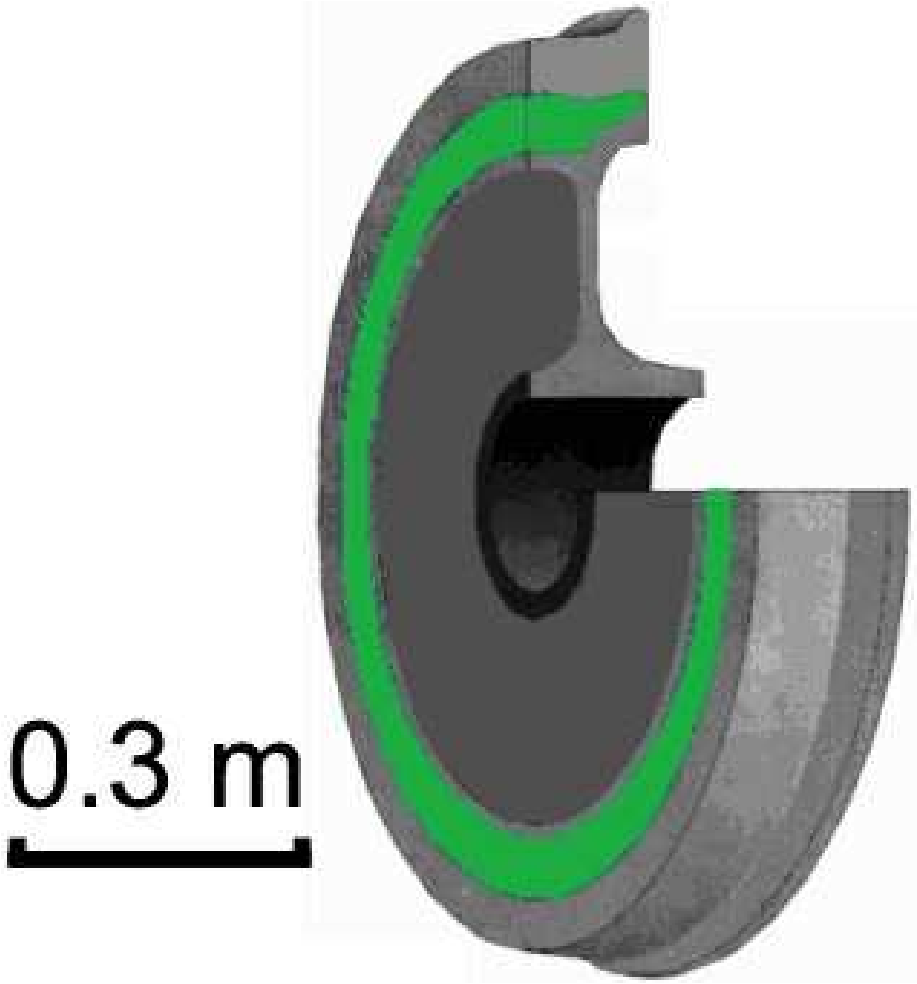
ICE ACCIDENT ESCHEDE (03 juin 1998)



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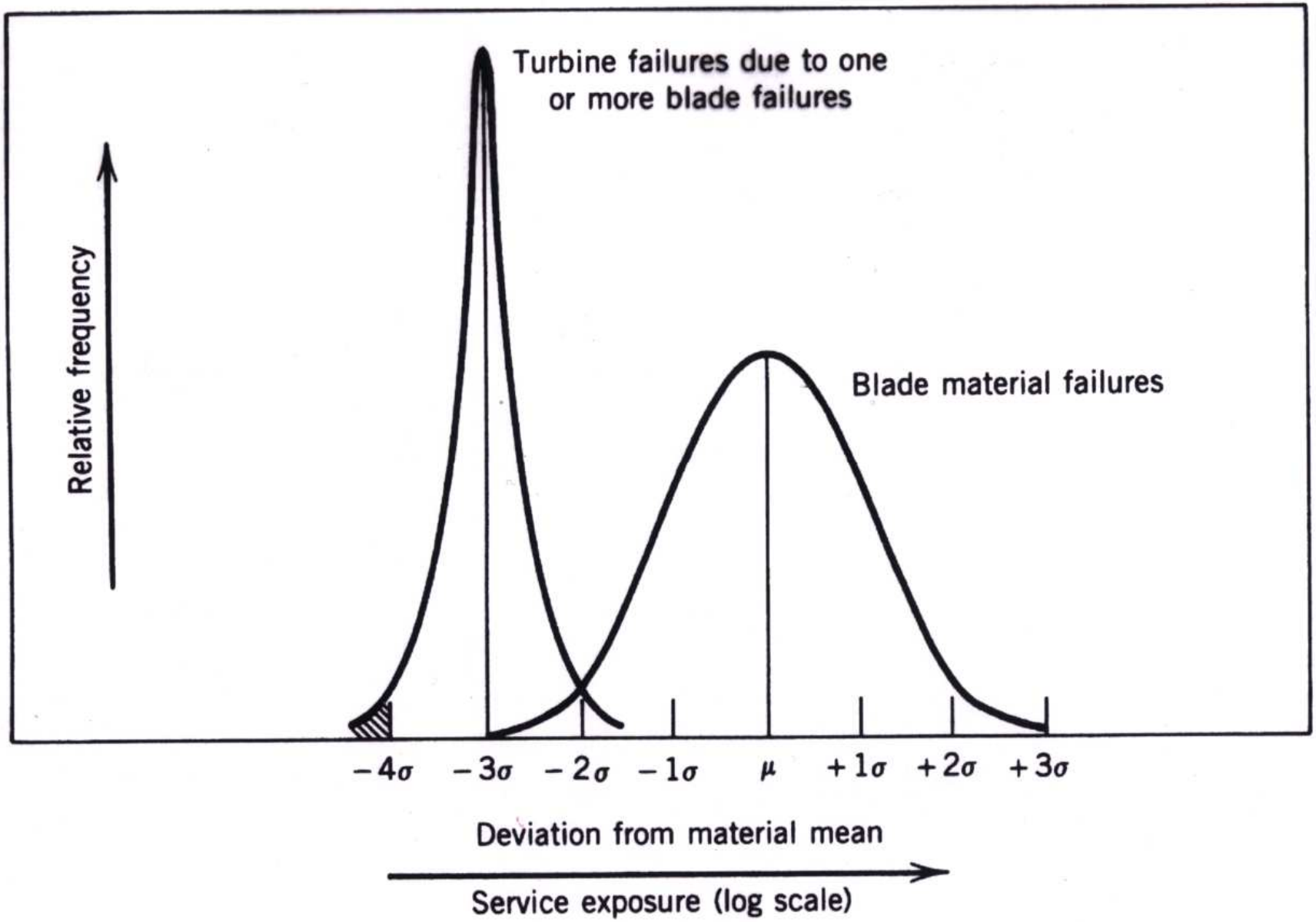
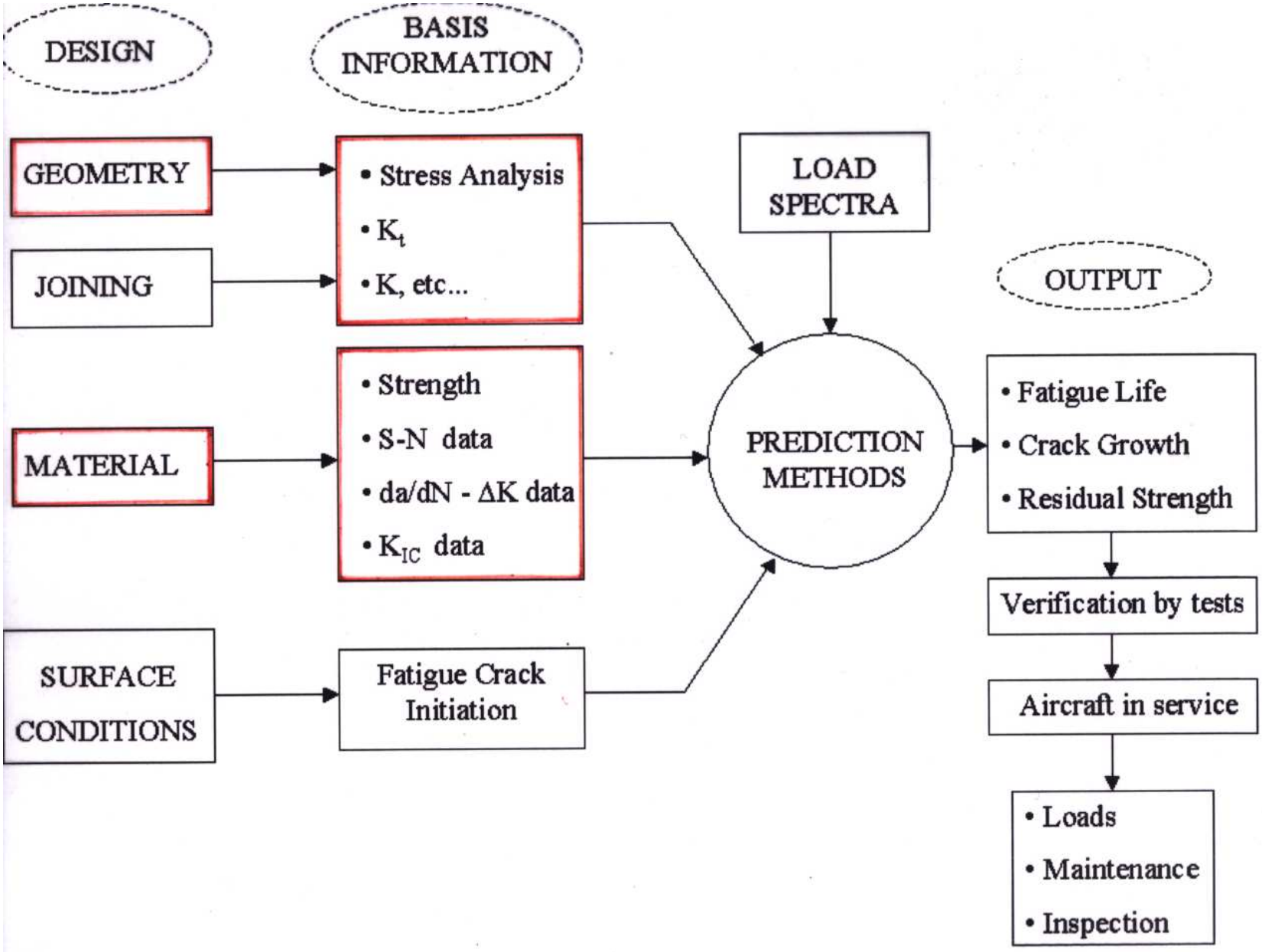
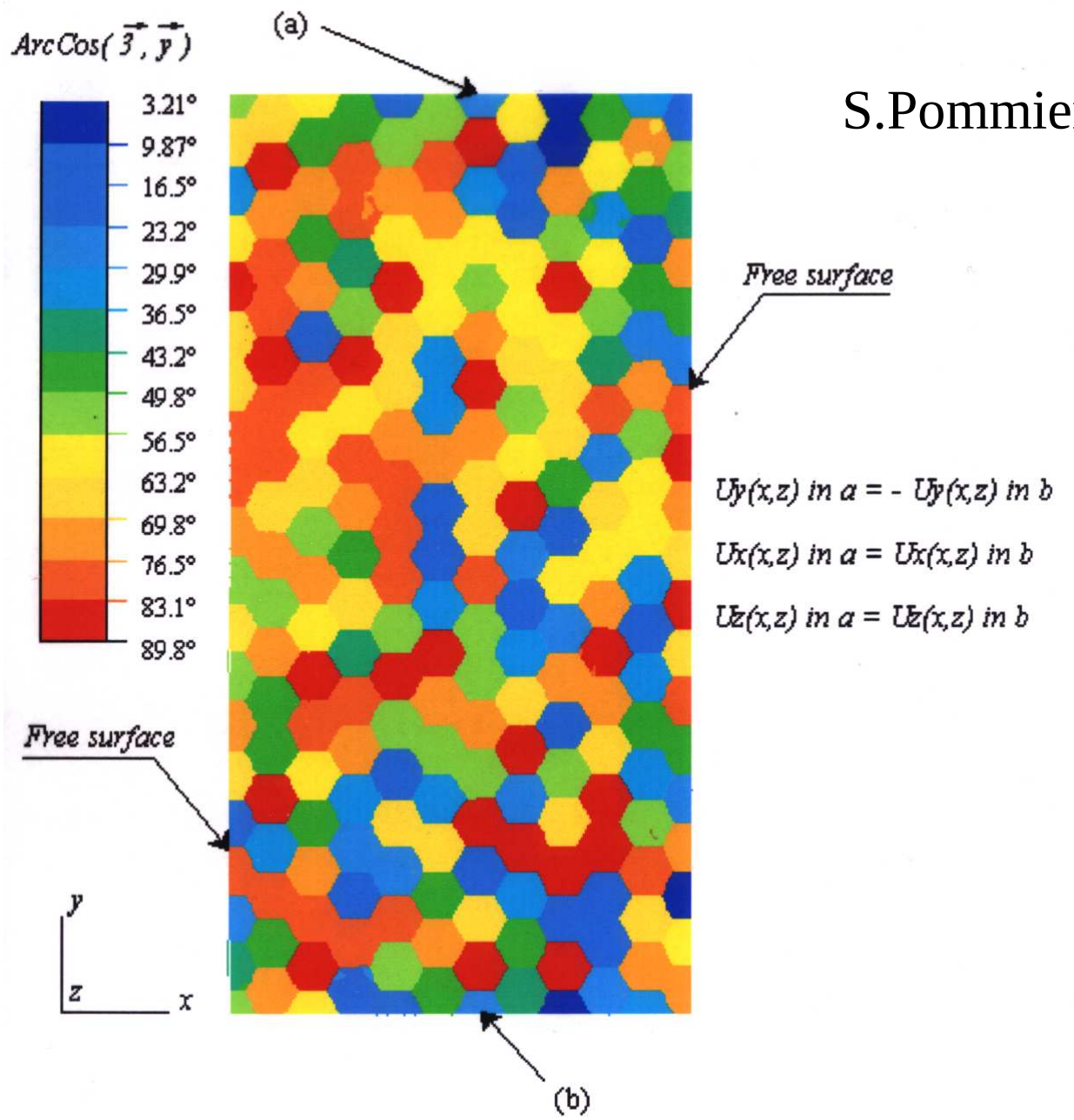
LENGTH SCALE IN STRUCTURAL MATERIALS

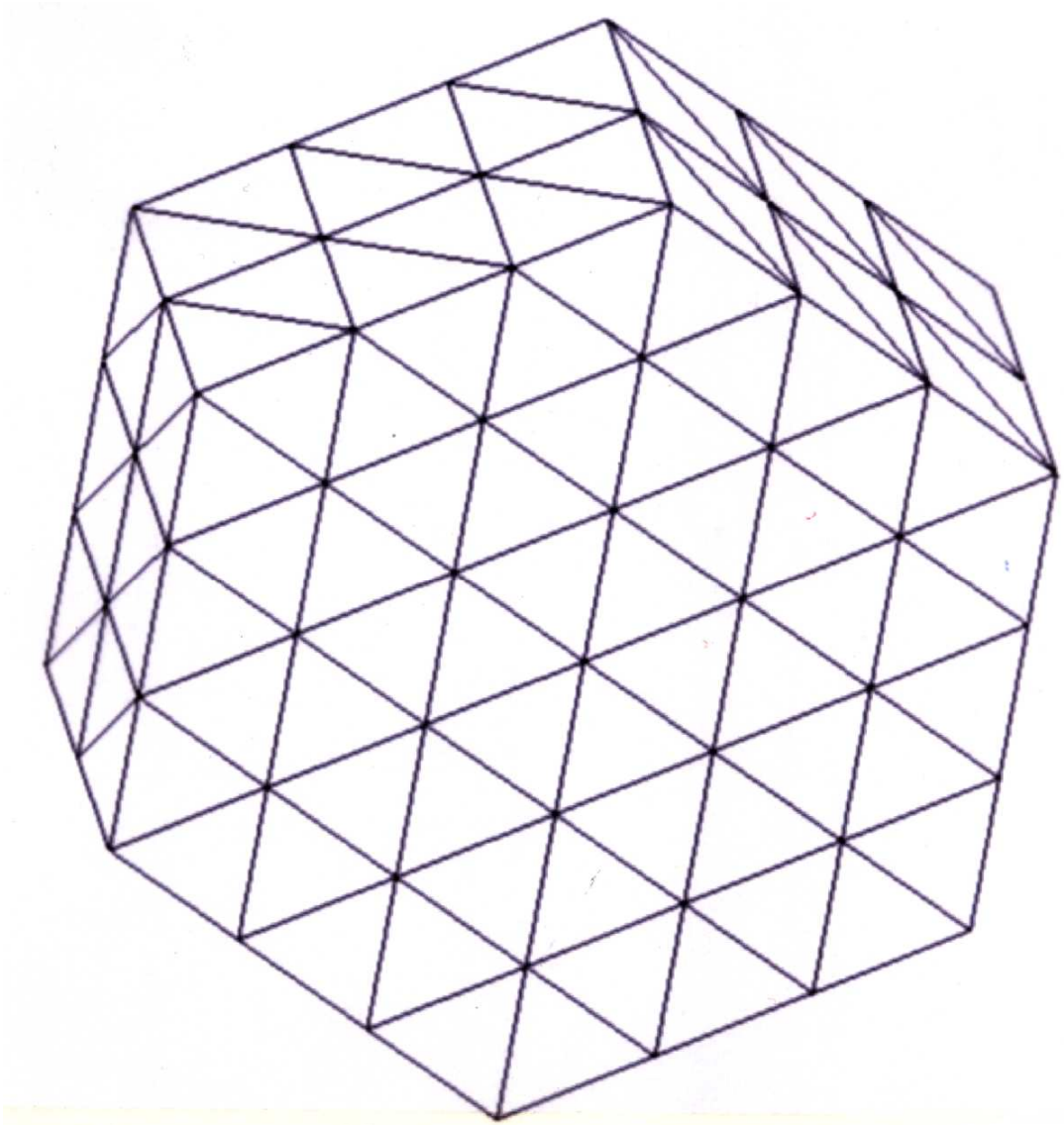
	(Å)		(µm)		(mm)					
	10^{-10}	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1} (m)
Phenomena	- Solid solution Strengthening - Impurities segregation - Strain aging		- Precipitation - Phase transformation		- Hall - Petch - Bainitic laths - Inclusions			- Casting defects - Macrosegregation - Texture (clusters of damaged grains)		
Consequences	- Jerky flow - Strengthening - Intergranular embrittlement		- Strengthening - Persistent slip band - intrusion and extrusions		- Strengthening - Ductile to brittle transition - Fatigue crack initiation			- Fatigue - Fracture		
Observations tools	- Atomic micro-proble - Electron microscopy - Auger Spectroscopy		- Transmission Electron microscopy - Microproble analysis		- Optical and Scanning - Electron microscopy - Acoustic Microscopy			- Naked eye - Non destructive inspection techniques		


Turbine failures due to one
or more blade failures
Blade material failures
Relative frequency
−4σ
−3σ
−2σ
−1σ
μ
+1σ
+2σ
+3σ
Deviation from material mean
Service exposure (log scale)


DESIGN
BASIS INFORMATION
GEOMETRY
JOINING
• Stress Analysis
• K_t
• K, etc...
LOAD SPECTRA
OUTPUT
MATERIAL
• Strength
• S-N data
• da/dN - ΔK data
• K_{IC} data
PREDICTION METHODS
• Fatigue Life
• Crack Growth
• Residual Strength
Verification by tests
Aircraft in service
• Loads
• Maintenance
• Inspection
SURFACE CONDITIONS
Fatigue Crack Initiation

S.Pommier


Arc Cos($\vec{3}$, $\vec{y}$)
3.21°
9.87°
16.5°
23.2°
29.9°
36.5°
43.2°
49.8°
56.5°
63.2°
69.8°
76.5°
83.1°
89.8°
(a)
Free surface
Uy(x,z) in a = - Uy(x,z) in b
Ux(x,z) in a = Ux(x,z) in b
Uz(x,z) in a = Uz(x,z) in b
Free surface
y
z
x
(b)



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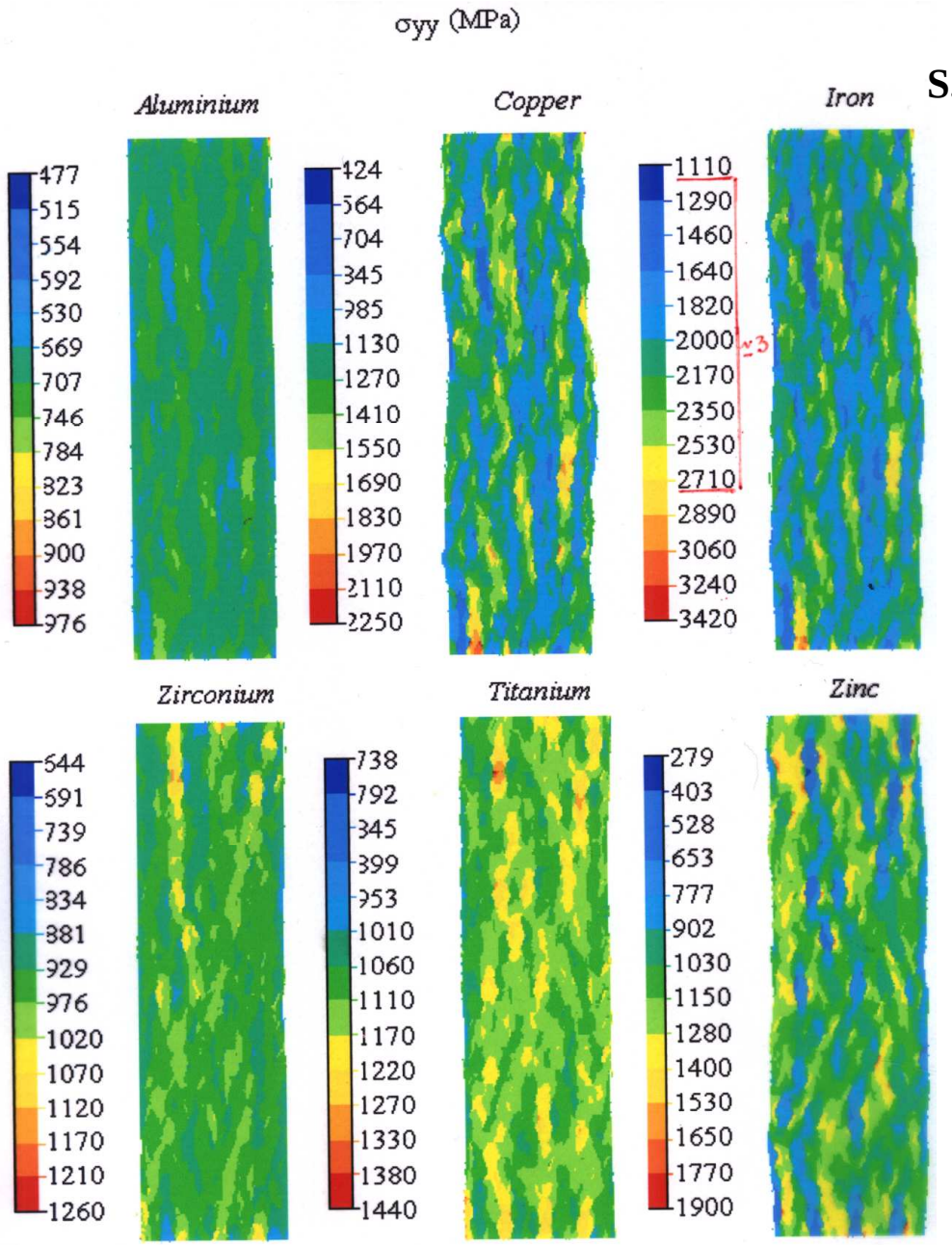
$$\begin{pmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{pmatrix} = \begin{pmatrix} D_{1111} & D_{1122} & D_{1133} & 0 & 0 & 0 \\ & D_{1111} & D_{1133} & 0 & 0 & 0 \\ & & D_{3333} & 0 & 0 & 0 \\ & & & D_{1212} & 0 & 0 \\ & & & & D_{1313} & 0 \\ & & & & & D_{1313} \end{pmatrix} \cdot \begin{pmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{12} \\ 2\varepsilon_{13} \\ 2\varepsilon_{23} \end{pmatrix}$$

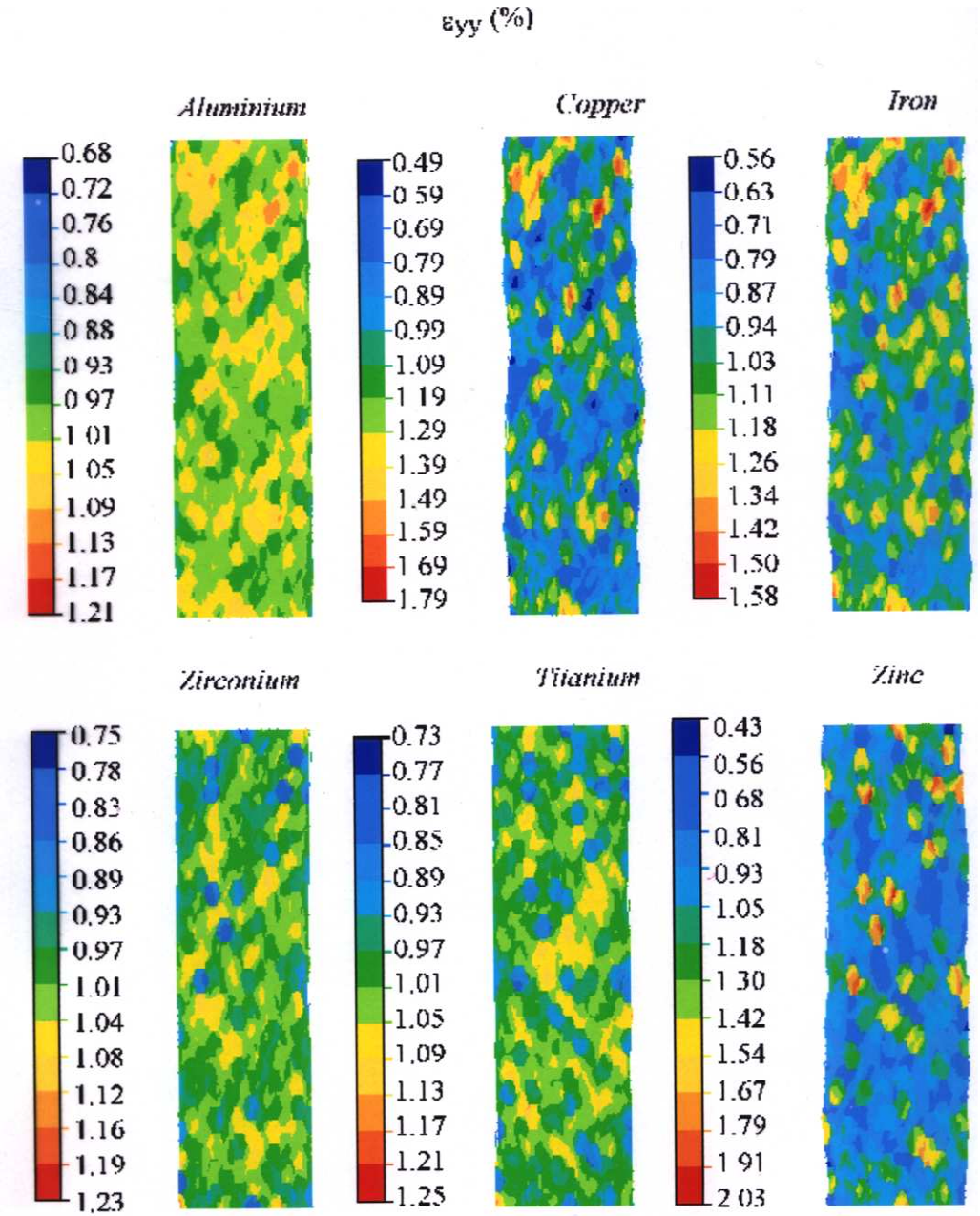
Anisotropy coefficients $A\%_{shear} = \dfrac{2D_{1212}}{D_{1111} - D_{1122}}$; $A\%_{tension} = \dfrac{D_{1111} + D_{1122} - 2D_{1133}}{D_{3333} - D_{1133}}$

Material	Symmetry	Elasticity	D_{1111}	D_{1122}	D_{1133}	D_{3333}	D_{1212}	D_{1313}	A_s %	A_f %
Titanium	HCP	Trans Isotropic /3	162	92	69	180.7	35.2	46.7	133	120
Zinc	HCP	Trans Isotropic /3	165	31	50	62	67	39.6	59	800
Zirconium	HCP	Trans Isotropic /3	144	72.8	65.3	165	35.6	32.1	90.2	126
Copper	FCC	Cubic / (1,2,3)	168.4	121.4	121.4	168.4	75.5	75.5	321	100
Aluminium	FCC	Cubic / (1,2,3)	107	60.8	60.8	107	28.3	28.3	122.5	100
Iron	CC	Cubic / (1,2,3)	231.4	134.6	134.6	231.4	116.4	116.4	100	240

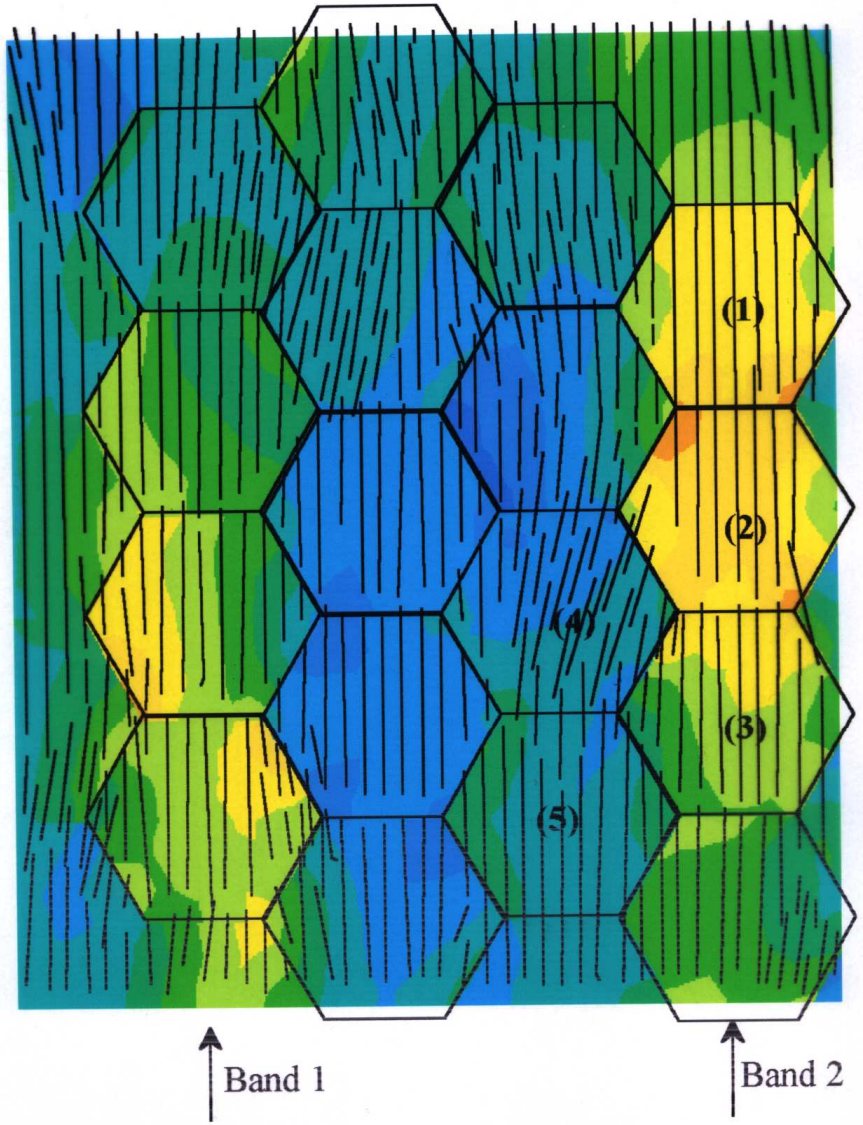
(All values of D coefficients are given in MPa)


σyy (MPa)
Aluminium
477
515
554
592
530
569
707
746
784
823
861
900
938
976
Copper
424
564
704
345
985
1130
1270
1410
1550
1690
1830
1970
2110
2250
Iron
1110
1290
1460
1640
1820
2000
2170
2350
2530
2710
2890
3060
3240
3420
≈3
Zirconium
544
591
739
786
834
881
929
976
1020
1070
1120
1170
1210
1260
Titanium
738
792
345
399
953
1010
1060
1110
1170
1220
1270
1330
1380
1440
Zinc
279
403
528
653
777
902
1030
1150
1280
1400
1530
1650
1770
1900

S.Pommier

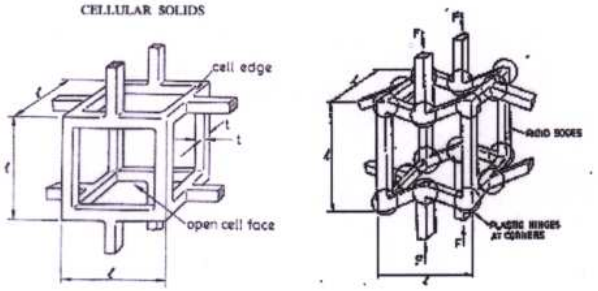

εyy (%)
Aluminium
0.68
0.72
0.76
0.8
0.84
0 88
0 93
0 97
1 01
1 05
1.09
1.13
1.17
1.21
Copper
0.49
0 59
0.69
0.79
0.89
0.99
1.09
1 19
1.29
1.39
1.49
1.59
1 69
1.79
Iron
0.56
0.63
0.71
0.79
0.87
0.94
1.03
1.11
1.18
1.26
1.34
1.42
1.50
1.58
Zirconium
0.75
0.78
0.83
0.86
0.89
0.93
0.97
1.01
1.04
1.08
1.12
1.16
1.19
1.23
Titanium
0.73
0.77
0.81
0.85
0.89
0.93
0.97
1.01
1.05
1.09
1.13
1.17
1.21
1.25
Zinc
0.43
0.56
0 68
0.81
0.93
1.05
1.18
1 30
1.42
1.54
1.67
1.79
1 91
2 03

Maximum principal stress isocontours and direction



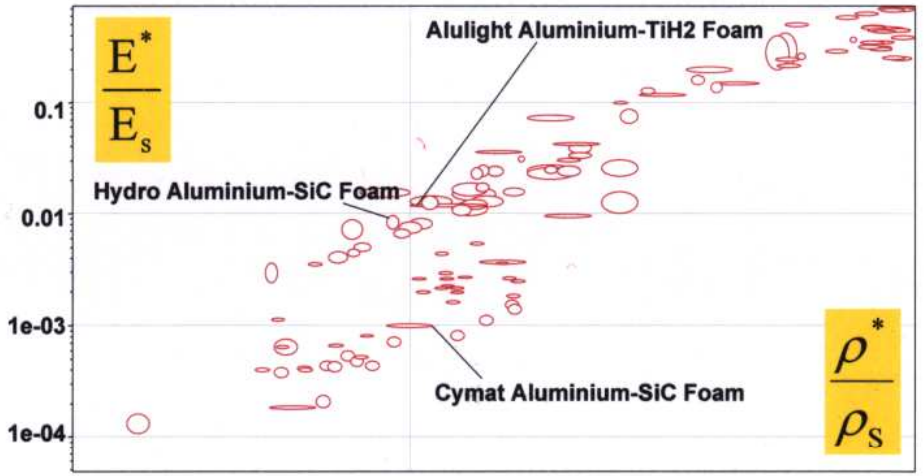
Mechanical properties

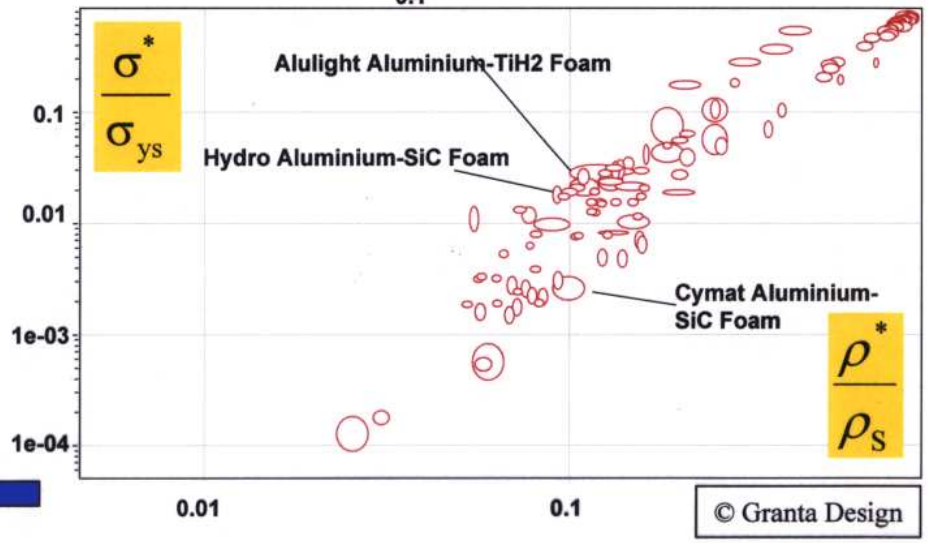
Gibson & Ashby



$$\frac{E^*}{E_s} \propto \left(\frac{\rho^*}{\rho_s}\right)^2 \qquad \frac{\sigma^*}{\sigma_{ys}} \propto \left(\frac{\rho^*}{\rho_s}\right)^{\frac{3}{2}}$$

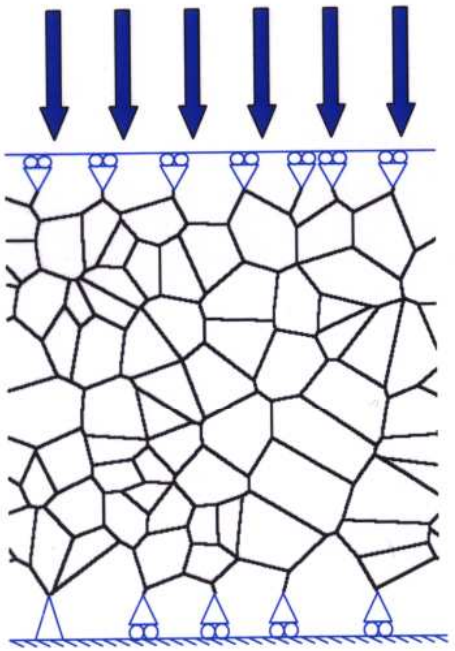
E_s, σ_s, ρ_s : constitutive material





large dispersions

Numerical simulation



Foam = assembly of beams

→ Identification in elasticity : E

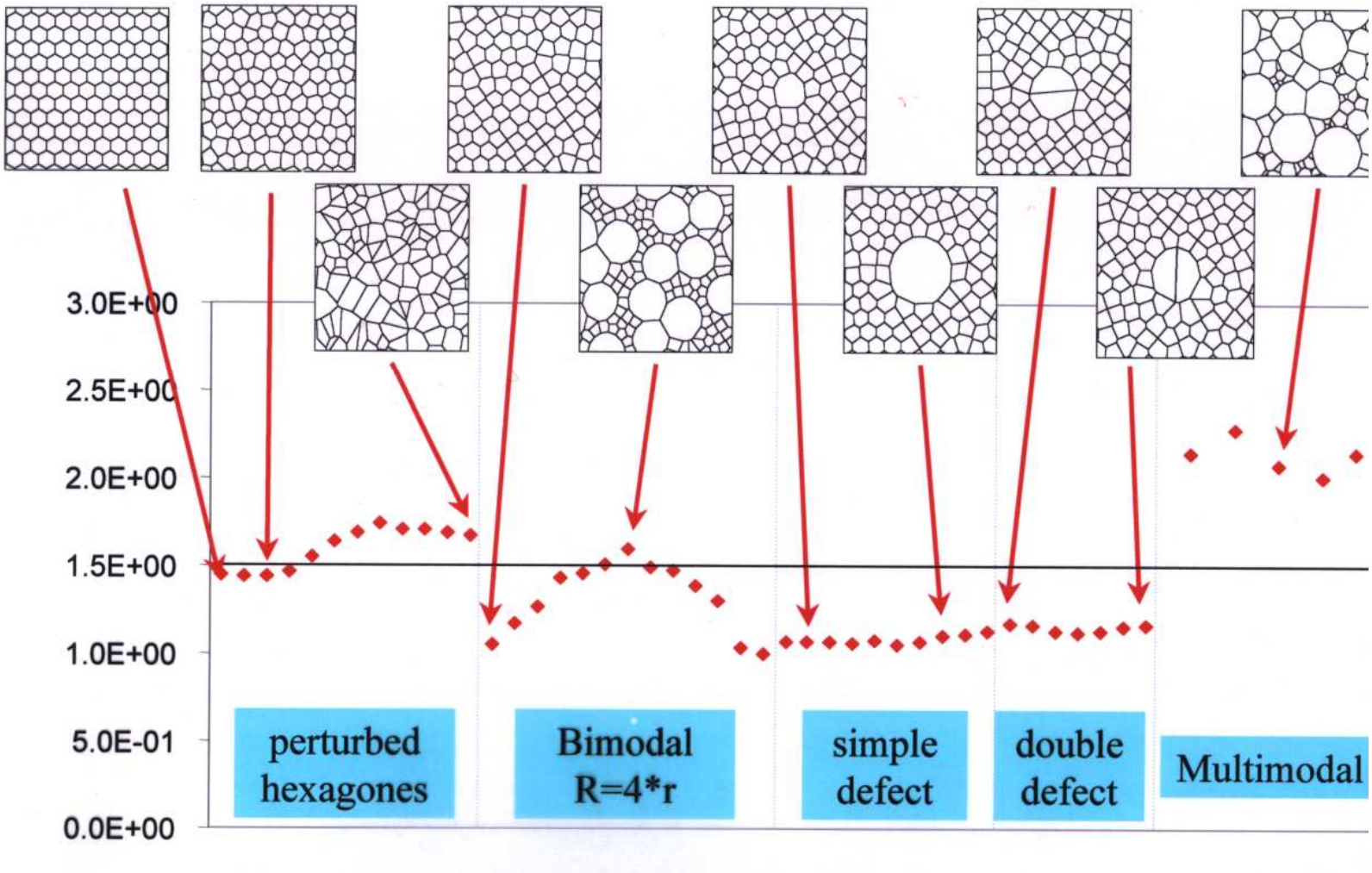
$$\frac{E^*}{E_S} = C_E \left(\frac{\rho^*}{\rho_S} \right)^1$$

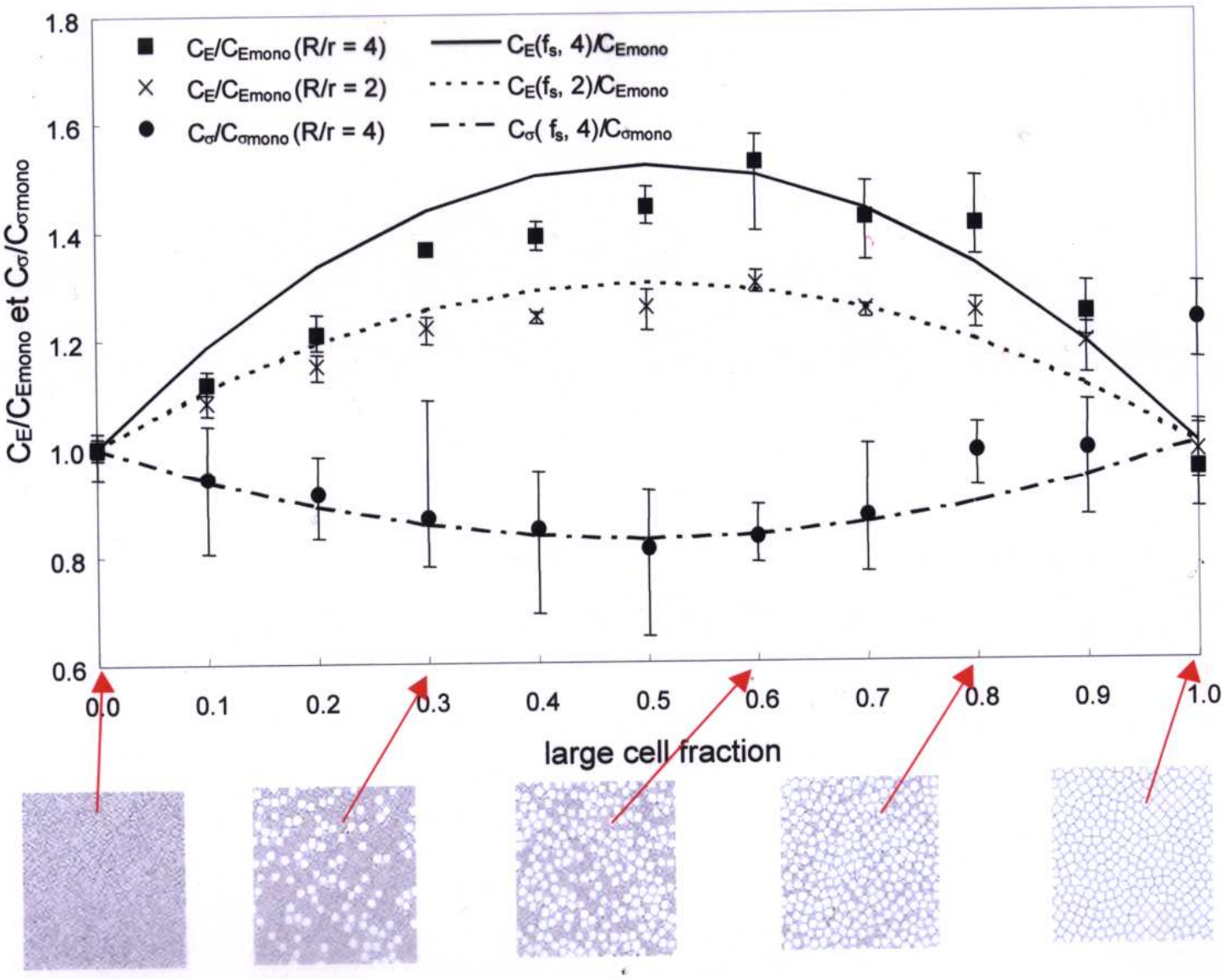
→ Identification in plasticity : σ

$$\frac{\sigma^*}{\sigma_{ys}} = C_\sigma \left(\frac{\rho^*}{\rho_S} \right)^{3/2}$$

(for low density)

Evolution of C_E




C_E/C_{Emono} (R/r = 4)
C_E/C_{Emono} (R/r = 2)
$C_\sigma/C_{\sigma mono}$ (R/r = 4)
$C_E(f_s, 4)/C_{Emono}$
$C_E(f_s, 2)/C_{Emono}$
$C_\sigma(f_s, 4)/C_{\sigma mono}$
C_E/C_{Emono} et $C_\sigma/C_{\sigma mono}$
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
large cell fraction

INTRODUCTION TO MATERIAL VARIABILITY OF MECHANICAL PROPERTIES AND LENGTH SCALE

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I - INTRODUCTION - CASE STUDIES

II - ELASTICITY

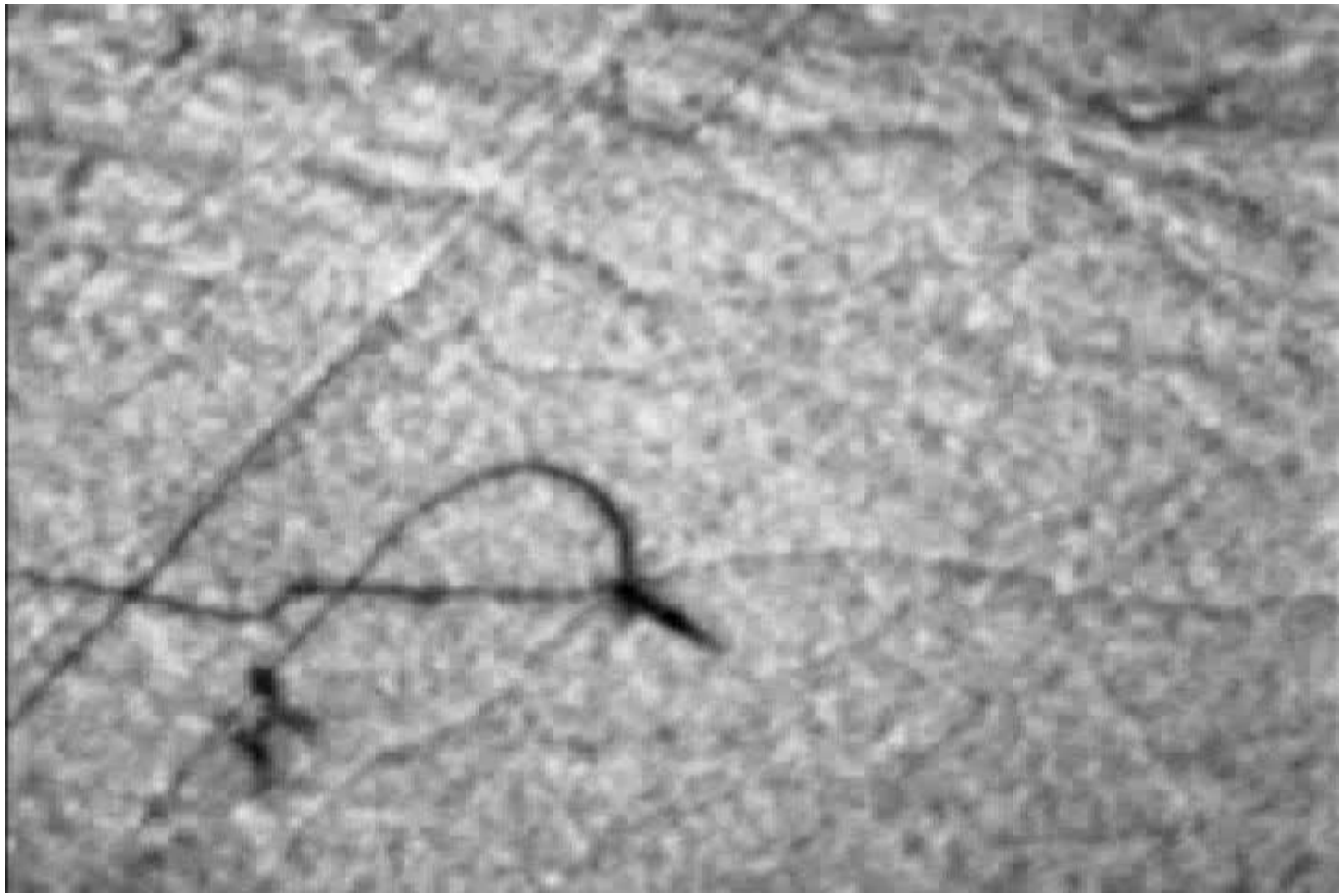
III - PLASTICITY

IV - FRACTURE : 2 Case Studies
- Duplex Stainless Steels
- Welds

V - A SIMPLE MODEL BASED ON WEAKEST LINK THEORY

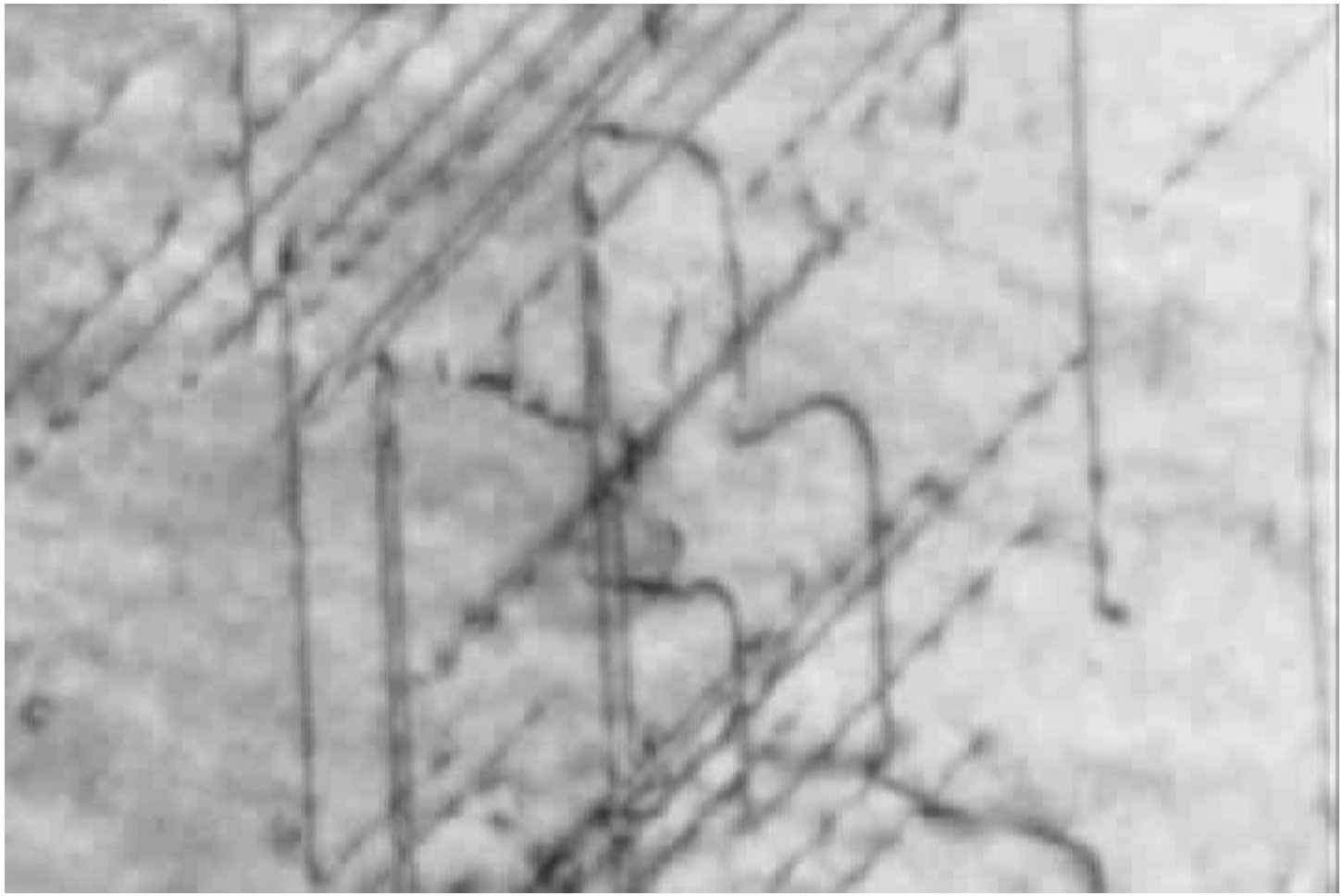
VI - CONCLUSIONS

D.Caillard , Acta Materialia ,2010,pp.3493-3503 & pp.3504-3515 – Kinetics of dislocations in pure Iron Part I. In situ straining experiments at RT – Part II. In situ deformation experiments at low temperature



300 K

D.Caillard , Acta Materialia ,2010,pp.3493-3503 & pp.3504-3515.– Kinetics of dislocations in pure Iron Part I. In situ straining experiments at RT – Part II. In situ deformation experiments at low temperature



250 K

D.Caillard , Acta Materialia ,2010,pp.3493-3503 & pp.3504-3515 – Kinetics of dislocations in pure Iron Part I. In situ straining experiments at RT – Part II. In situ deformation experiments at low temperature

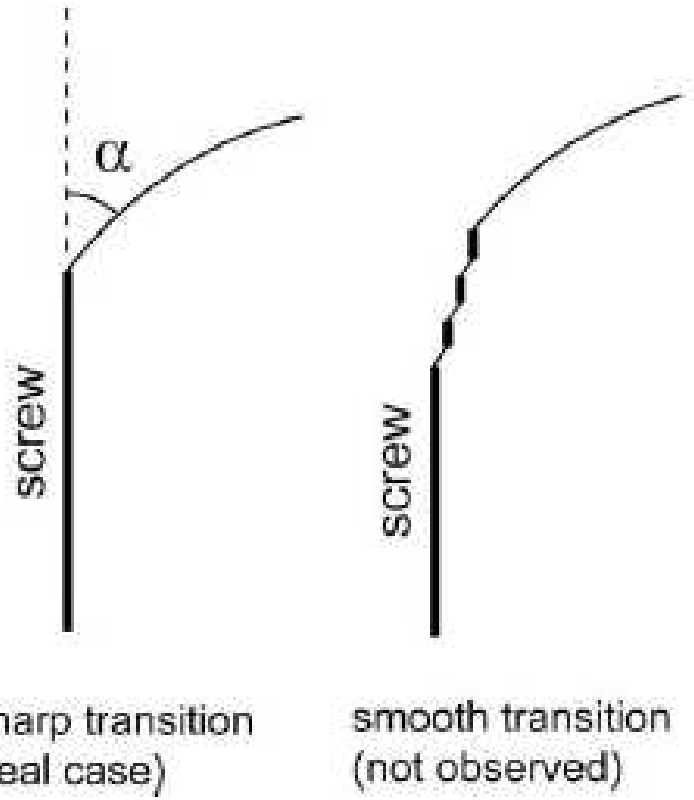


Fig. 5. Schematic description of a sharp and a smooth transition, between the screw and near-screw parts of a dislocation loop.

D.Caillard , Acta Materialia ,2010,pp;3493-3503 & pp.3504-3515– Kinetics of dislocations in pure Iron

Part I. In situ straining experiments at RT – Part II. In situ deformation experiments at low temperature

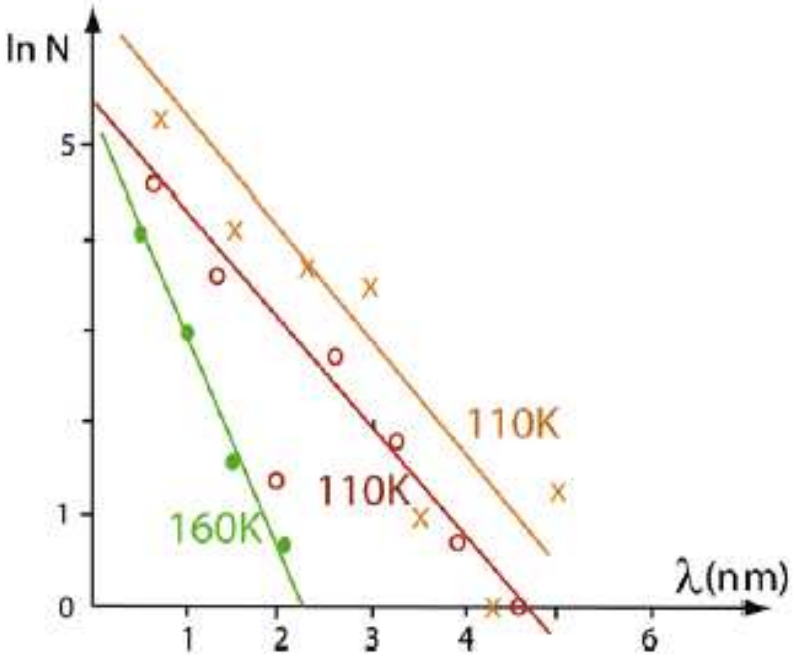


Fig. 8. Distribution of jump lengths at 110 K (two measurements) and 160 K. N is the number of jumps over the length λ. Crosses correspond to the data of Fig. 7.

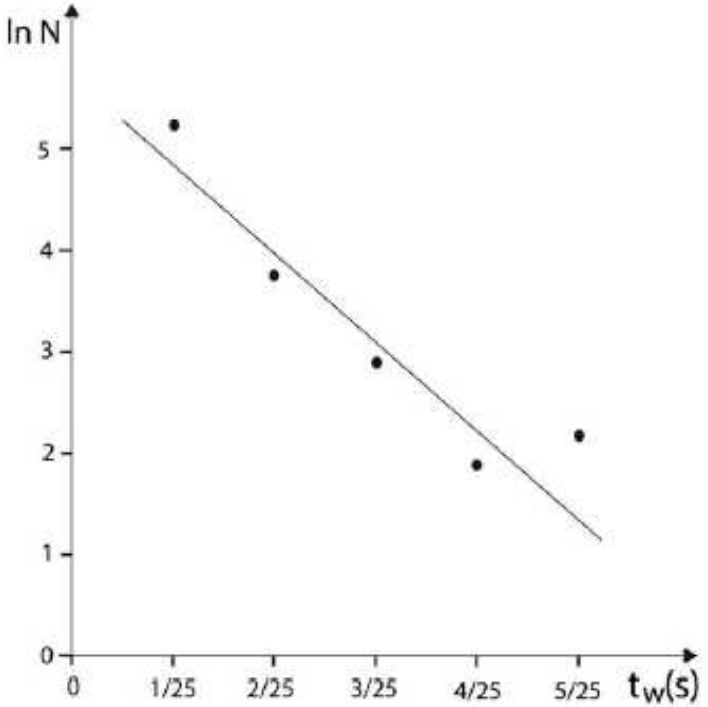
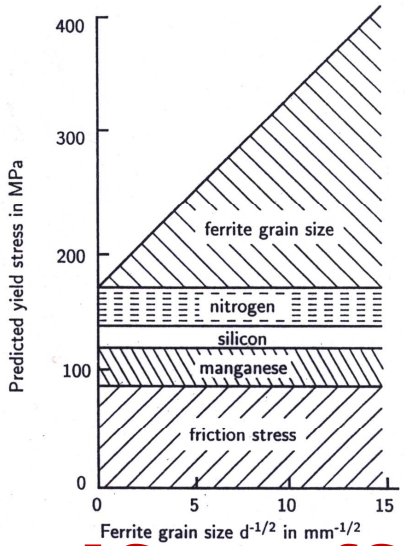


Fig. 9. Distribution of waiting times, from the data of Fig. 7. N is the number of jumps preceded by the waiting time t_w.



Grain Size Effect

Solid Solution

Friction Stress

LG **SG 4.4 µm**

Figure II.1 : *Exemple des différentes contributions au durcissement d'un acier ferrito-perlitique (0.20 %C, 1.0 %Mn, 0.20 %Si, 0.010 %N, (Pickering, 1992b)).*

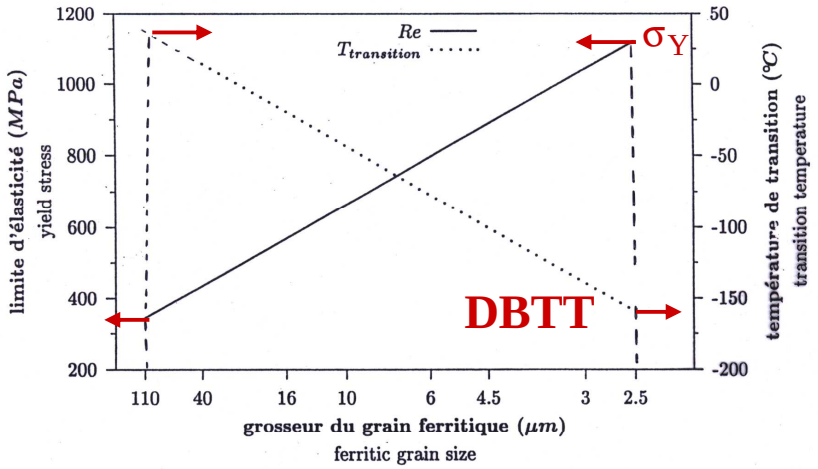
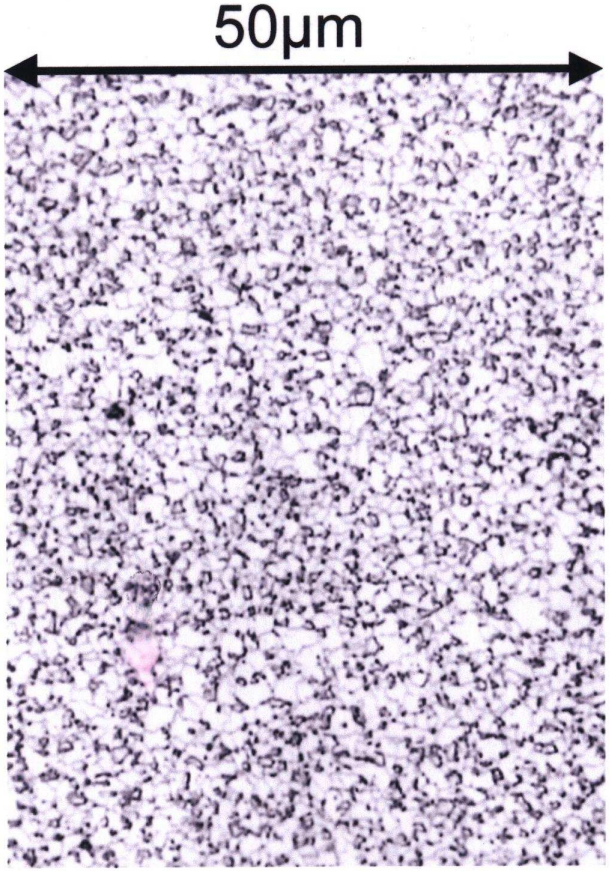


Figure II.2 : *Effet de la taille du grain ferritique sur la limite d'élasticité et la température de transition (acier à 0.1 %C, 0.5 %Mn, 0.2 %Si, 0.006 %N, d'après* IRVINE, *cité par (Constant et al., 1992)).*

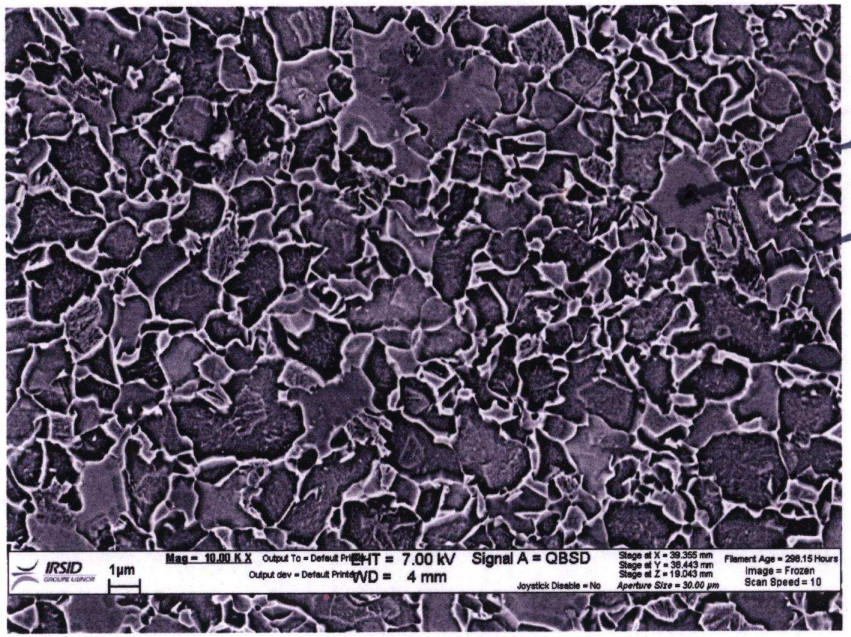
$\sigma_Y \propto d^{-1/2}$

Hall – Petch Eq.

Ultra-fine DP steels characterization



UFG-DP cold rolled microstructure

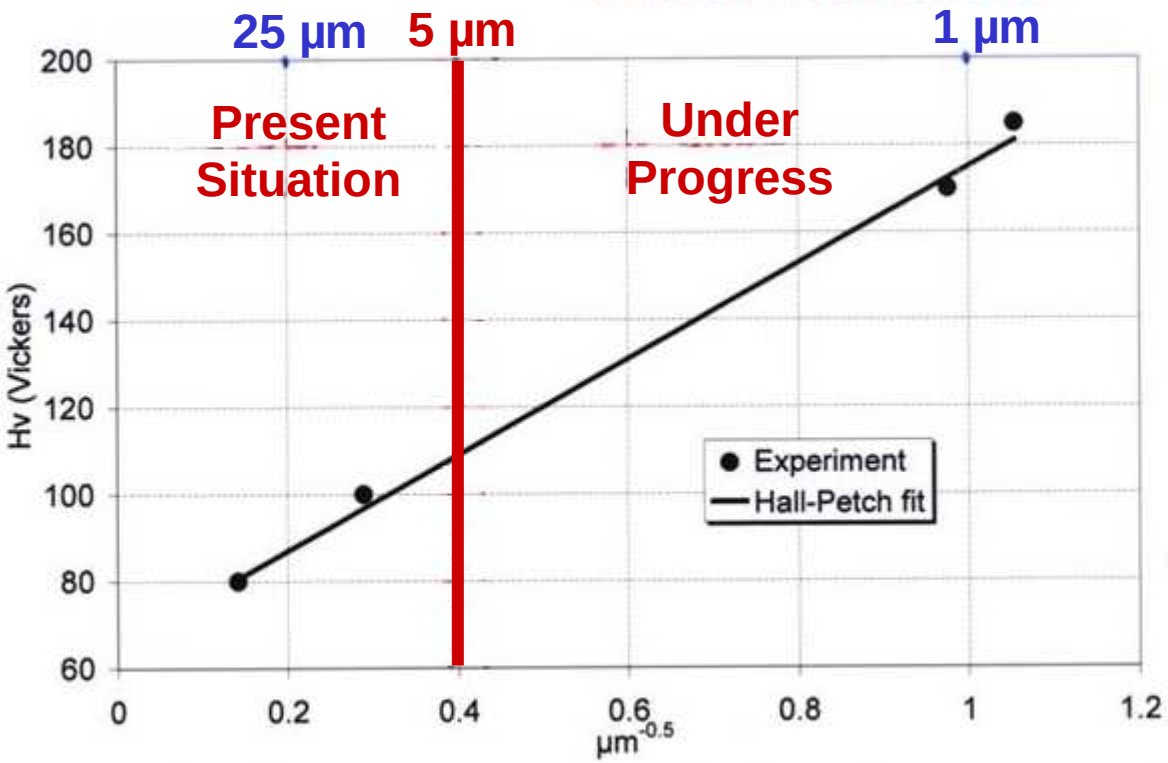


FEG

$F_{\alpha'}$: 23%

d_{α} : 1.05µm, $d_{\alpha'}$: 0.95µm

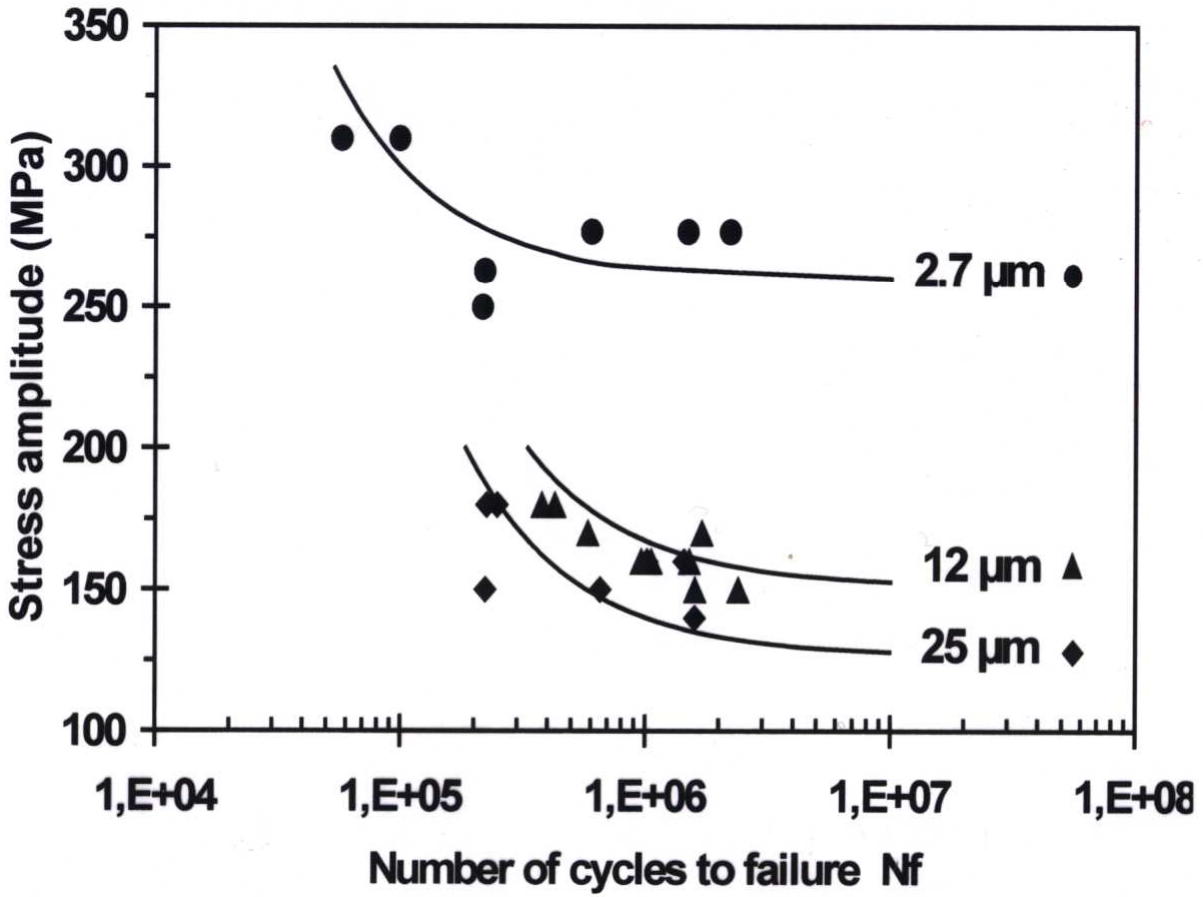
Hardness



$$Hv = 65 + \frac{110}{\sqrt{d}}$$

- Hall-Petch type law suitable up to 1 µm grain size refinement

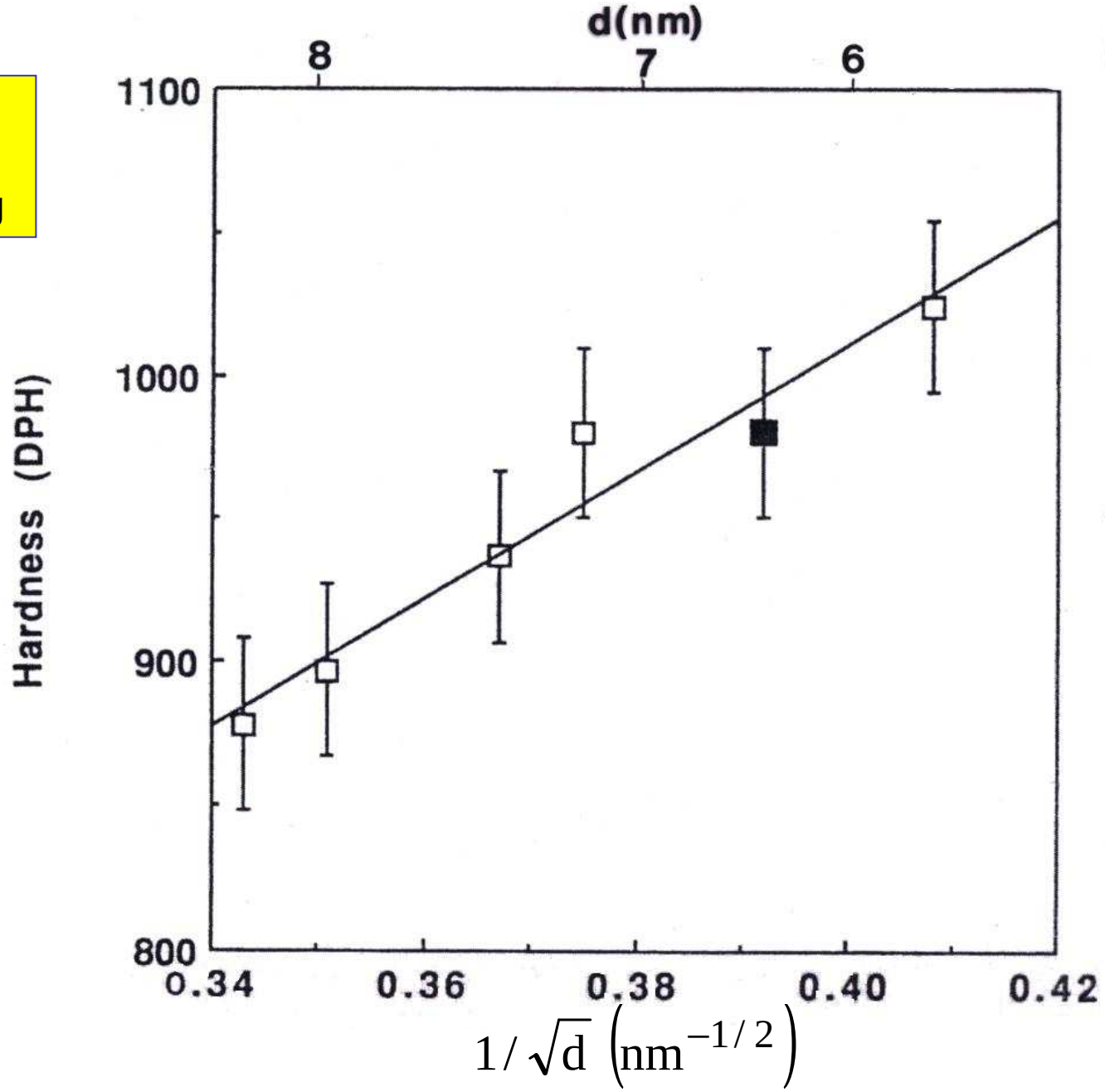
Fatigue properties : bending test (25Hz)



Pure Iron

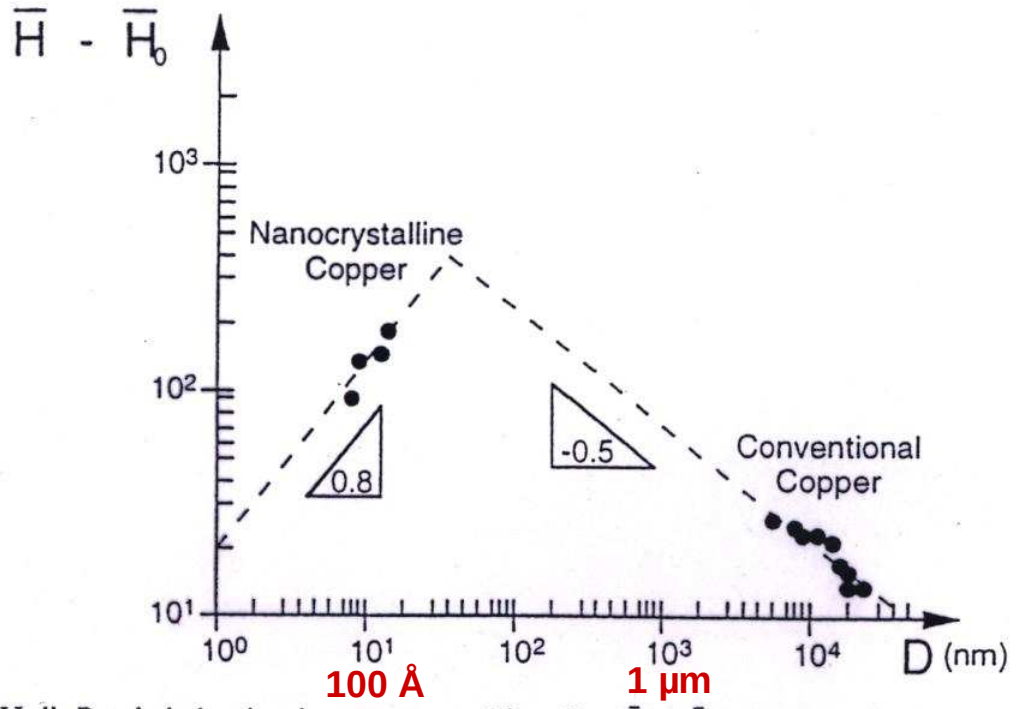
Mechanical Milling

J.S.C. JANG and
CC. KOCK.
Scripta Metall. Vol. 24
(1990), pp. 1599 - 1604



E. ARZT., Acta Mater., Vol 46, (1998), pp. 5611 - 5626

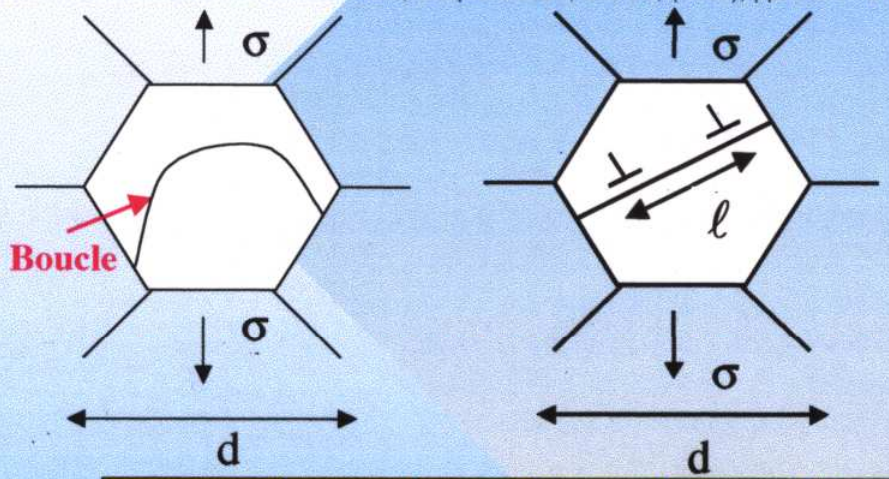
Pure Copper - Deposition



Inverse Hall–Petch behavior in nanocrystalline Cu ($\bar{H} - \bar{H}_0$ denotes the hardness increment. D the grain size): the classical behavior breaks down at a grain size of about 50 nm, in agreement with an estimate based on the loop diameter [equations (13a)–(b)]. Replotted after Chokshi *et al.* [23].

Limitations à HALL - PETCH

- E. ARZT. Acta Mater, Vol. 46, (1998), pp. 5611 - 5626
- T.G. NIEH and J. WADSWORTH. Scripta Metall., Vol. 25, (1991), pp. 955 - 958
- A.H. CHOKSHI, A. ROSEN, J. KARCH and H. GLEITER, Scripta Metall., Vol. 23, (1989), pp. 1679 - 1684
- J.S.C. JANG and C.C. KOCH, Scripta Metall., Vol. 24, (1990), pp. 1599 - 1604
- H.J. HÖFLER and R.S. AVERBACH, Scripta Metall., Vol. 24, (1990), pp. 2401 - 2406



$$\ell_c \approx \frac{3\,\mu b}{\pi\,(1-\nu)\,H}$$

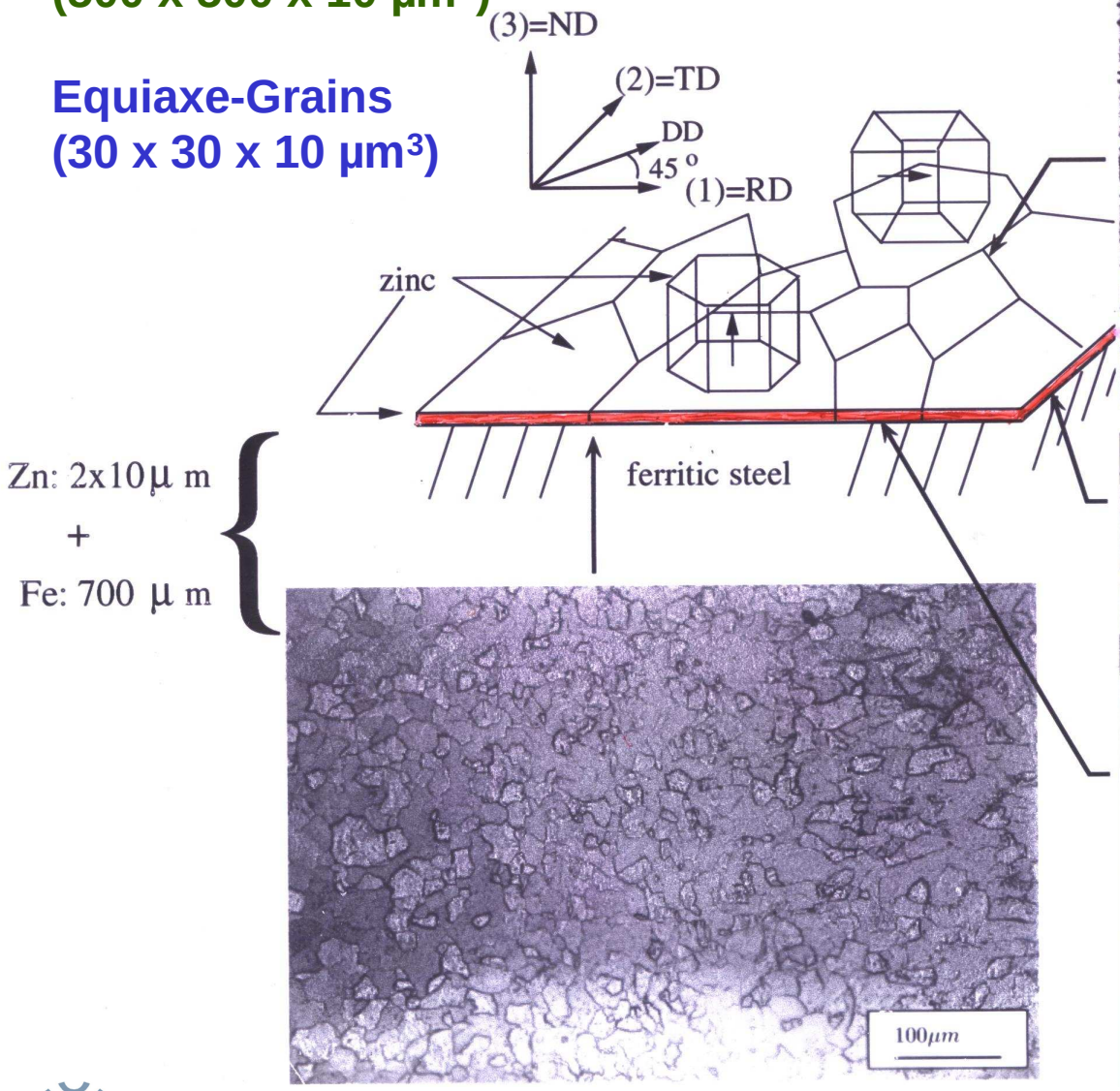
H : Dureté

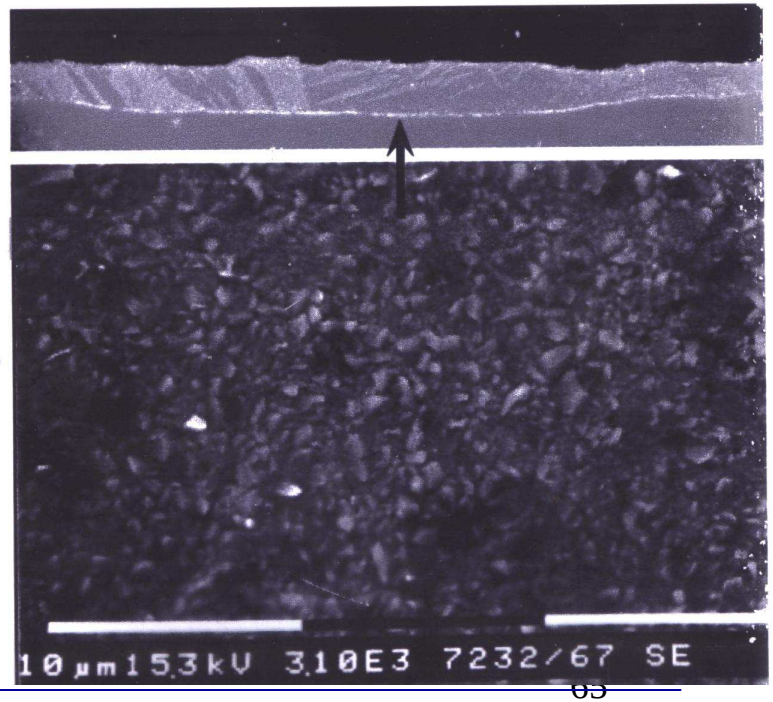
Matériaux	μ (GPa)	b (nm)	ν	H (GPa)	ℓ_c (nm)	d (nm)	HP ?
Cu	77	0.256	0.34	1.5	19.3	8-16	Non
Pd	51	0.275	0.52	2.5	11.2	7-13	Non
Fe	81	0.248	0.29	8	3.4	6-60	Oui
Ni - P	76	0.249	0.31	10.5	2.5	7.5-120	Non
Ni	76	0.249	0.31	10.5	2.5	12-12.5	Oui
TiO_2	105	≈ 0.4	0.30	7.4	7.4	14-400	Oui

Vérification de la loi HP et Valeurs de ℓ_c pour divers matériaux à grains ultrafins.

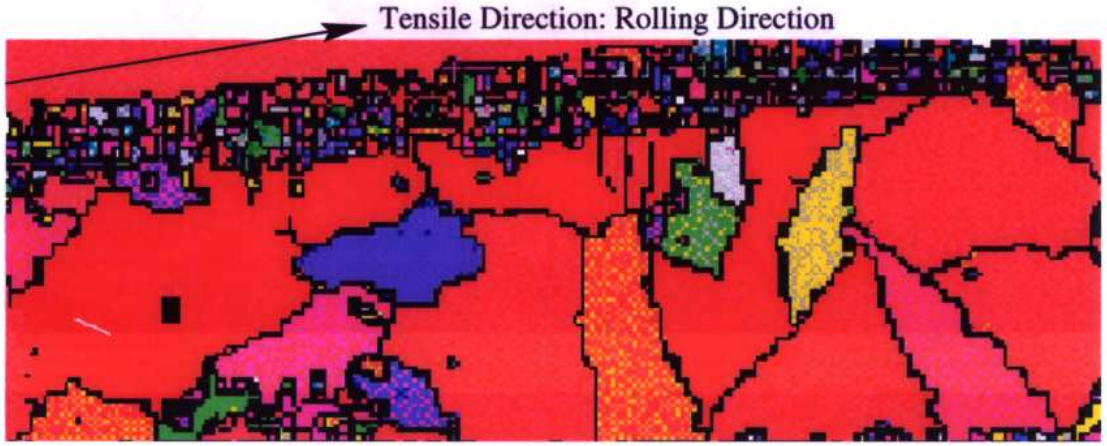
Pancake-Grains
(500 x 500 x 10 µm³)

Equiaxe-Grains
(30 x 30 x 10 µm³)

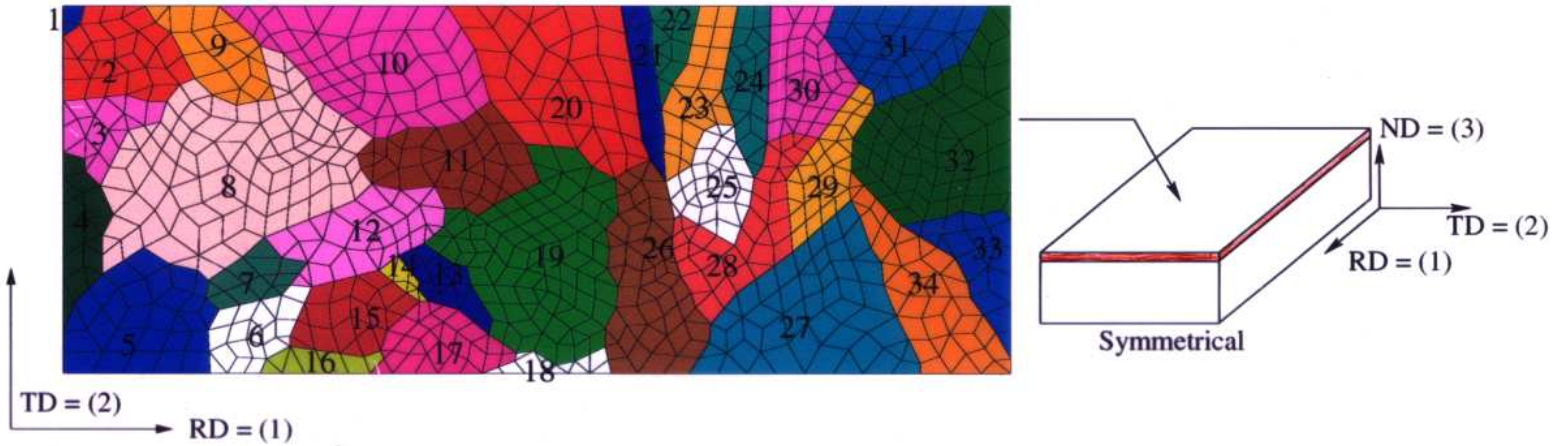




Caracterization of thin layers and coatings



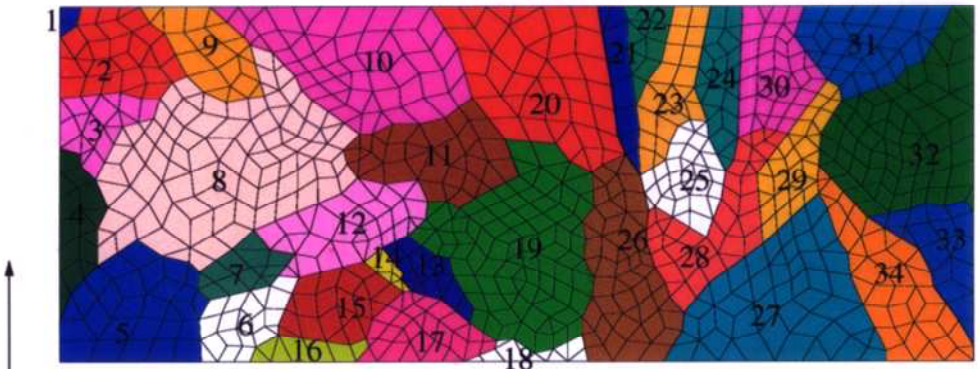
coating of a galvanized
steel sheet
EBSD analysis

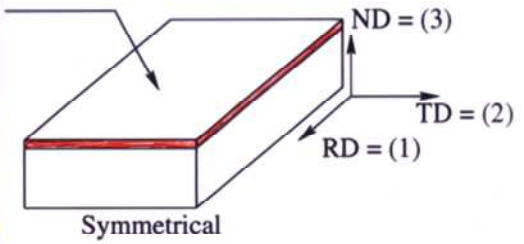


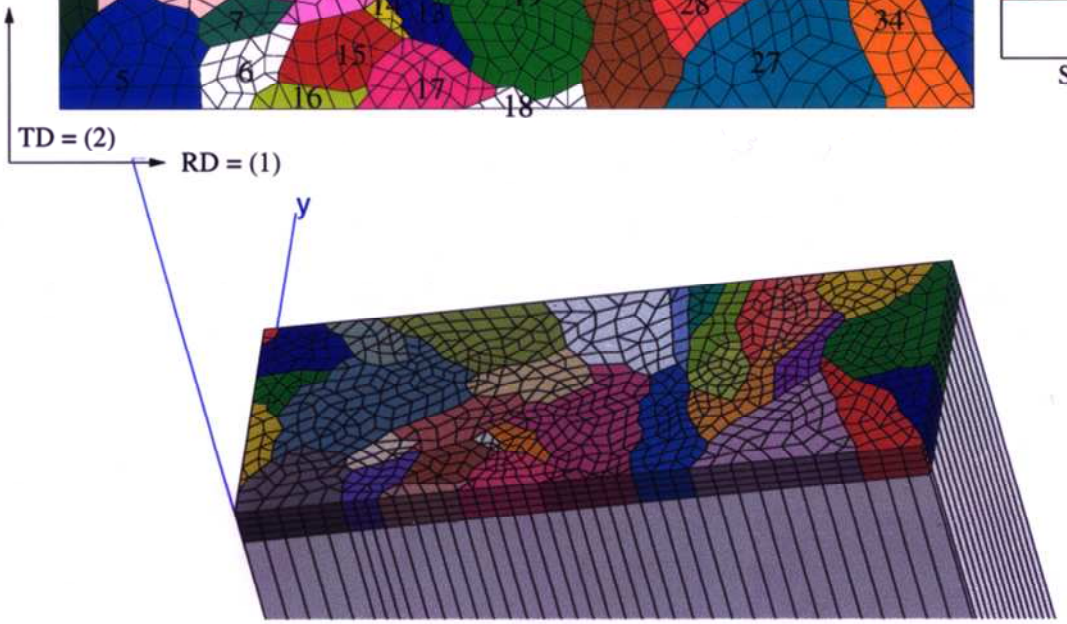
2D geometry but 3D deformation modes!

[R. Parisot 2(

Modélisation – Multicristal





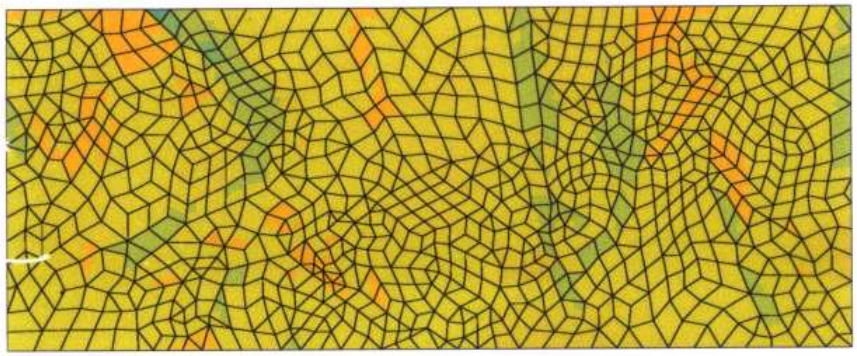


16686 degrés de liberté gradients ? localisation ?

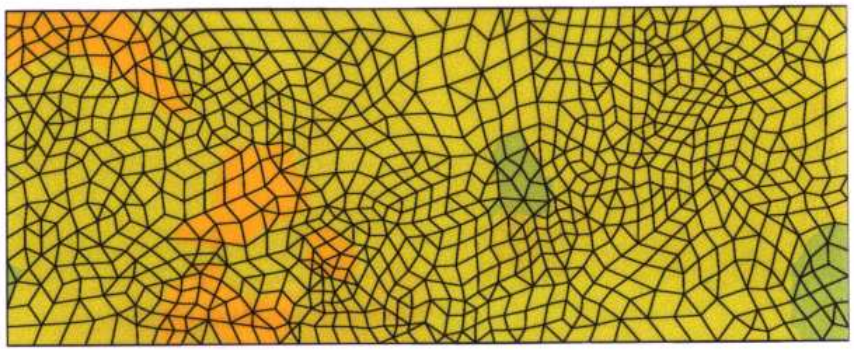
Essai de traction dans le sens long à $E_{11} = 1\%$

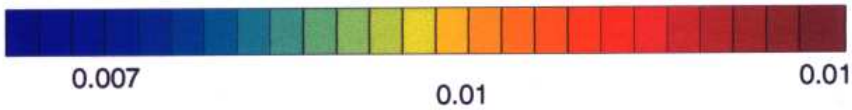
Gros grains — Effet de la taille de grains — Petits grains

ε_{11} Interface

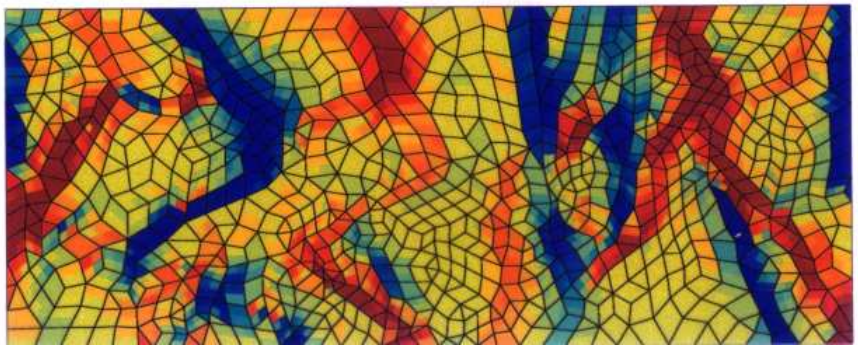


ε_{11} Interface

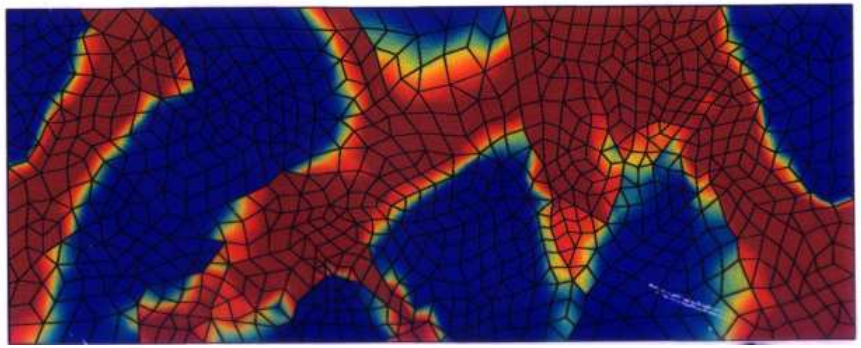




ε_{11} Surface libre

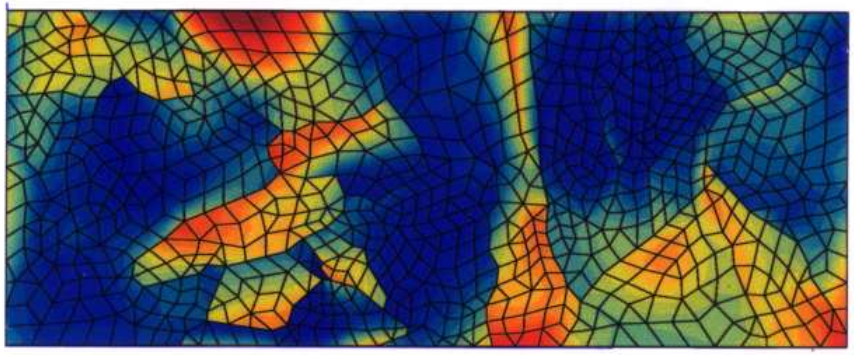


ε_{11} Surface libre

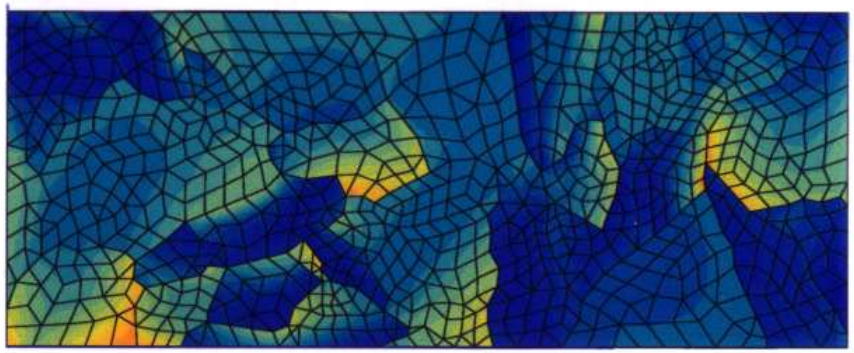


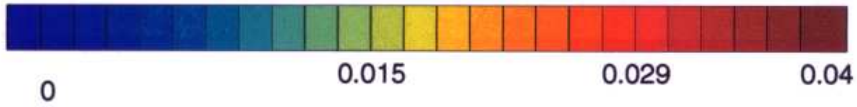
Modélisation – Multicristal – Petits grains

Basal – Interface

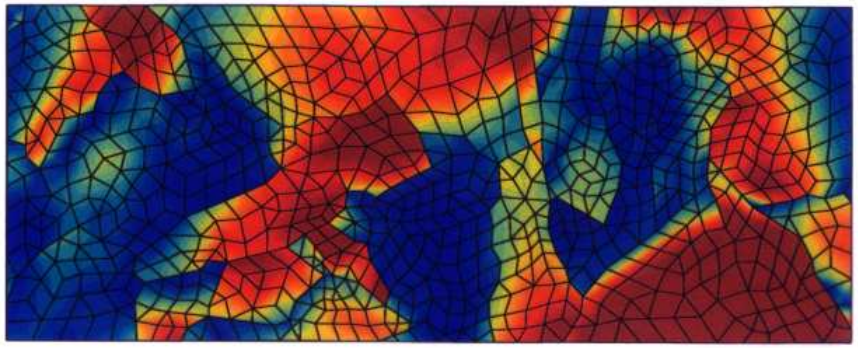


Pyramidal π_2 – Interface

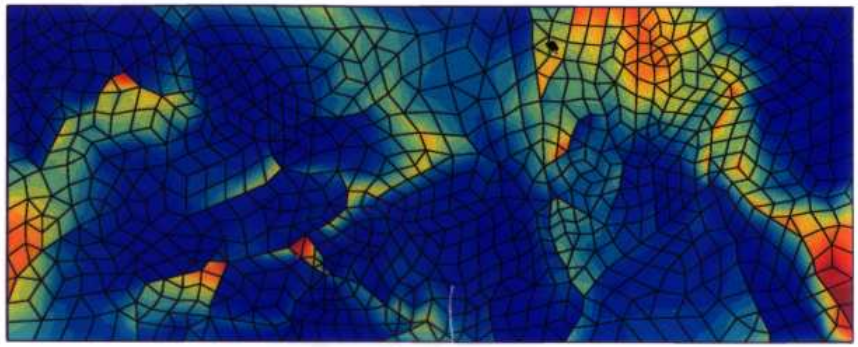


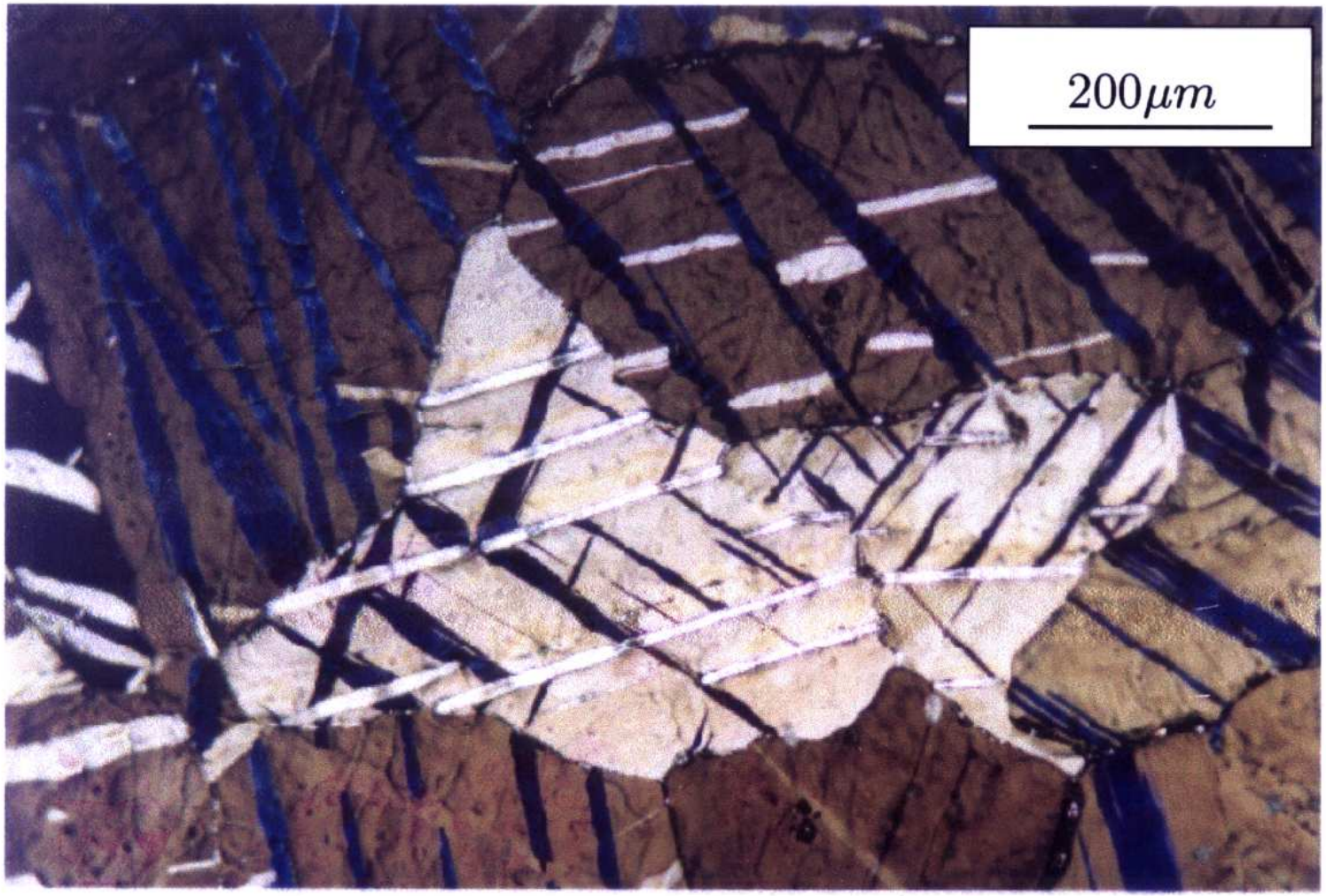


Basal – Surface libre



Pyramidal π_2 – Surface libre





Expansion Equibiaxiale, $\varepsilon_{eq} = 11.3\%$

INTRODUCTION TO MATERIAL VARIABILITY OF MECHANICAL PROPERTIES AND LENGTH SCALE

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- **Welds**

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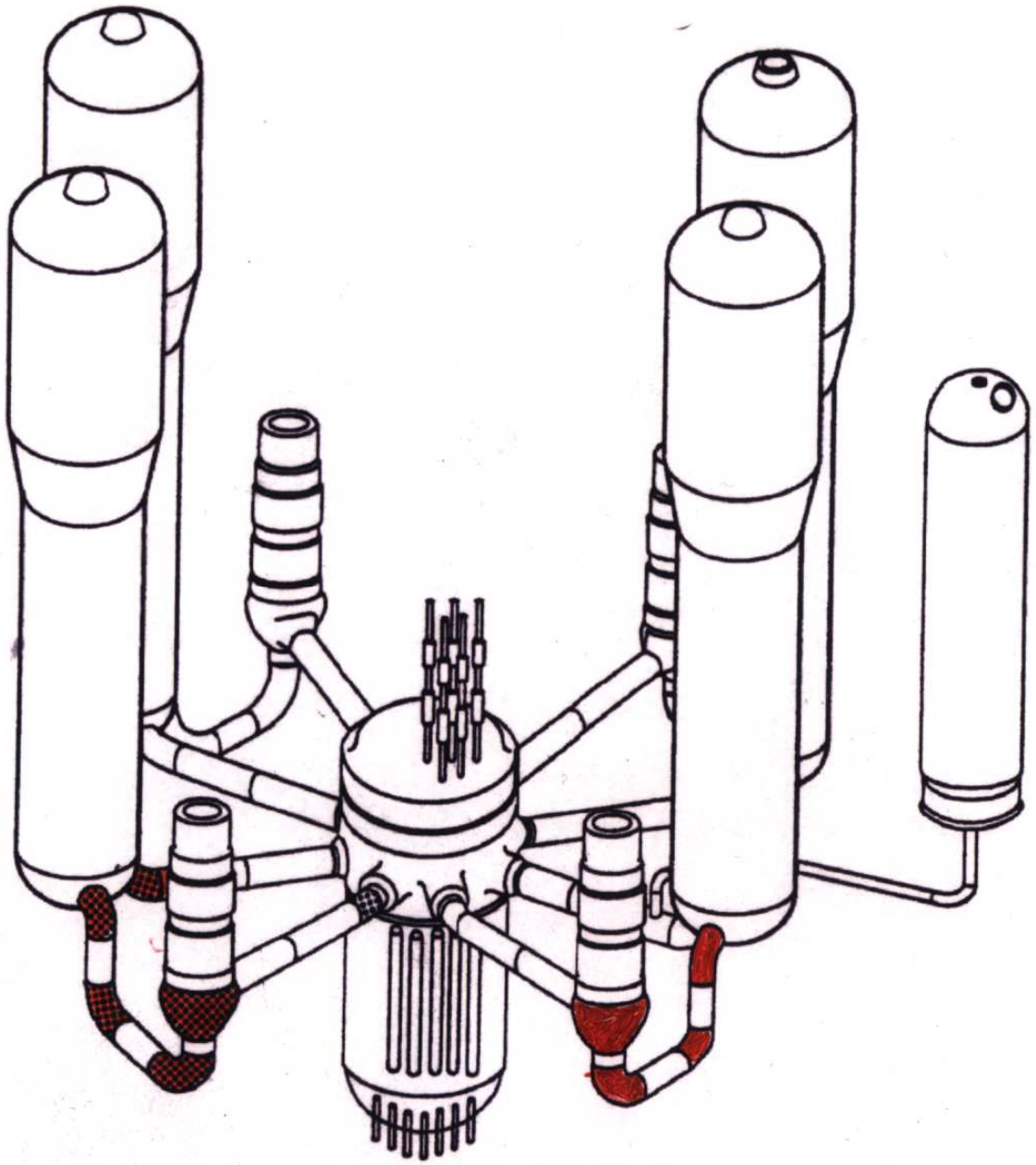
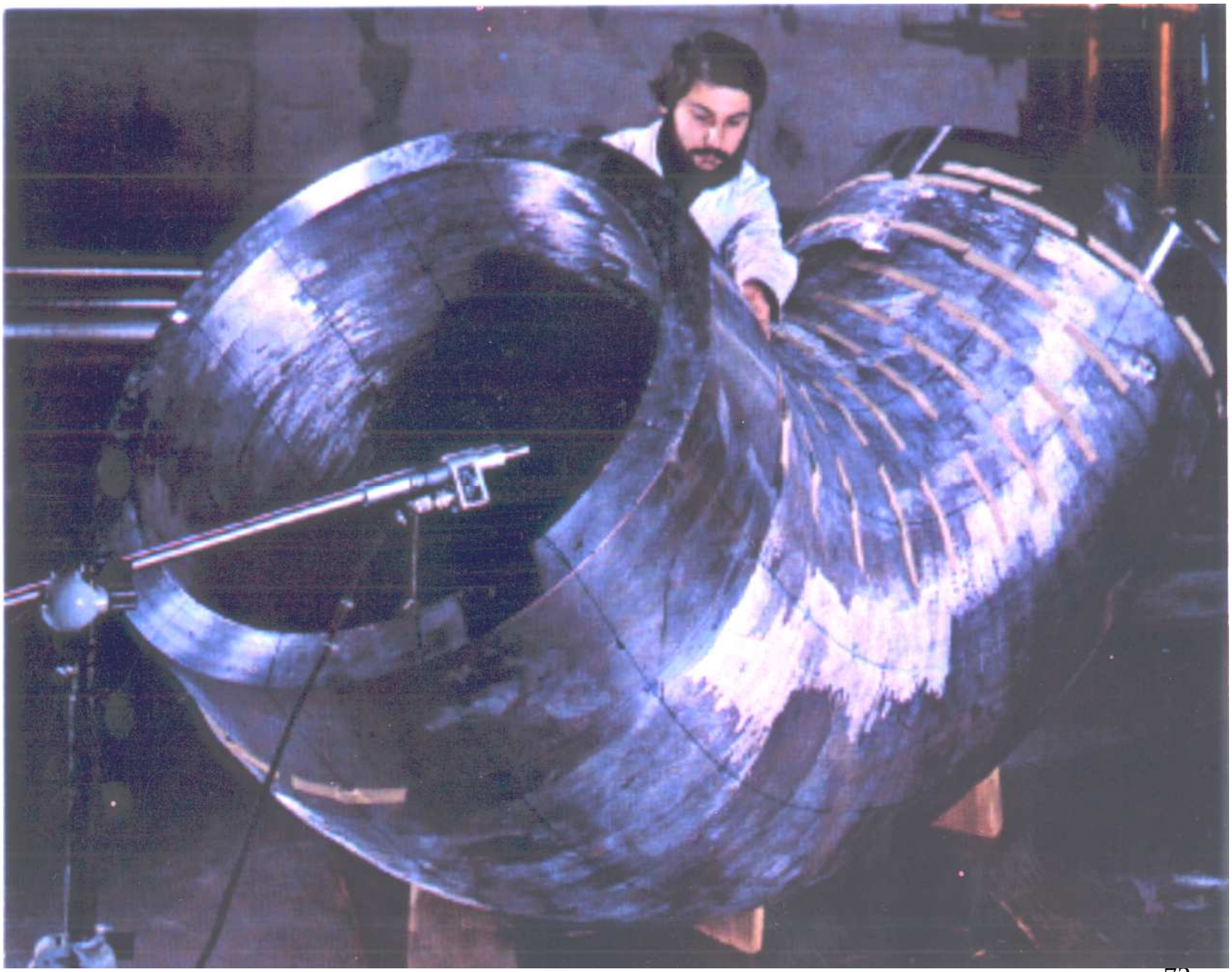
VI - CONCLUSIONS





Material CF8M : Fe + 20 Cr + 10 Ni + 2.5 Mo
In Service Conditions ~ 320°C – 30/40 years

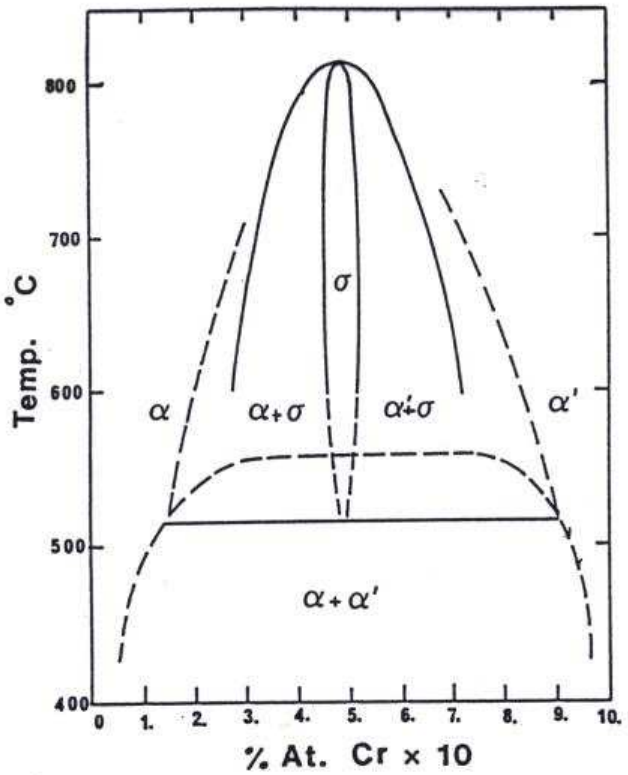


Figure (1.1): Diagramme de phase du système Fe-Cr. (Extrait de [1-20]).

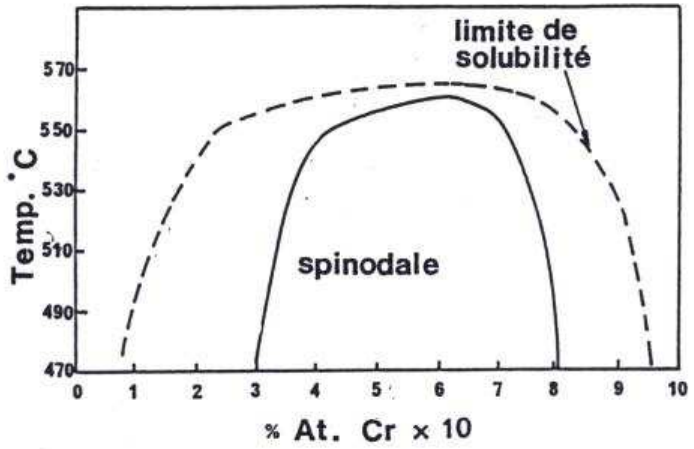
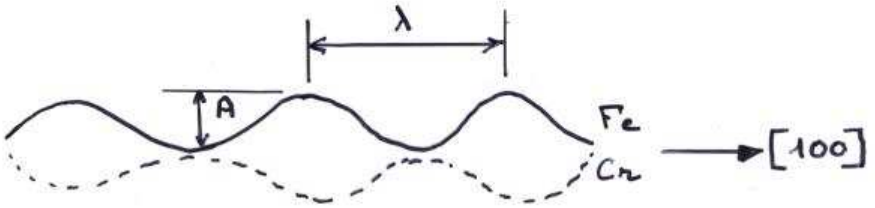


Figure (1.3): Diagramme de phase du système Fe-Cr, indiquant la limite de la décomposition spinodale. (Extrait de [1-9]).

SPINODAL DECOMPOSITION



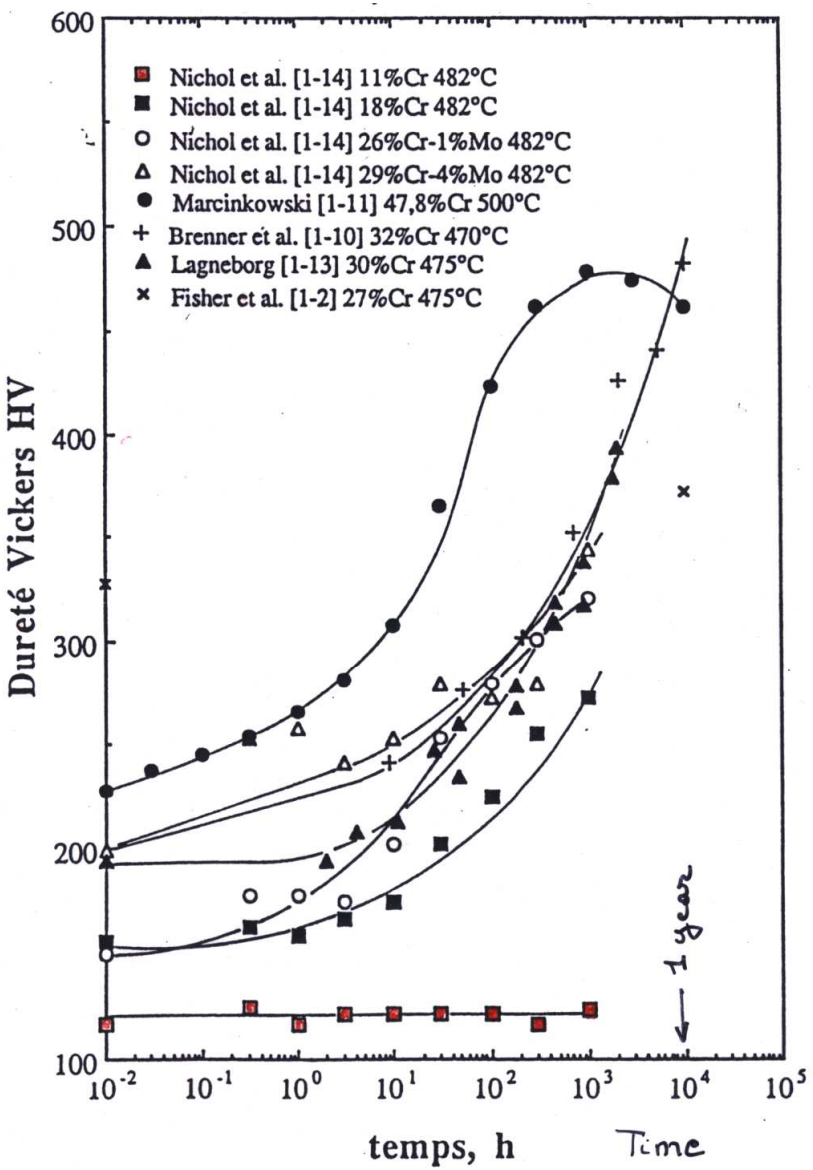


Figure (1.4): Compilation de données de dureté d'aciers ferritiques riches en Cr, pour un vieillissement à une température proche de 475°C.

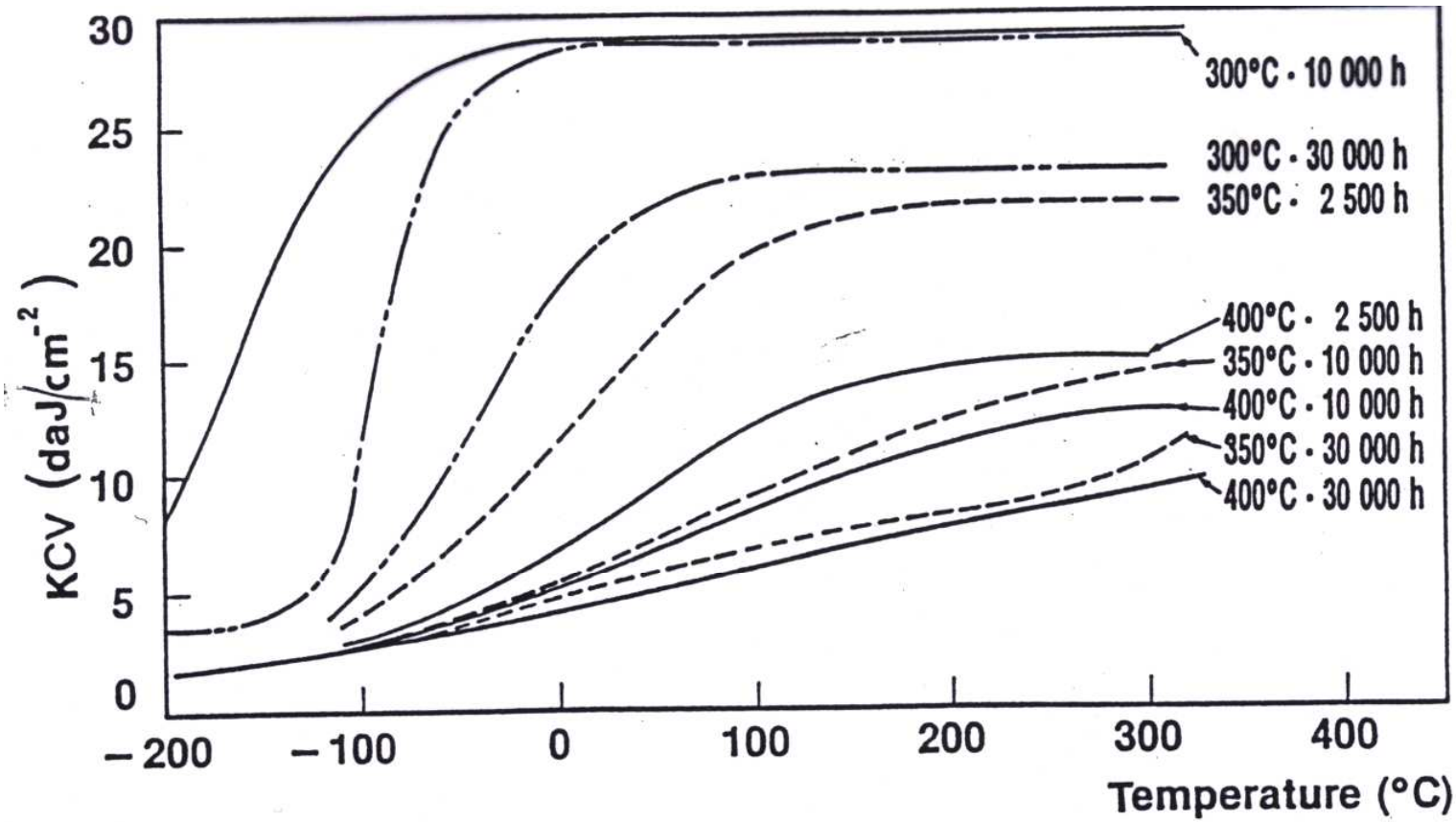


Figure (1.13): Evolution de la courbe de transition Charpy KCV, pour un acier austéno-ferritique au Mo, en fonction du vieillissement. (Extrait de [1-31]).

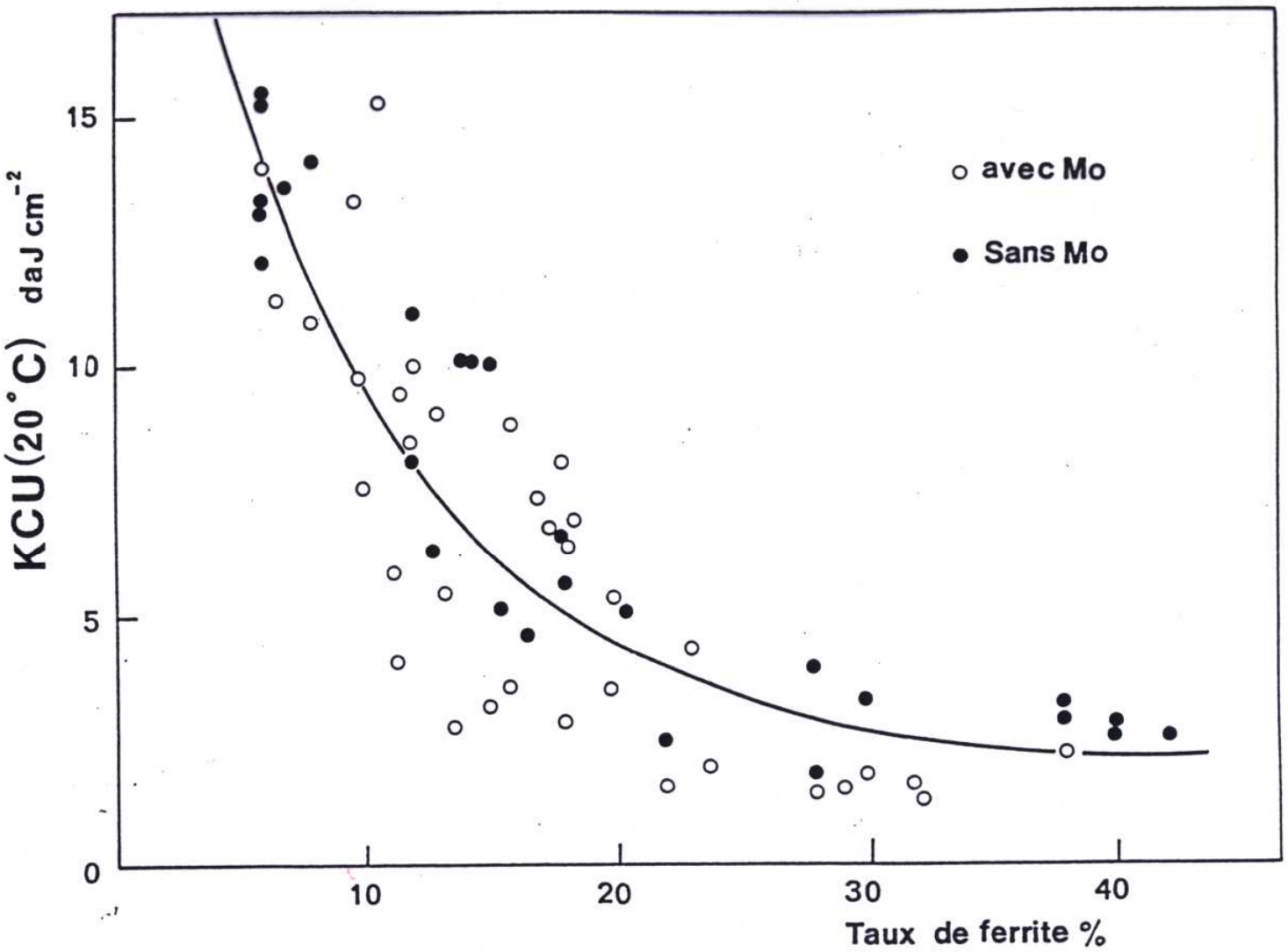


Figure (1.14): Variation de la résilience Charpy KCU avec la fraction volumique de ferrite, pour des aciers austéno-ferritiques vieillis 10 000 hr à 400°C. (Extrait de [1-31]).

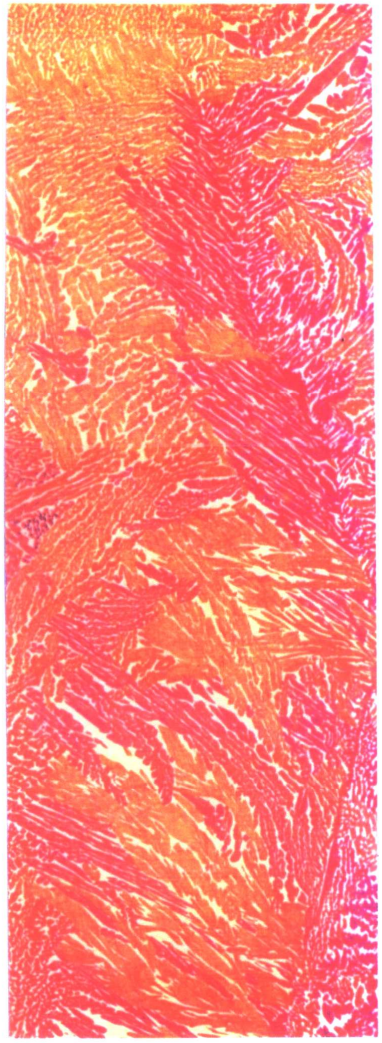


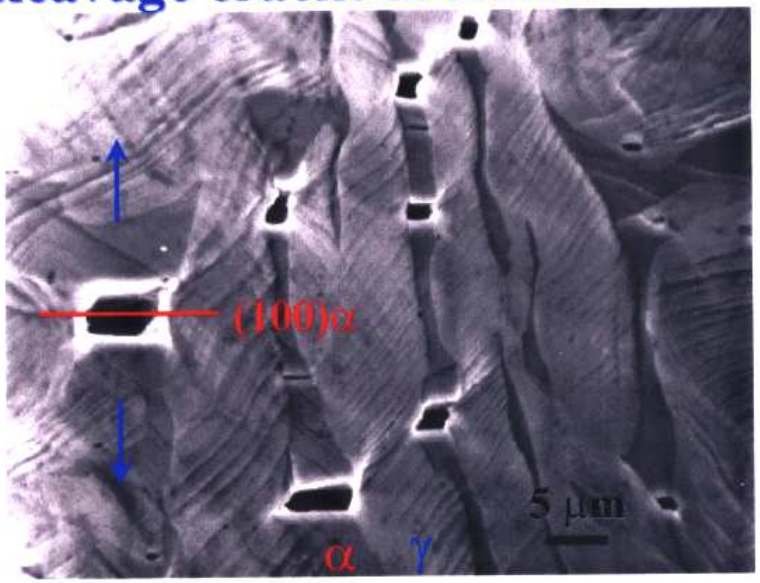
Figure (2.5) (a): Microgaphique optique. Alliage Y4331. Attaque thermique. (Ferrite en jaune clair. Austénite en orange ou viol et).

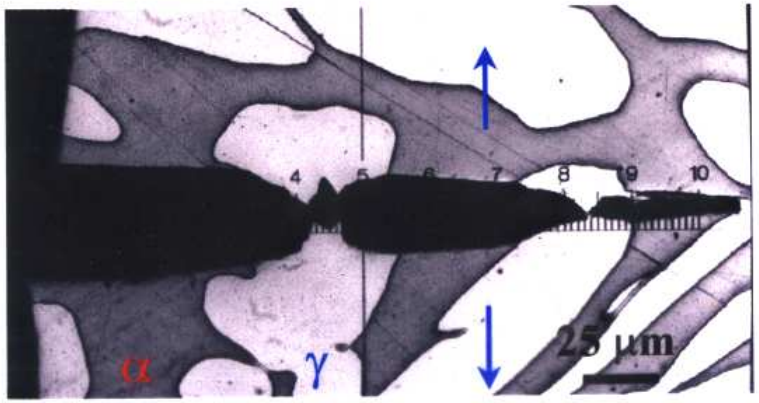
Consequences of ferrite embrittlement

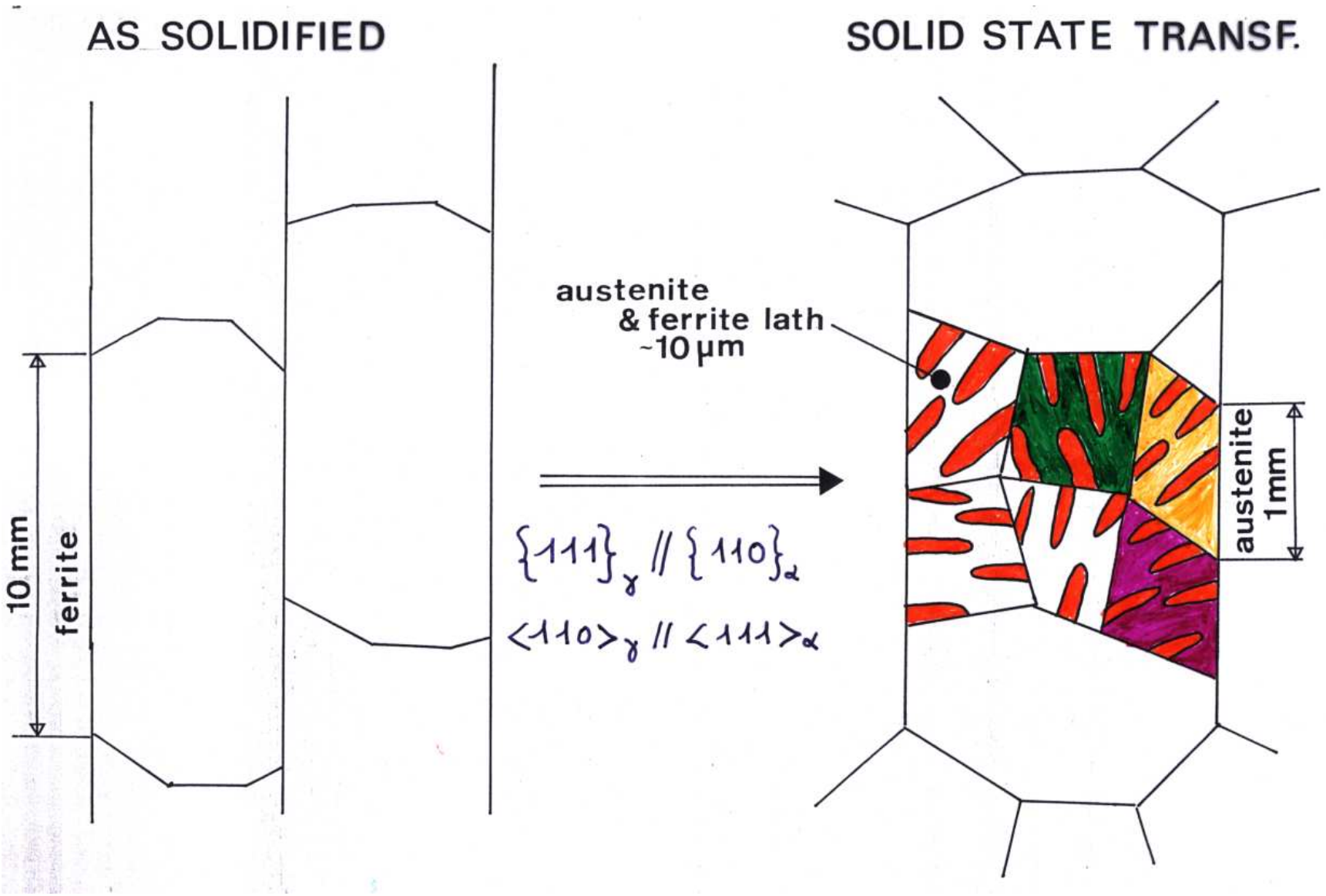
Damage by nucleation of cleavage cracks in ferrite

White phase : austenite γ

Dark phase : ferrite α



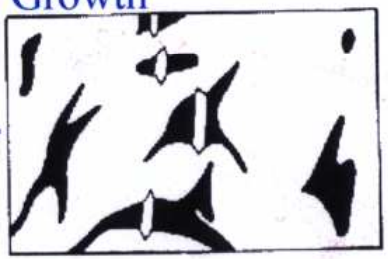



AS SOLIDIFIED
SOLID STATE TRANSF.
austenite
& ferrite lath
~10 µm
10 mm
ferrite
austenite
1 mm
{111}γ // {110}α
<110>γ // <111>α

Characteristics of cleavage damage

Nucleation

Growth



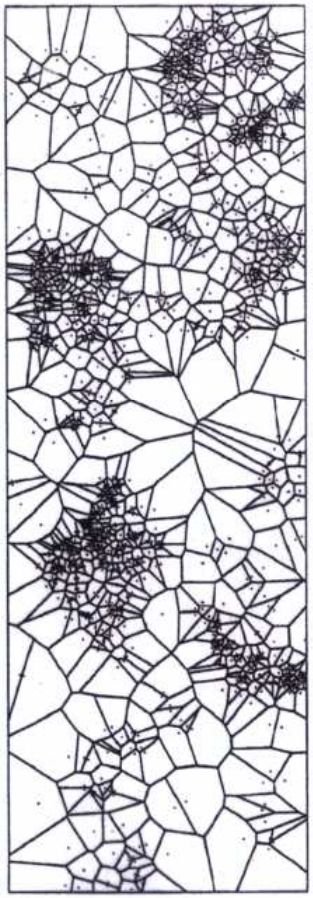
Coalescence

- Continuous process controlled by plastic deformation
- Initiates at the onset of plastic strain :

  Yield potentials integrating damage
- Heterogeneous nucleation in millimetric clusters (An)

  Scatter, size effects

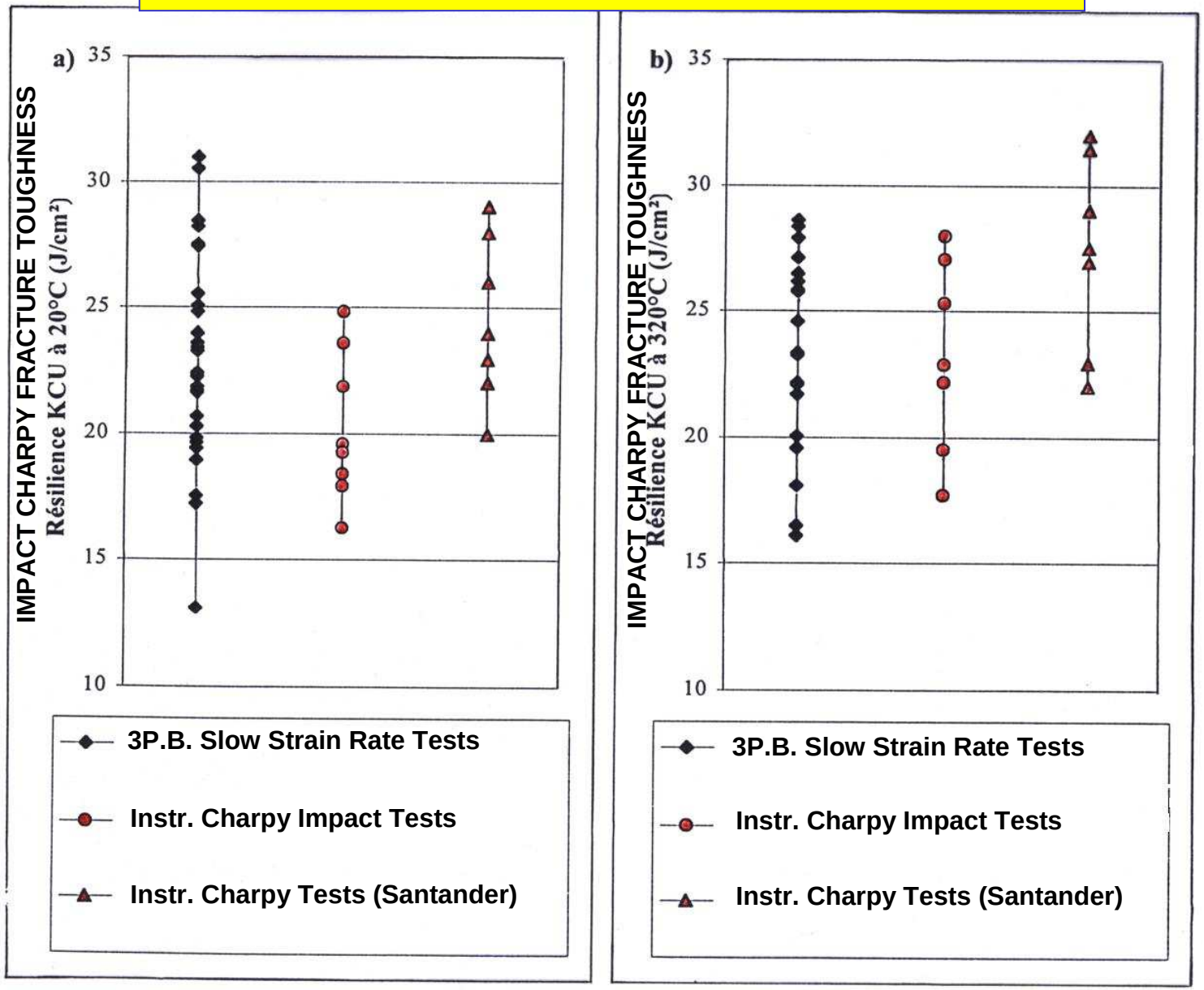
[Slama, Petrequin and Mager, 1982]



Voronoï Cells

2 mm

AGED DUPLEX STAINLESS STEELS



HUGE SCATTER IN TEST RESULTS OF FRACTURE TOUGHNESS MEASUREMENTS

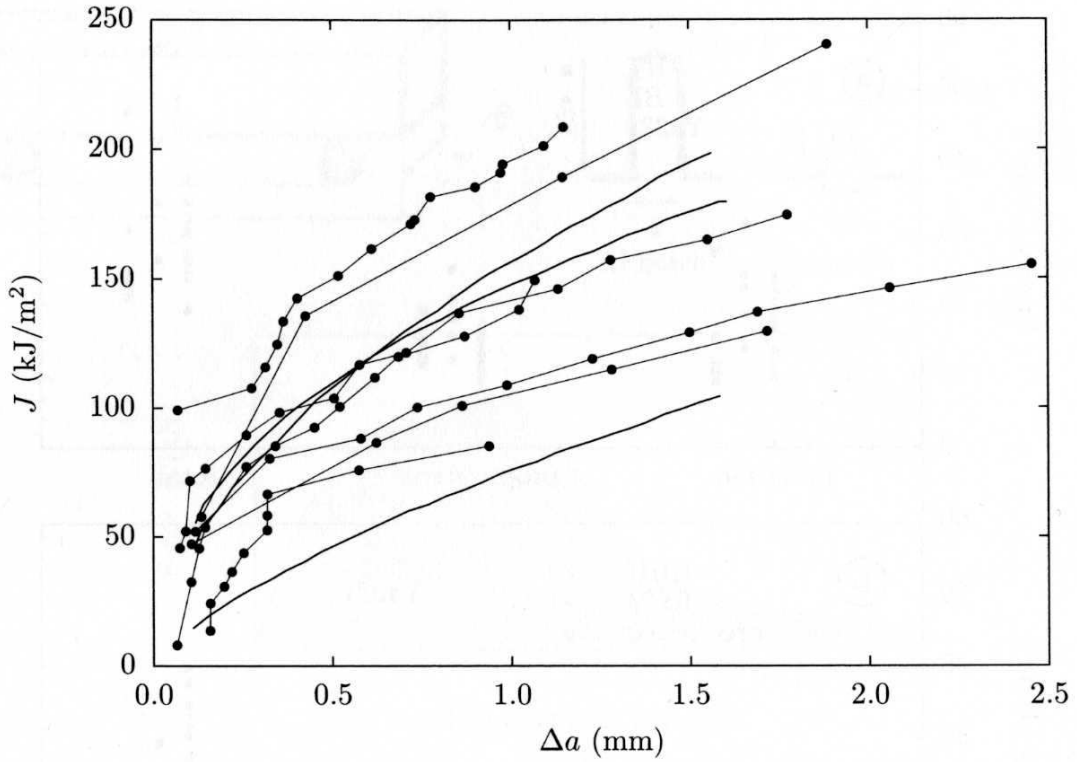


Figure 5.31. *Steel Y4331 tested at 20°C. Experimental $J/\Delta a$ curves (full lines, taken from Devillers [DEV 98]; symbols, taken from Joly [JOL 92a])*

MODELLING OF SCATTER AND SIZE EFFECTS

Cavity Nucleation is scattered and inhogeneously distributed

This can be modelled using FEM simulation

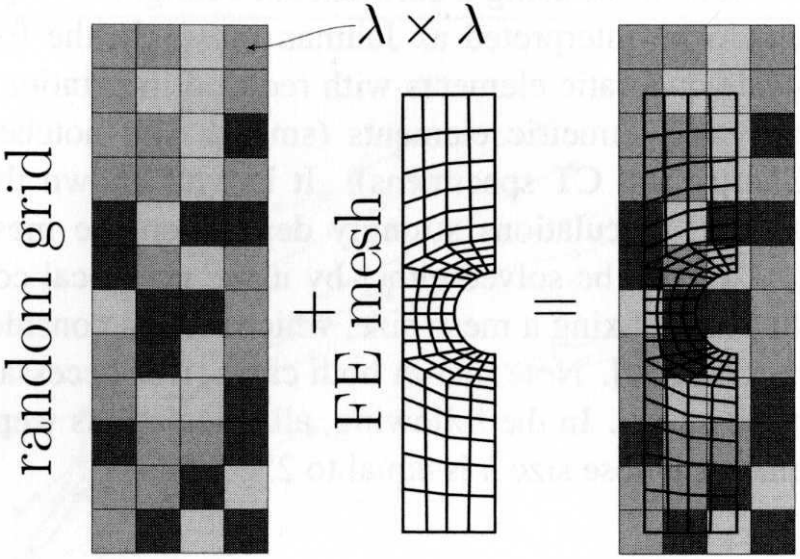


Figure 5.32. *Schematic representation showing how a random value is attributed to each Gauss point of a mesh. The position of each Gauss point in the grid is used to determine the value of the random parameter*

NUNERICAL SIMULATION OF NOTCHED SPECIMENS

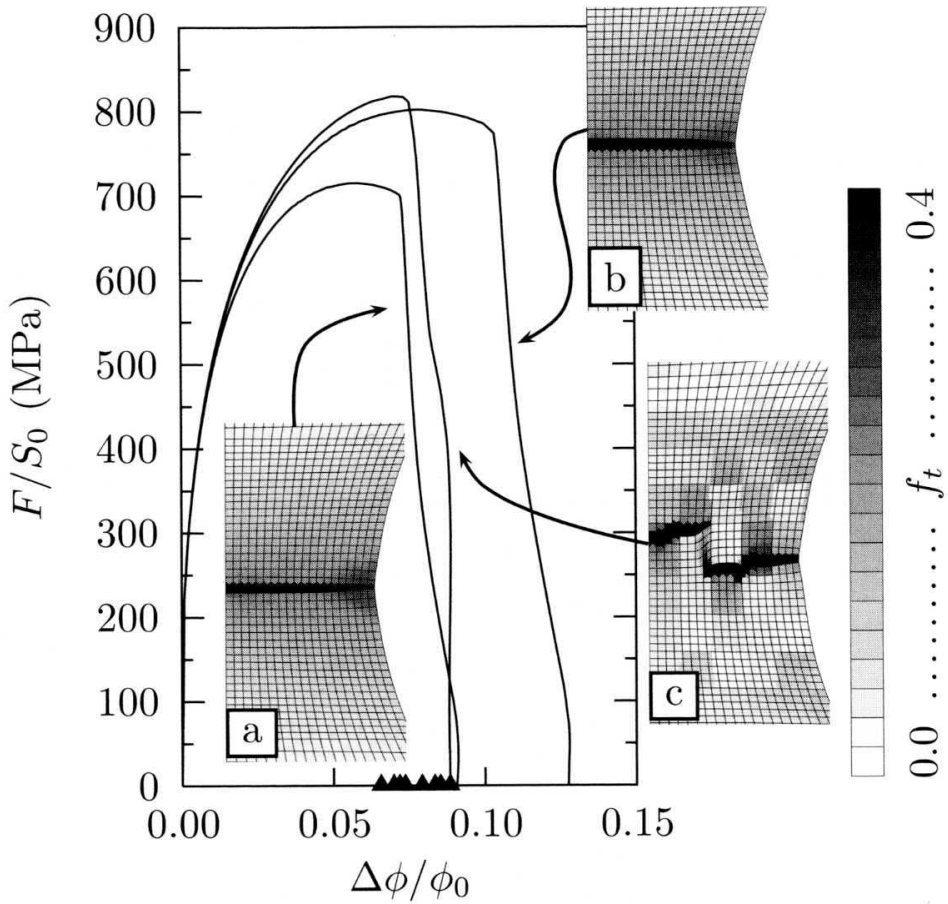


Figure 5.33. *Notched bar (NT_{10}): a) Homogenous with $A_n = 1.0$, b) Homogenous with $A_n = 0.6$, c) Heterogenous. Gray level contours show the values of f_t at Gauss points. Solid symbols on the x–axis indicate simulated strains to failure for other specimens computed with random values for A_n. (ϕ_0: Minimum initial specimen diameter, $\Delta\phi$: diameter variation, F: force, S_0: initial minimum cross-section)*

SIMULATION OF SIZE EFFECT IN NOTCHED SPECIMENS

The Strain to failure decreases with increasing the size of the specimens

which is in good agreement with experiemental results

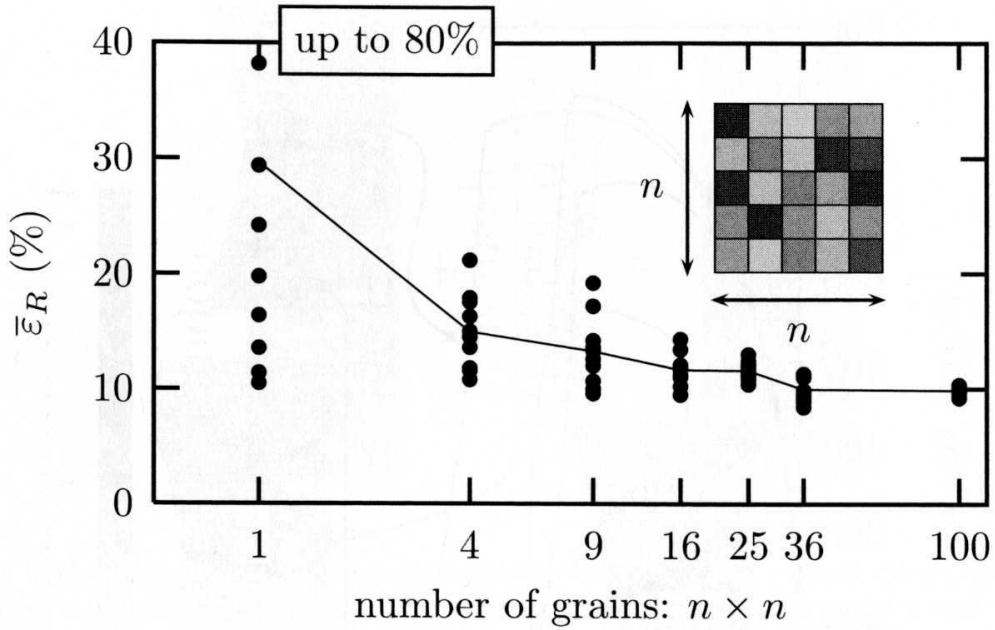


Figure 5.34. *Simulation of size effects*

SIMULATION OF FRACTURE TOUGHNESS

and

COMPARISON WITH EXPERIMENTS

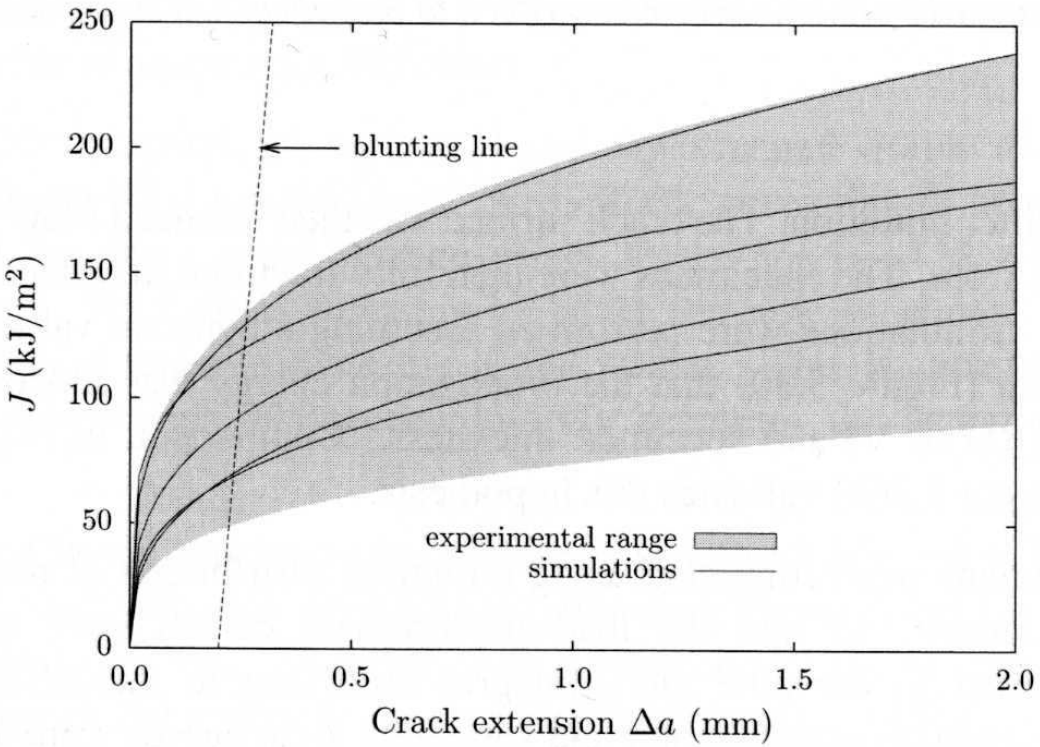
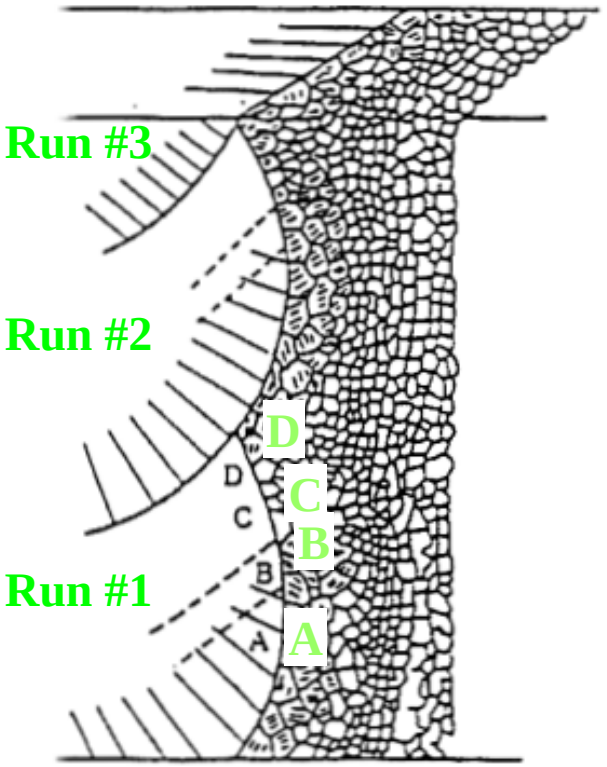


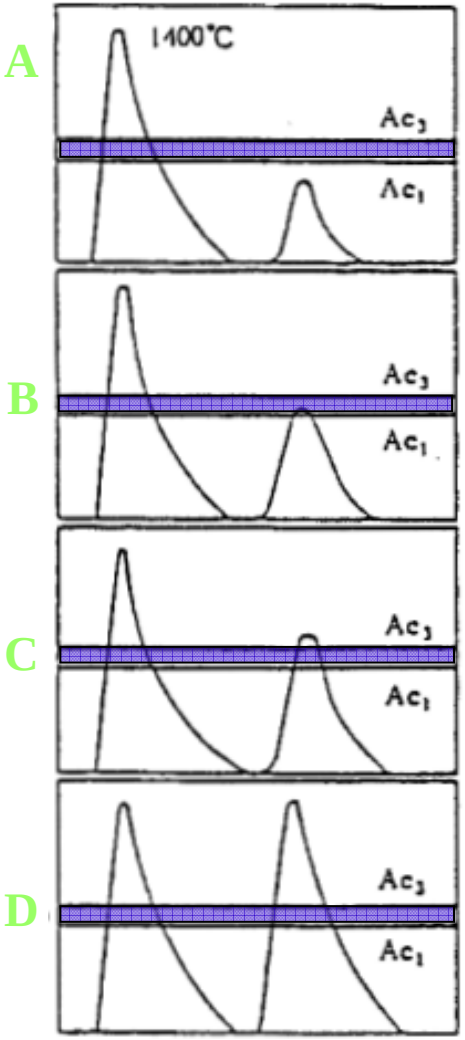
Figure 5.37. *Simulation of C(T) specimens. Material Y4331*

METALLURGICAL INHOMOGENEITIES IN WELDS

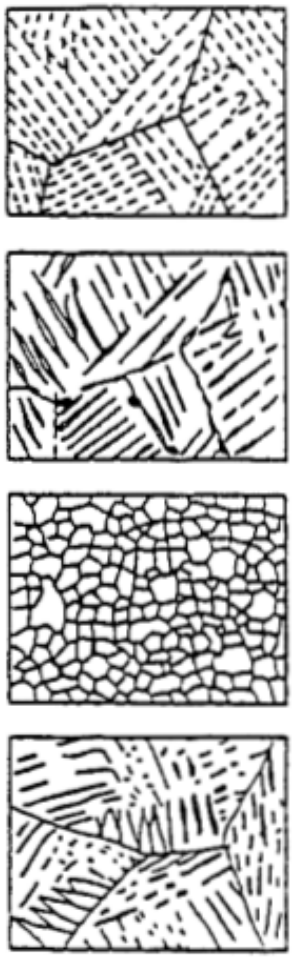
A. Lambert-Perlade et al., Metall. And Mater. Trans. A (2004), Vol. 35A, pp. 1039-1053



Weld structure



Corresponding thermal cycles



Coarse gained HAZ (CG HAZ)

Intercritically reheated CG HAZ

Supercritically reheated CG HAZ (fine grains)

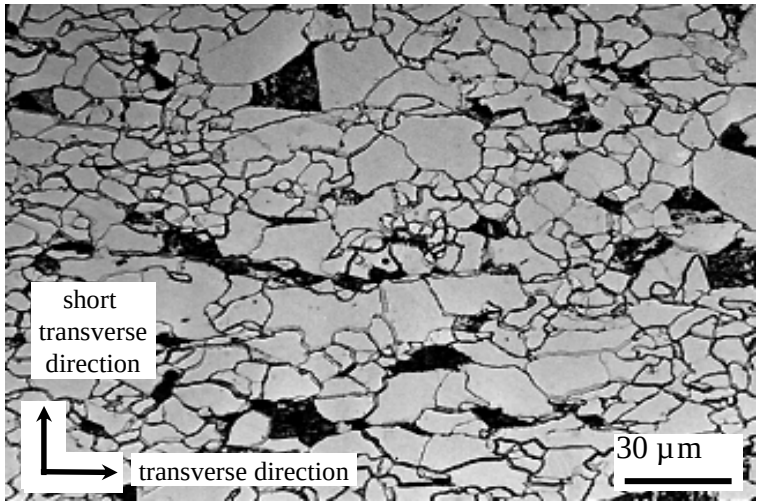
~ CG HAZ

Corresponding HAZ microstructures

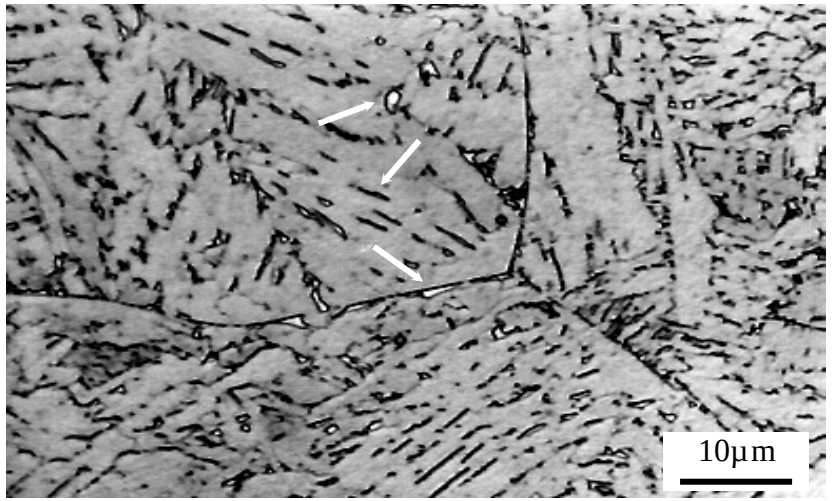
A. Lambert-Perlade et al., Metall and Mater. Trans. A, (2004), Vol. 35A, pp. 1039-1053

E 450

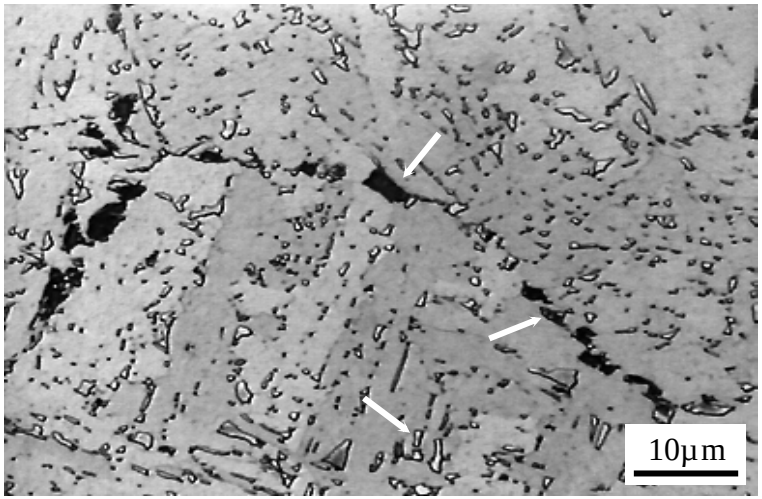
BASE METAL



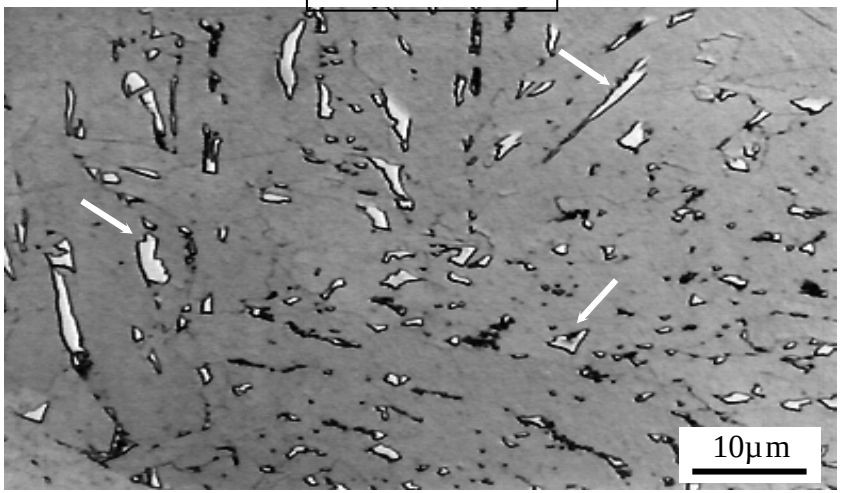
CGHAZ-25



ICCGHAZ-25

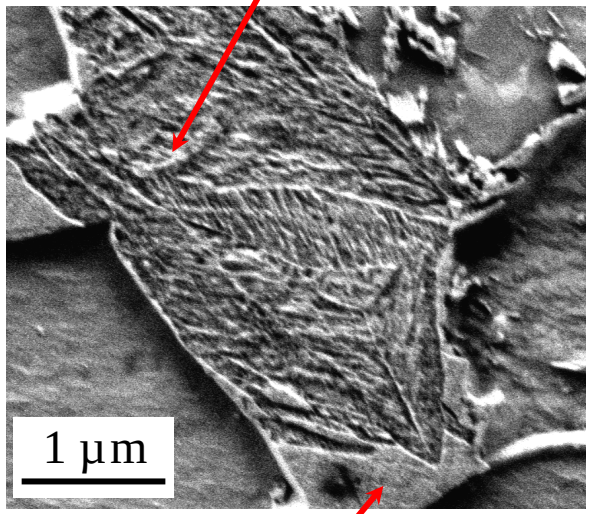


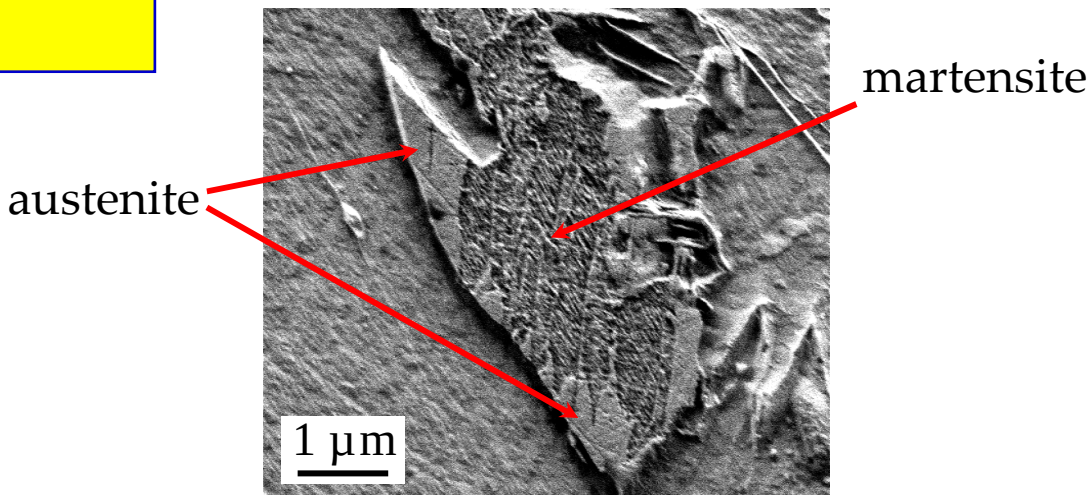
CGHAZ-120

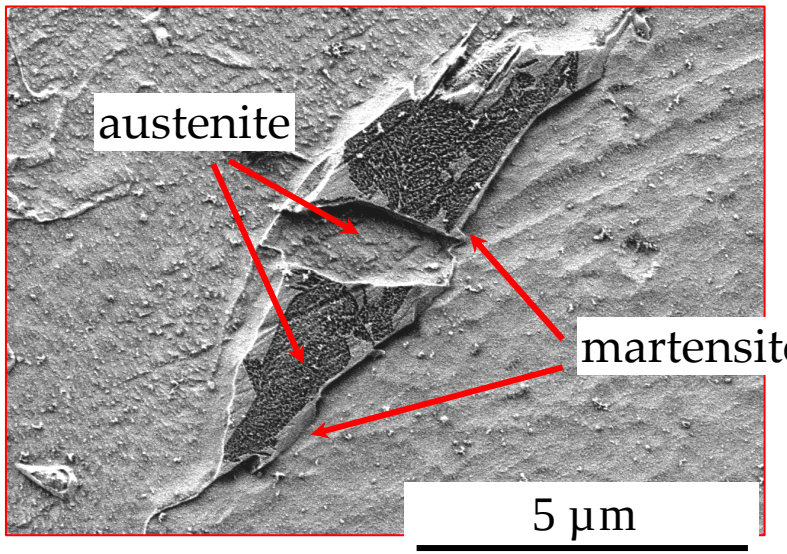


MARTENSITE - AUSTENITE CONSTITUENTS

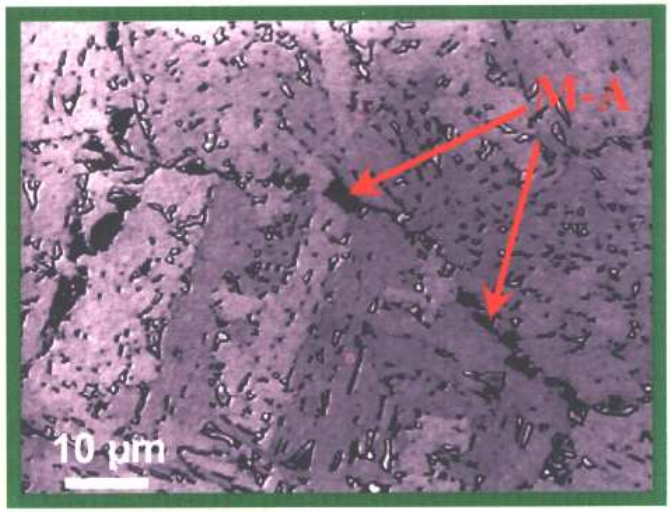
E 450 STEEL

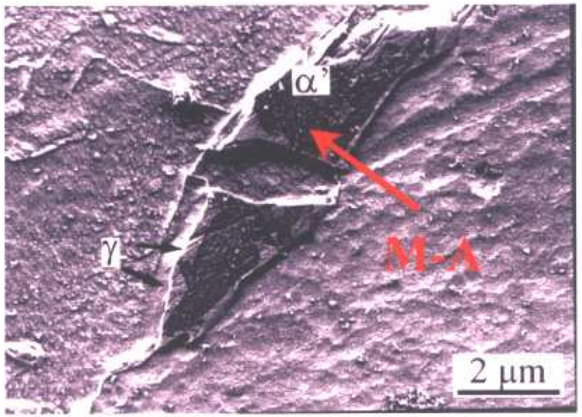


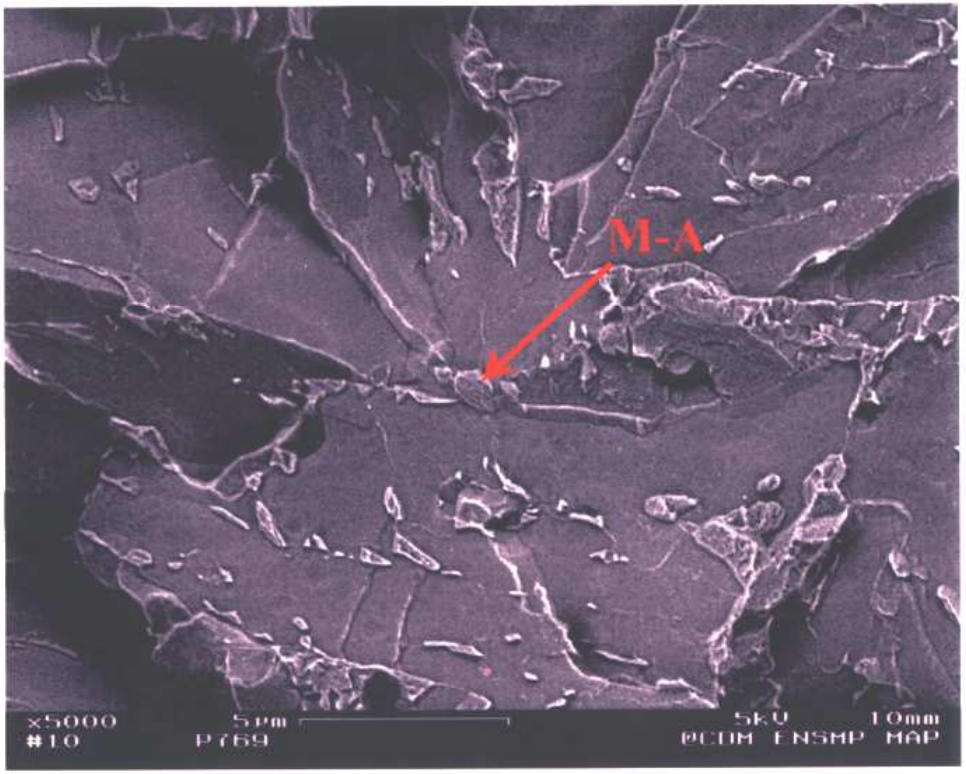




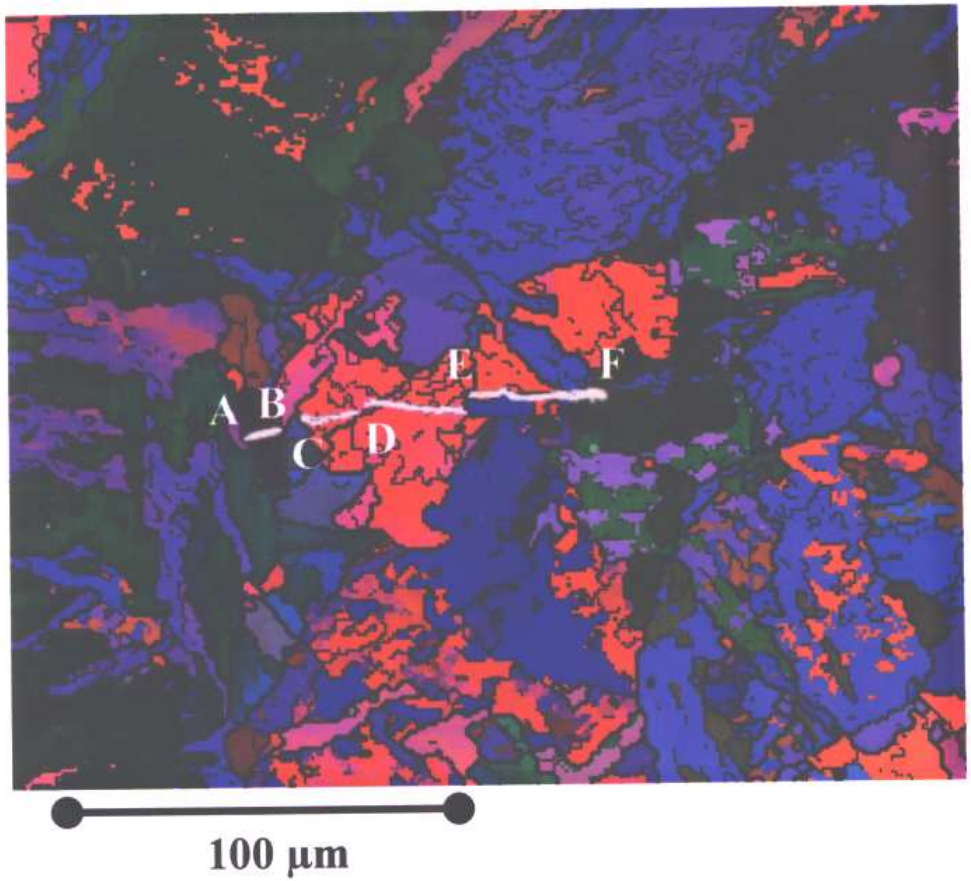
M-A constituents and cleavage fracture

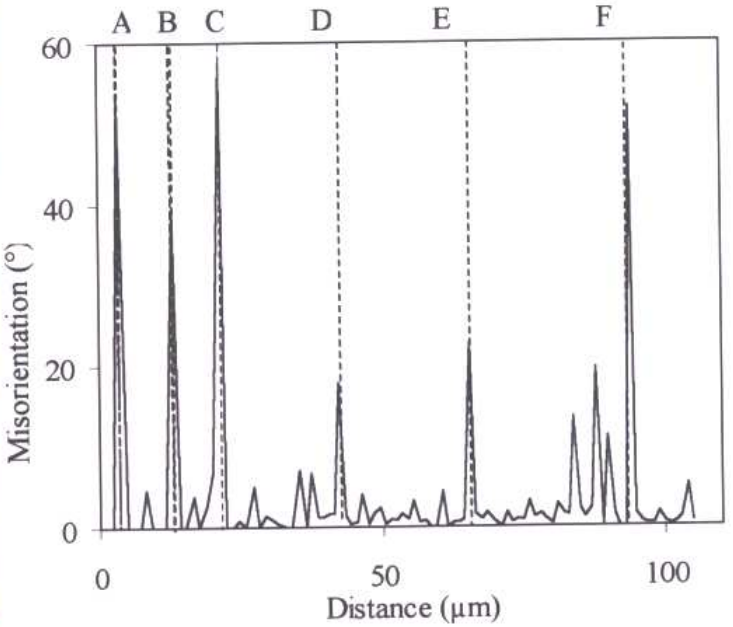






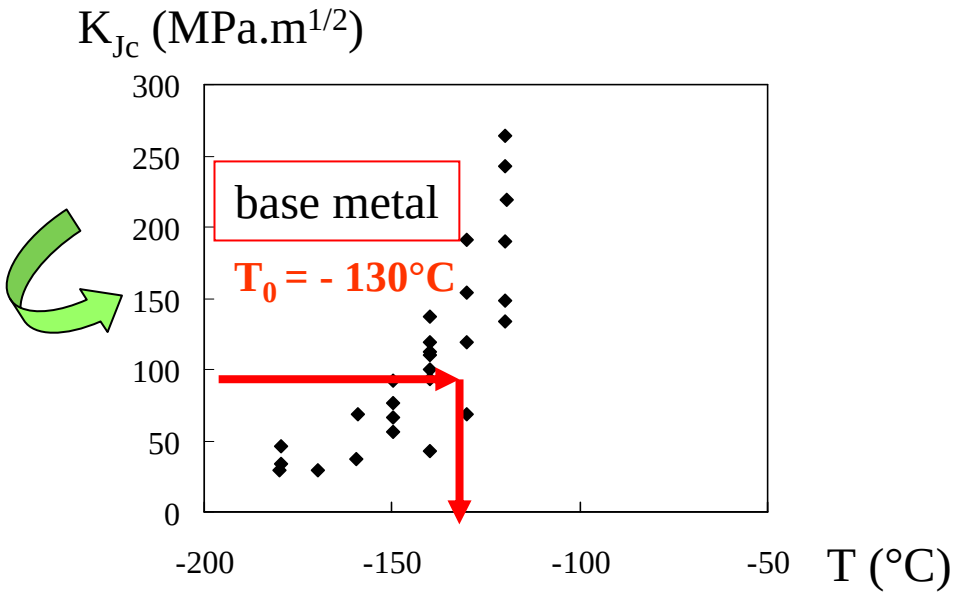
Bainite and cleavage fracture

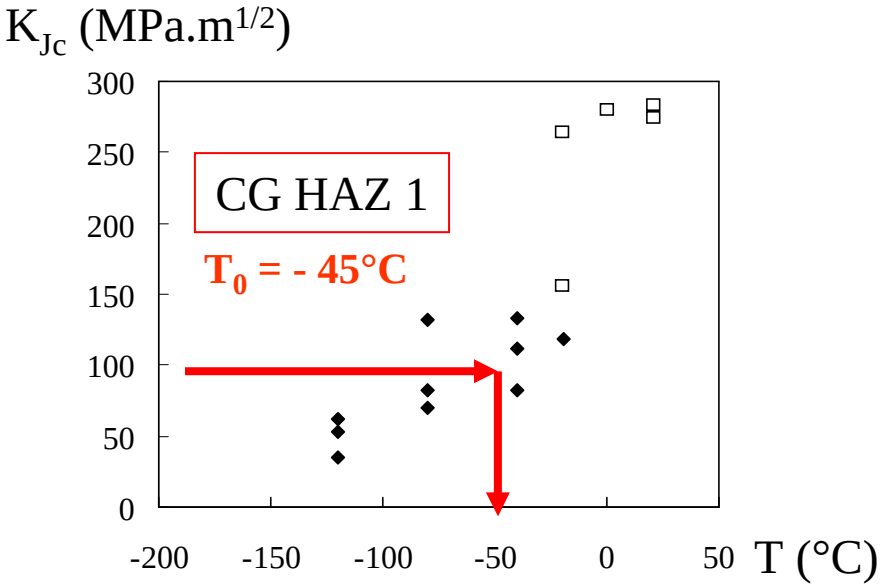


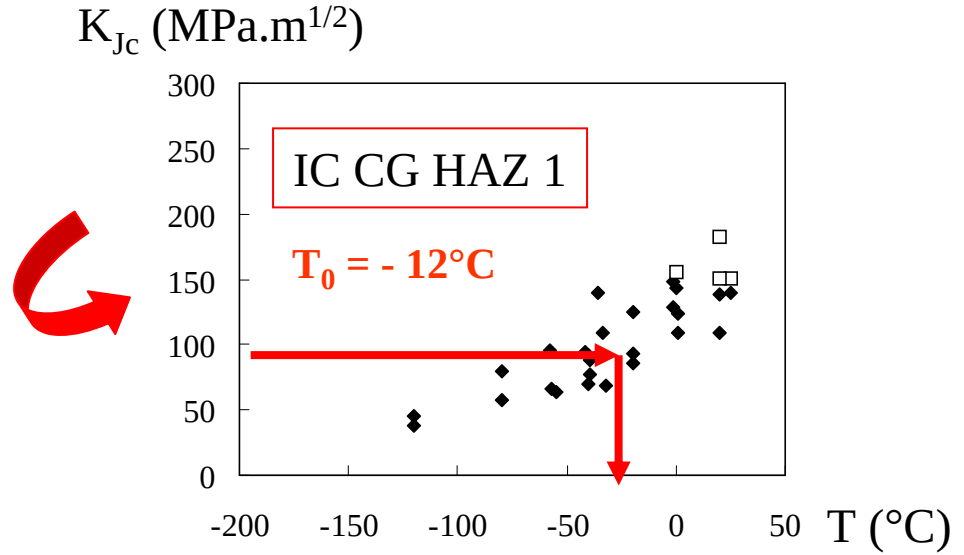


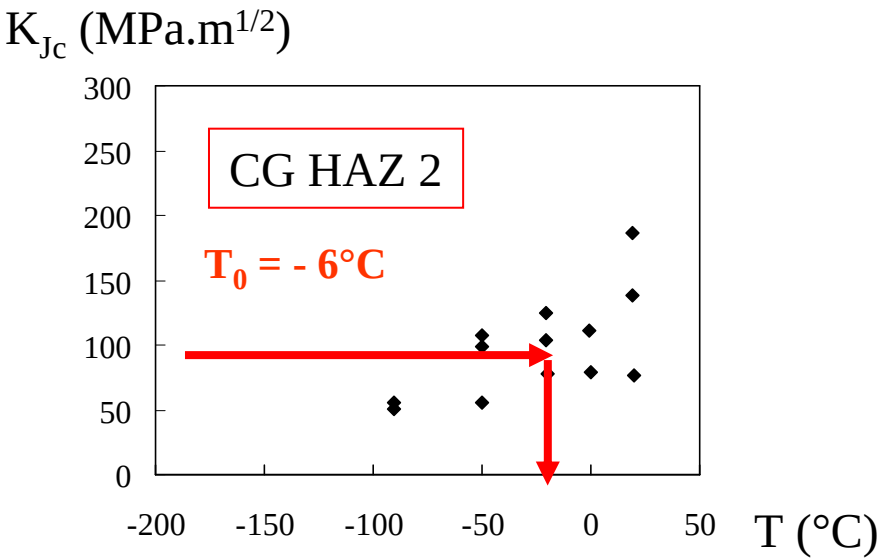
- ductile stable crack propagation over > 0.2 mm

A. Lambert-Perlade et al., Metall. Mater. Trans. A, (2004), Vol. 35A, pp. 1039-1053





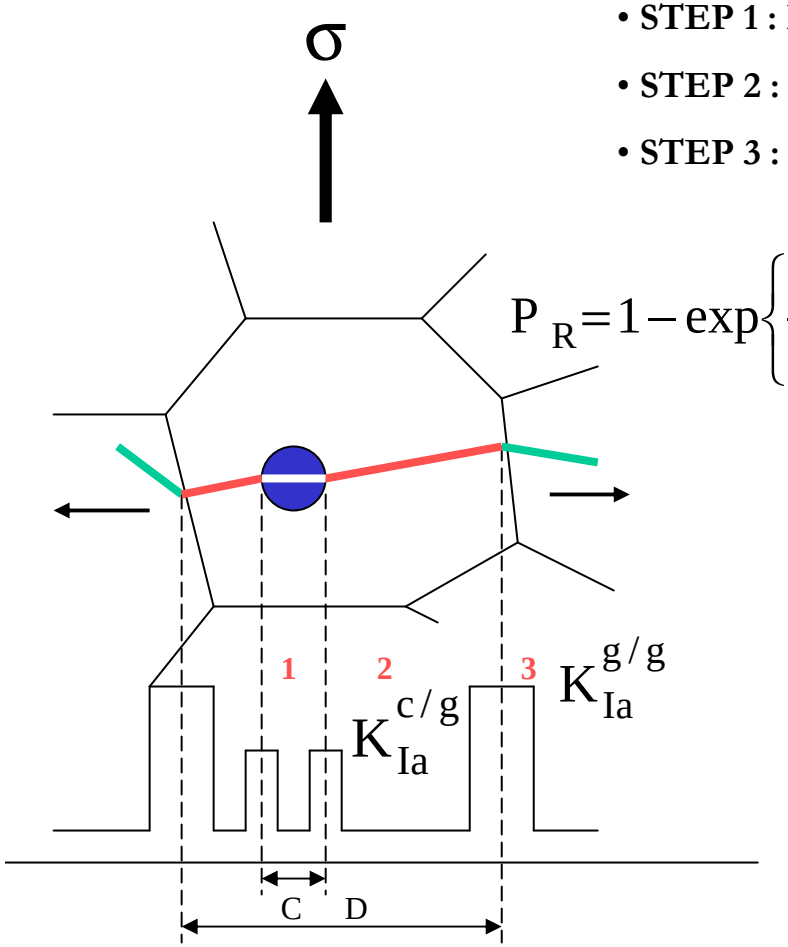




A DOUBLE BARRIER MODEL FOR CLEAVAGE FRACTURE

A. Martin-Meizoso et al, Acta Metall. Mater. (1994), Vol. 42, pp. 2057-2068.

- **STEP 1 : Fracture Probability of a M-A constituent / Critical Stress Criterion.**
- **STEP 2 : Probability of propagating a crack at the MA/Matrix Interface.**
- **STEP 3 : Probability of crossing a packet boundary.**



$$P_R = 1 - \exp\left\{ -\int_{PZ} \left[N_v^g \; x \; F_g\left(C^* \langle C \langle D^* \right) + N_v^c \; x \; F_c\left(C \rangle C^* \right) \right] \right\} dV$$

F_g & F_c Determined by Metallography

$$C^* = \frac{\pi E \gamma^{c/g}}{\left(1-\nu^2\right)\sigma_1^2} = \beta \left(\frac{K_{Ia}^{c/g}}{\sigma_1} \right)^2$$

$$D^* = \frac{\pi E \gamma^{g/g}}{\left(1-\nu^2\right)\sigma_1^2} = \beta \left(\frac{K_{Ia}^{g/g}}{\sigma_1} \right)^2$$

Modelling fracture toughness

F.M. Beremin

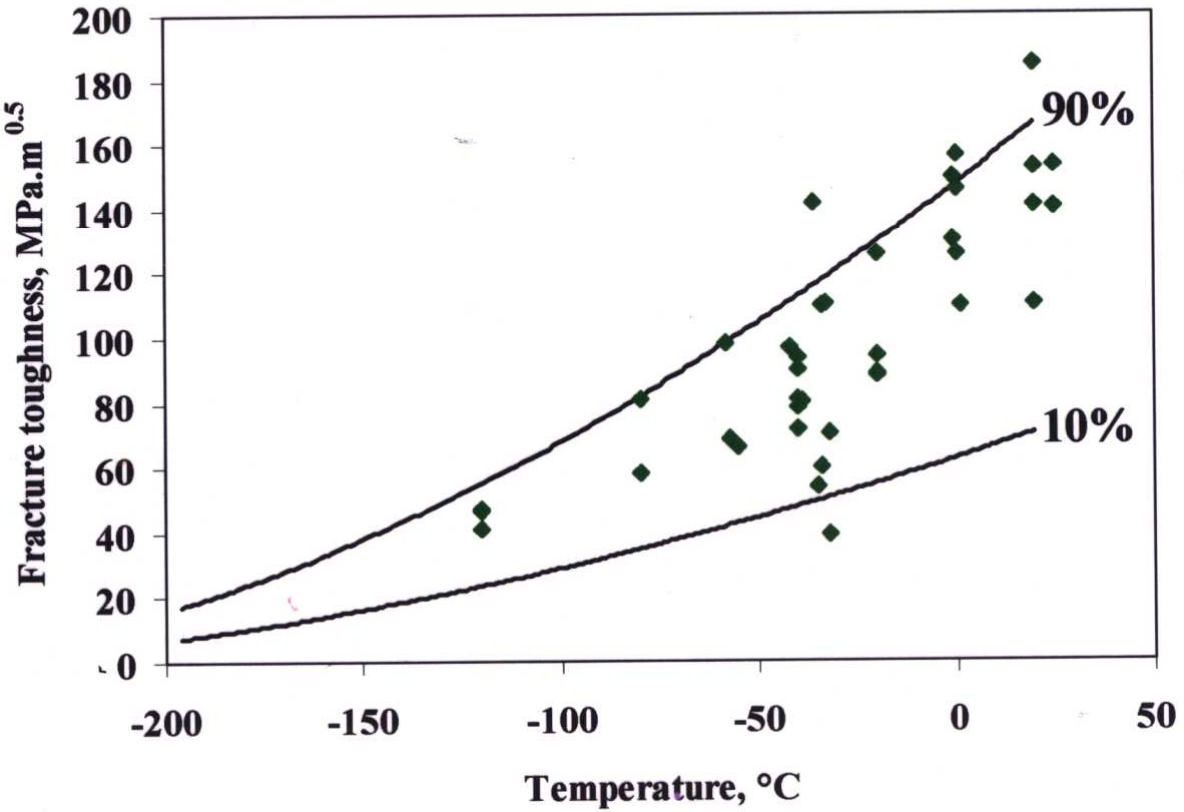
Met. Trans 1983,

vol.14A, 2277-2287

Beremin

Weibull

$$P_R = 1 - \exp - \left[\frac{K_{1c}{}^4 B \sigma_0{}^{m-4} C_m}{V_0 \sigma_u{}^m} \right]$$



INTRODUCTION TO MATERIAL VARIABILITY OF MECHANICAL PROPERTIES AND LENGTH SCALE

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B.P. 87 - 91003 EVRY Cedex
e-mail : andre.pineau@ensmp.fr

I - INTRODUCTION - CASE STUDIES

II - ELASTICITY

III - PLASTICITY

IV - FRACTURE : 2 Case Studies
- Duplex Stainless Steels
- Welds

V - A SIMPLE MODEL BASED ON WEAKEST LINK THEORY

VI - CONCLUSIONS

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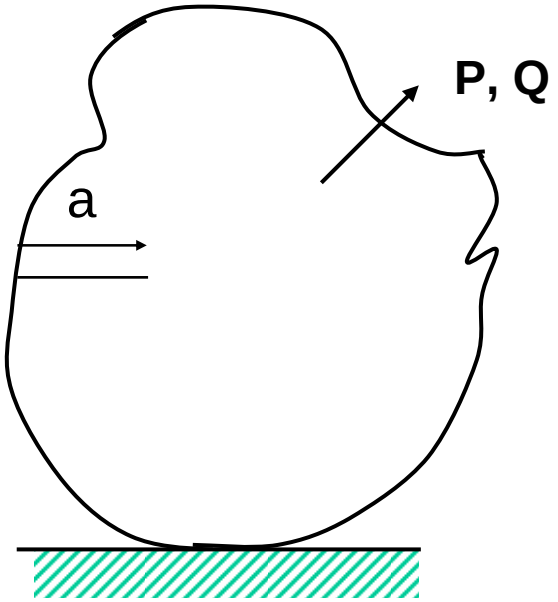
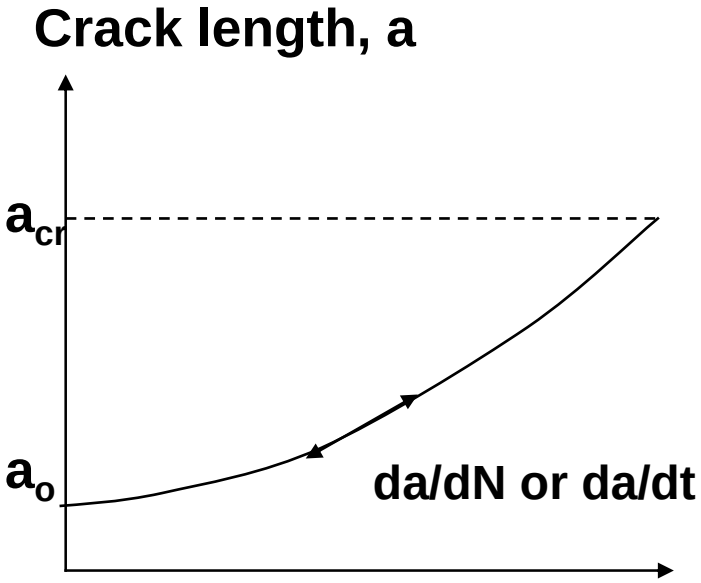
andre.pineau@ensmp.fr



- Non Destructive Testing (NDT)
- Inspection Intervals



Critical Crack Length, a_{cr}

- Leak Before Break
- Linear and Non Linear Fracture Mechanics

$$a_{cr} = \frac{K_{IC}^2}{\pi\sigma^2}$$

K_{IC} : Fracture Toughness (MPa$\sqrt{m}$)

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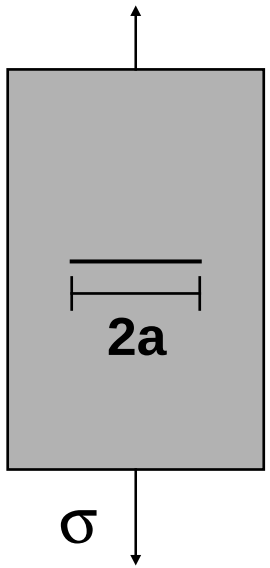
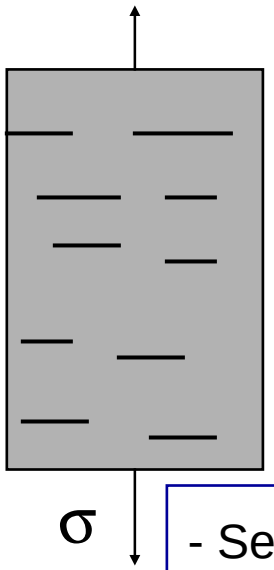
FRACTURE UNDER MONOTONIC LOADING FROM PREEXISTING DEFECTS WITH a GIVEN LENGTH or SIZE DISTRIBUTION

Homogeneously Loaded Structure

A single defectA population of defects





$$a_{cr} = \frac{K_{IC}^2}{\pi\sigma^2}$$

- Defect size distribution $q(a) = Q\, a^{-n}$ ($Q > o$; $n > 1$)
- Weakest link theory $\Rightarrow$

$$S(\sigma, V) = 1 - \exp\left\{-\frac{V}{V_c}\left(\frac{\sigma}{\sigma_c}\right)^{2(n-1)}\right\}$$

$S(\sigma, V) = \text{Probability to failure}$

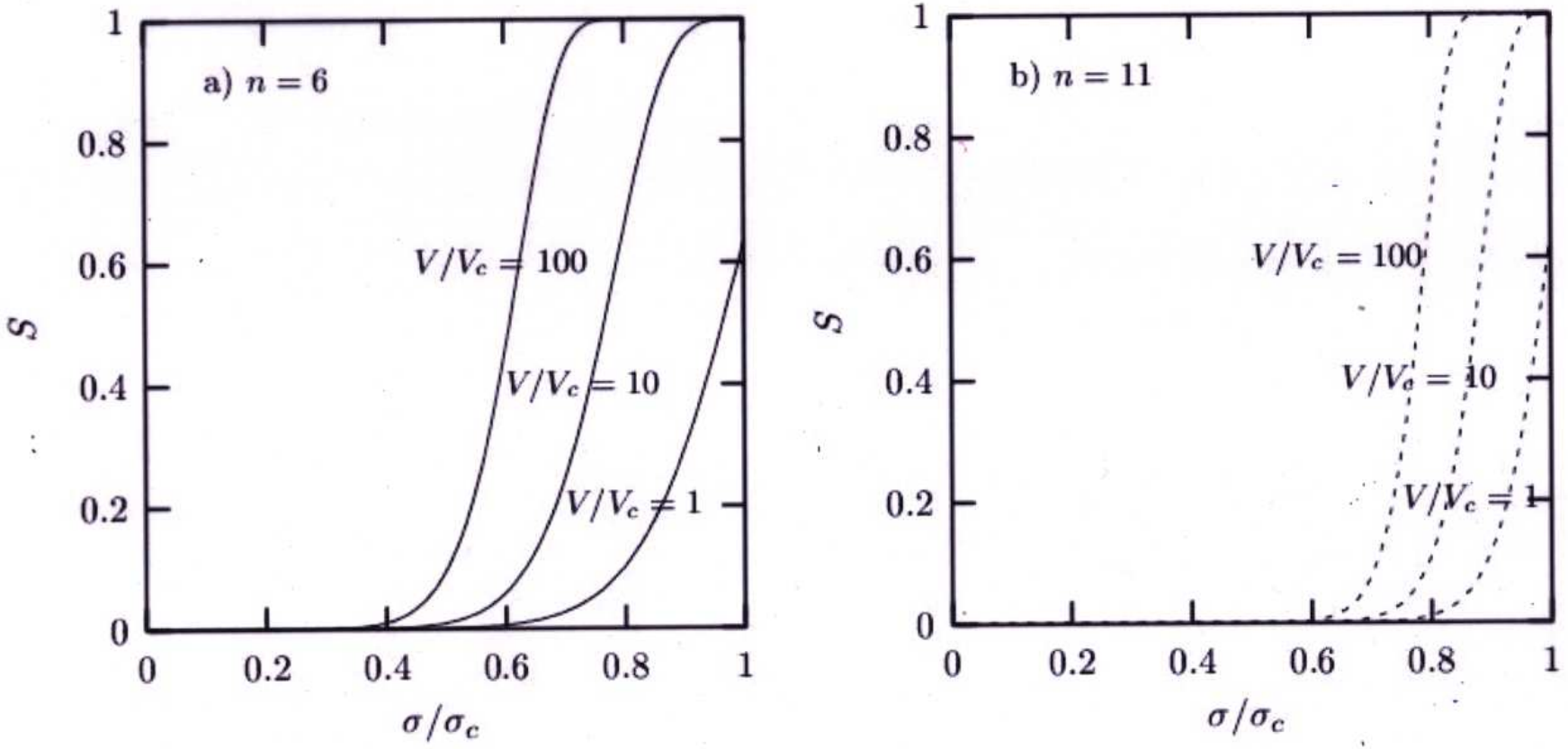
$$V_c = \frac{n-1}{Q}\left(\frac{K_{IC}}{\sqrt{\pi}\,\sigma_c}\right)^{2(n-1)} \quad : \text{material parameter}$$

- See examples of $S(\sigma/\sigma_c, V/V_c)$ curves for $n = 6$ ie $2(n-1) = 10$; $n = 11$ ie $2(n-1) = 20$

For a large number of identical structures (or specimens), S(σ specifies the fraction expected to fail when σ is first applied.

n = Shape factor for defect distribution

2 (n-1) = Shape factor for Weibull distribution



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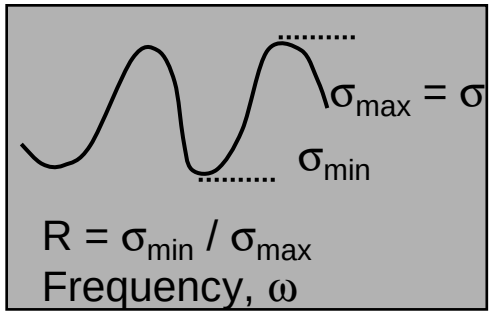
FRACTURE UNDER CYCLIC LOADING FROM GROWING DEFECTS



- a_i (σ, R, t) : Initial size of defects which have grown to the critical size ($K_{IC}^2 / \pi\sigma^2$) after time, t.

Paris law : $da/dN = \alpha (\Delta K)^{2\nu}$ or $da/dt = \omega (da/dN)$

$$da/dt = \alpha \pi^{\nu} \omega (1-R)^{2\nu} \sigma^{2\nu} a^{\nu} \quad \left(K = \sigma\sqrt{a}\right) \qquad (1)$$

Integration of Eq (1) : $\left[a^{-\nu+1}\right]_{a_i}^{a_{cr}} = (1-\nu)\ A$

$$\Rightarrow a_i = \frac{\left(K_{IC}/\sqrt{\pi}\sigma\right)^2}{\left\{1 + \alpha\omega\ (\nu-1) K_{IC}^{2(\nu-1)} (1-R)^{2\nu} \pi\sigma^2 t\right\}^{1/(\nu-1)}} \qquad (2)$$

- **Fraction of components (specimens) expected to have failed at time t :**

$$F(\sigma, R, t) = 1 - \exp\left\{-V \int_{a_i}^{\infty} q(a)\ da\right\} \qquad (3)$$

Eqs (2) + (3)

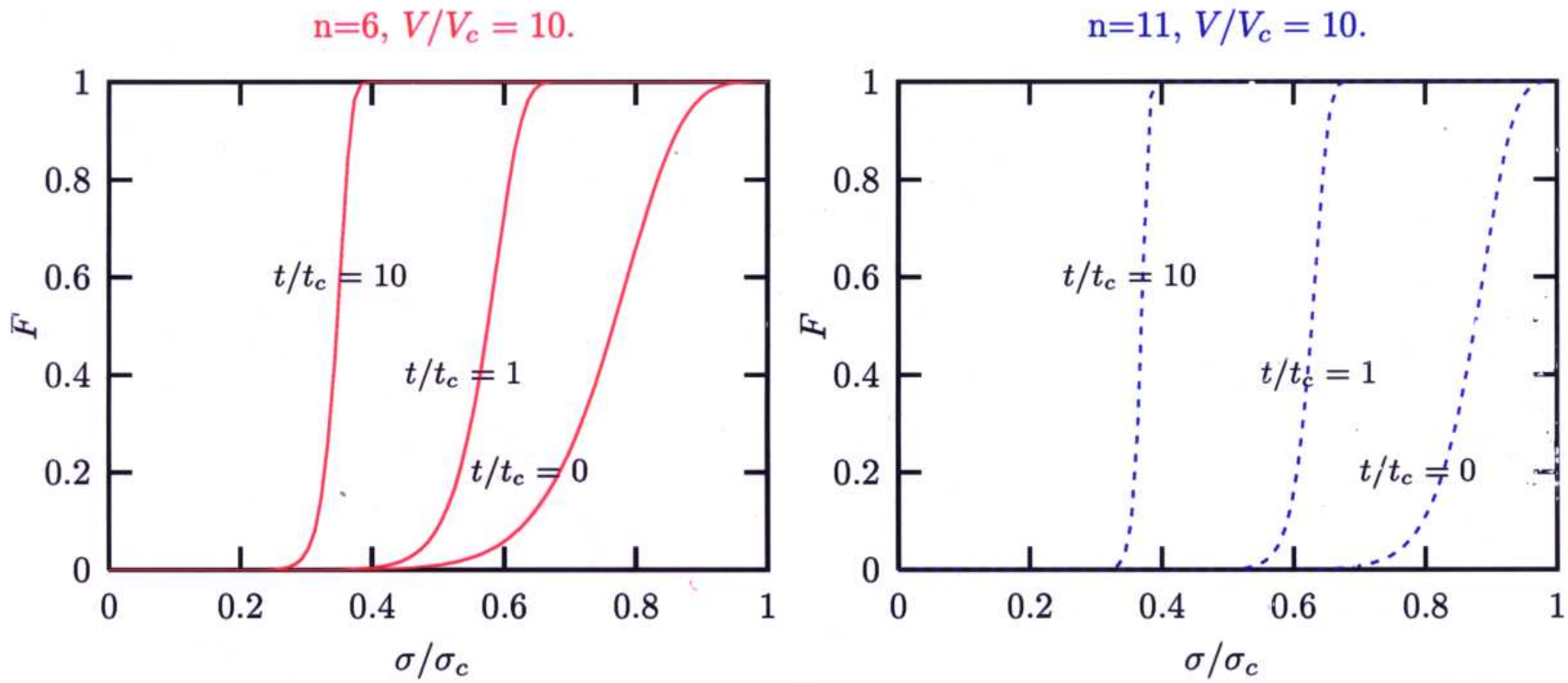
$$\Rightarrow F(\sigma, R, t) = 1 - \exp\left[-\frac{V}{V_c}\left(\frac{\sigma}{\sigma_c}\right)^{2(n-1)} \left\{1 + (1-R)^{2\nu}\left(\frac{\sigma}{\sigma_c}\right)^2 \frac{t}{t_c}\right\}^{\frac{n-1}{\nu-1}}\right] \qquad (4)$$

where $t_c = \dfrac{1}{\alpha\omega\ (\nu-1) K_{IC}^{2(\nu-1)} \pi\sigma_c^2}$

- **See examples of F (σ / σ_c , V / V_c) curves for n = 6 and n = 11**

n = Shape factor for defect distribution

2 (n-1) = Shape factor for Weibull distribution



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FRACTURE UNDER CYCLIC LOADING (Ctd)

F = failure rate, p (for a batch of N >> 1 specimens, nb of failures tolerated is Np)

- **p = F in Eq (4)**

$$\Rightarrow (1-R)^{2\nu}\,\frac{t}{t_c}=\left(\frac{\sigma_c}{\sigma}\right)^2\left[\left\{\frac{V_c}{V}\left(\frac{\sigma_c}{\sigma}\right)^{2(n-1)}Ln\left(\frac{1}{1-p}\right)\right\}^{(\nu-1)/(n-1)}-1\right] \qquad (5)$$

- **Design : - components of length**
  - load [LR, L]

Define cross sectional area A for a failure rate, p ?
⇨ Curves relating A to design life, t and failure rate, p

$$\frac{\sigma}{\sigma_c}=\frac{A_c}{A};\quad \frac{V}{V_c}=\frac{\ell A}{\ell_c A_c}$$

Eq (5)

$$\Rightarrow (1-R)^{2\nu}\,\frac{t}{t_c}=\left(\frac{A}{A_c}\right)^2\left[\left\{\frac{\ell_c}{\ell}\left(\frac{A}{A_c}\right)^{2n-3}\mathrm{Ln}\left(\frac{1}{1-p}\right)\right\}^{(\nu-1)/(n-1)}-1\right] \qquad (6)$$

When A / A_c large and p small, Eq (6)

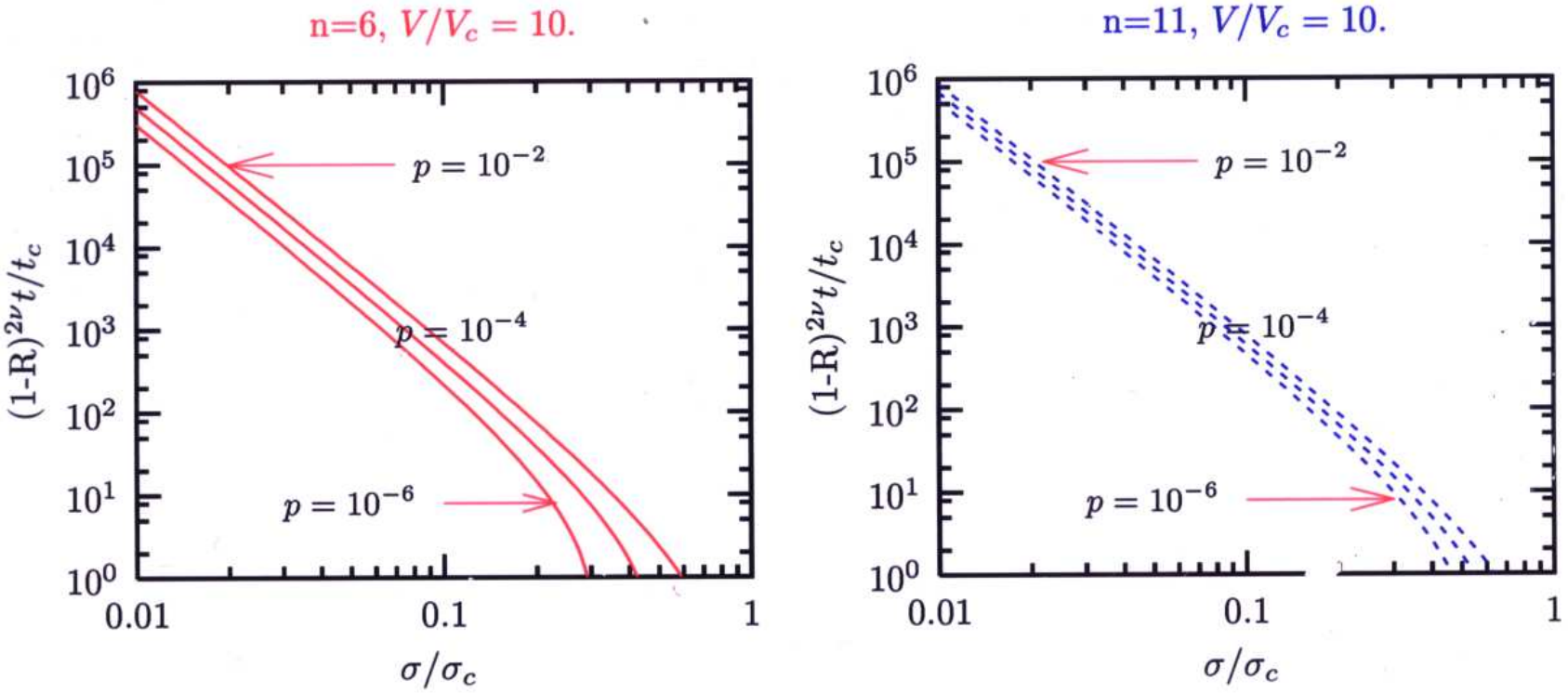
$$\Rightarrow \frac{A}{A_c}\approx\left(\frac{1}{p\ell_c}\right)^{\frac{\nu-1}{1+(2n-3)\nu}}\left\{(1-R)^{2\nu}\frac{t}{t_c}\right\}^{\frac{n-1}{1+(2n-3)\nu}} \qquad (7)$$

In Paris law ν =3/2, Eq (7)

$$\Rightarrow \frac{A}{A_c}\approx\left(\frac{1}{p\ell_c}\right)^{\frac{1}{6n-7}}\left\{(1-R)^3\frac{t}{t_c}\right\}^{\frac{2n-2}{6n-7}} \qquad (8)$$

n = Shape factor for defect distribution

2 (n-1) = Shape factor for Weibull distribution



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FRACTURE UNDER CYCLIC LOADING (Ctd and End)

SAFETY FACTOR in DESIGN ? $\quad A \rightarrow fA \quad (f > 1)$

Eq (8) $\Rightarrow A\alpha \left(\frac{t^{2n-2}}{p} \right)^{\frac{1}{6n-7}}$

⇨Application of safety factor, f, is equivalent to :

- either maintaining the design life, t, but decreasing **the failure rate**
  from p to $(p/f)^{6n-7}$
- or maintaining the failure rate, p, but increasing **the design life**
  from t_f to $(t_f)^{(6n-7)/(2n-2)}$

See figures showing these variations

LARGE DECREASE IN FAILURE RATE RESULTS FROM EVEN LOW VALUES OF SAFETY FACTOR

Further Readings :

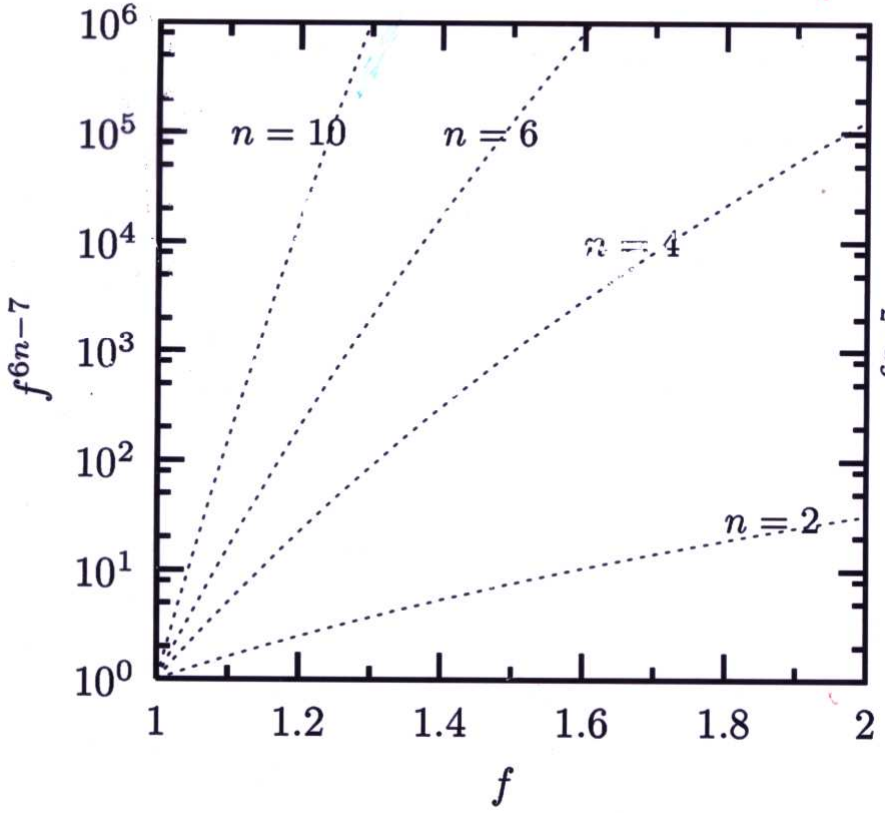
• L.N. Mc Cartney (1979). Int. Journal of Fracture, Vol. 15, pp. 477 - 487
• L.N. Mc Cartney (1979). Fatigue of Engineering Materials and Structures, Vol. 2, pp. 387 - 400

n = Shape factor for defect distribution

2 (n-1) = Shape factor for Weibull distribution

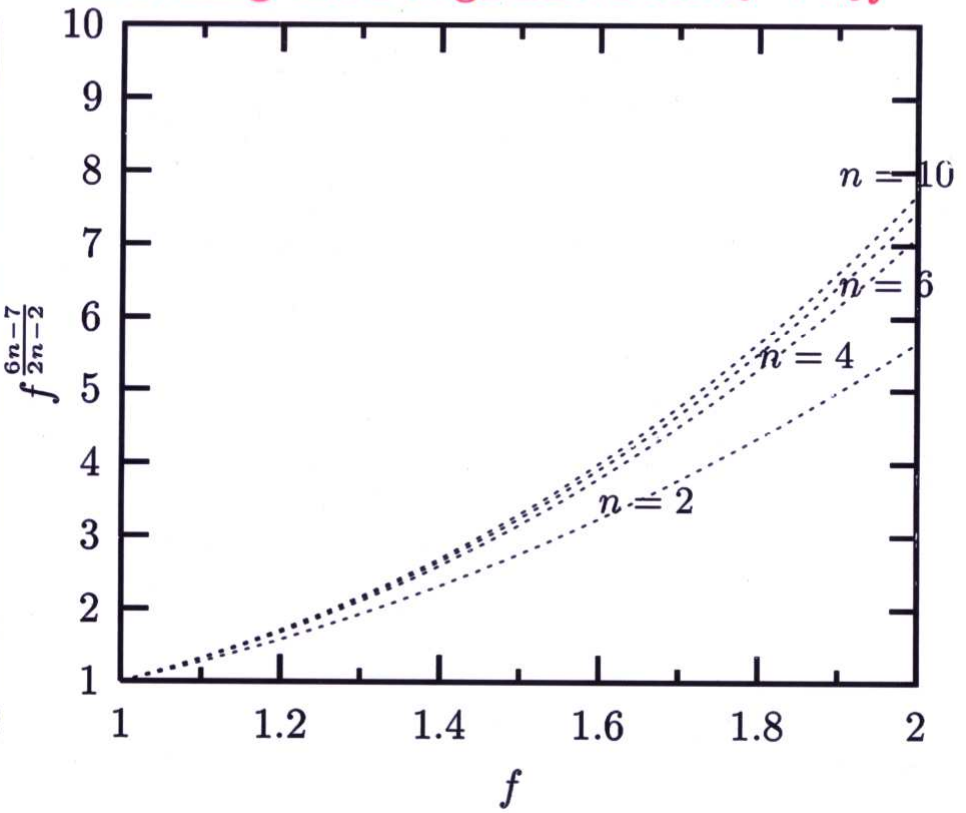
Maintaining the Design Life, t_0

Decreasing failure rate from $p_0 \rightarrow \frac{p_0}{f^{6n-7}}$



Maintaining the failure rate, p_0

Increasing the Design Life from $t_0 \rightarrow t_0 f^{\frac{6n-7}{2n-2}}$



INTRODUCTION TO MATERIAL VARIABILITY OF MECHANICAL PROPERTIES AND LENGTH SCALE

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I - INTRODUCTION - CASE STUDIES

II - ELASTICITY

III - PLASTICITY

IV - FRACTURE : 2 Case Studies
- Duplex Stainless Steels
- Welds

V - A SIMPLE MODEL BASED ON WEAKEST LINK THEORY

VI - CONCLUSIONS

CONCLUSIONS

- **Many sources of variability**
- **Other sources of variability related to loading**
  Not considered here except in the Introduction
- **Large length scale to cover**
- **Microstructure : A Key Parameter**