BRITTLE FRACTURE & BRITTLE to DUCTILE FRACTURE TRANSITION MICROMECHANISMS

André PINEAU
Centre des Matériaux - Ecole des Mines de Paris. ParisTech
UMR CNRS 7633
andre.pineau@ensmp.fr

I. INTRODUCTION : Various Scales / History of Fracture Mechaniscs

II. BRITTLE CLEAVAGE FRACTURE – THEORY
II.1. Main characteristics of Brittle Cleavage Fracture
II.2. Weibull – Beremin Theory
II.3. Multiple barrier models
II.4. Effect of Deformation – Second Order approximation

III. DUCTILE FRACTURE – THEORY (Introduction)
III.1. Cavity initiation, growth & coalescence. GTN model
III.2. Computational strategies to simulate ductile crack growth

IV. DUCTILE TO BRITTLE TRANSITION IN STEELS
IV-1. Qualitative explanations for the existence of DBT
IV-2. Fracture toughness transition
IV-3. Impact Charpy test

V. CONCLUSIONS

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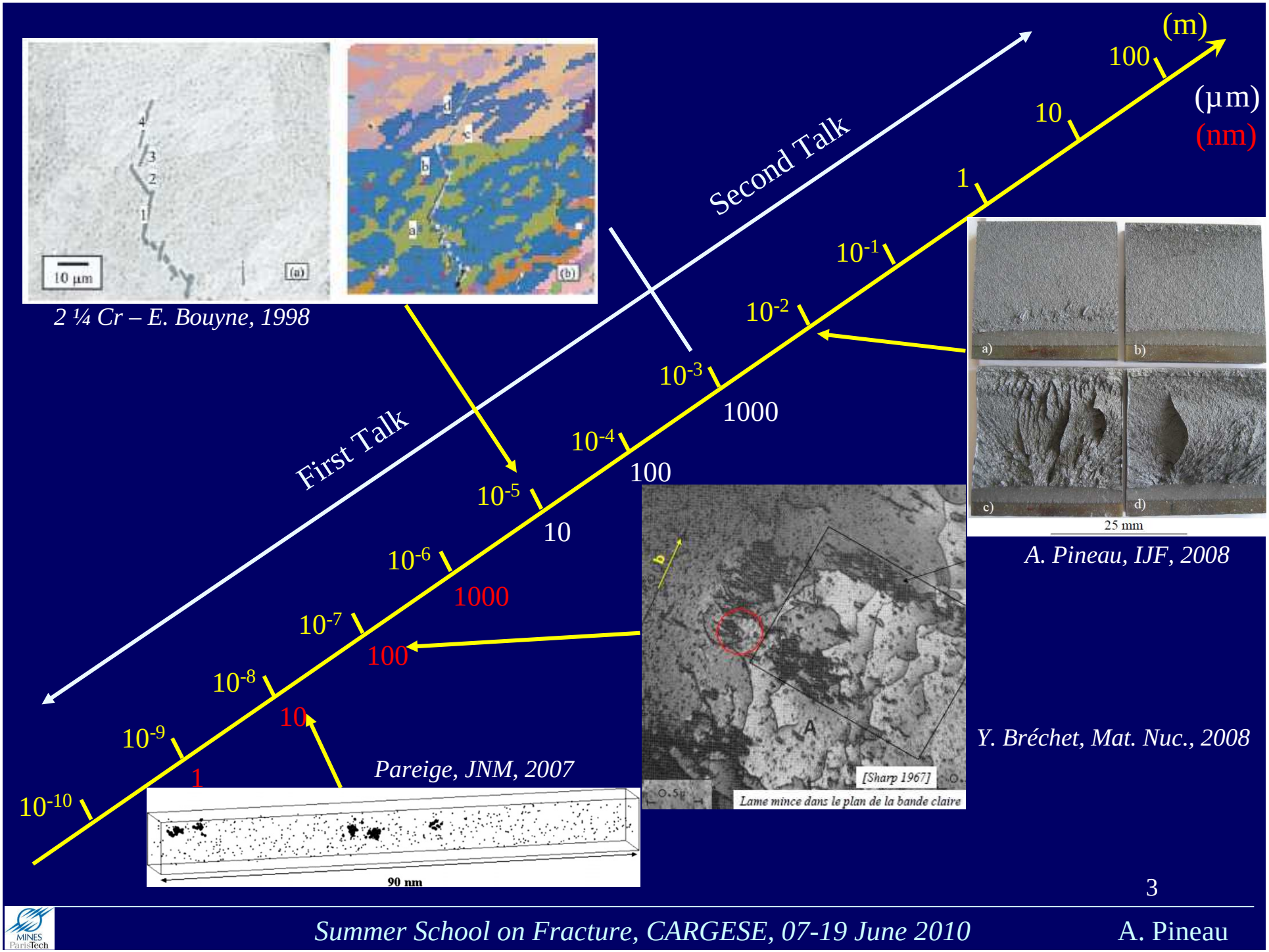
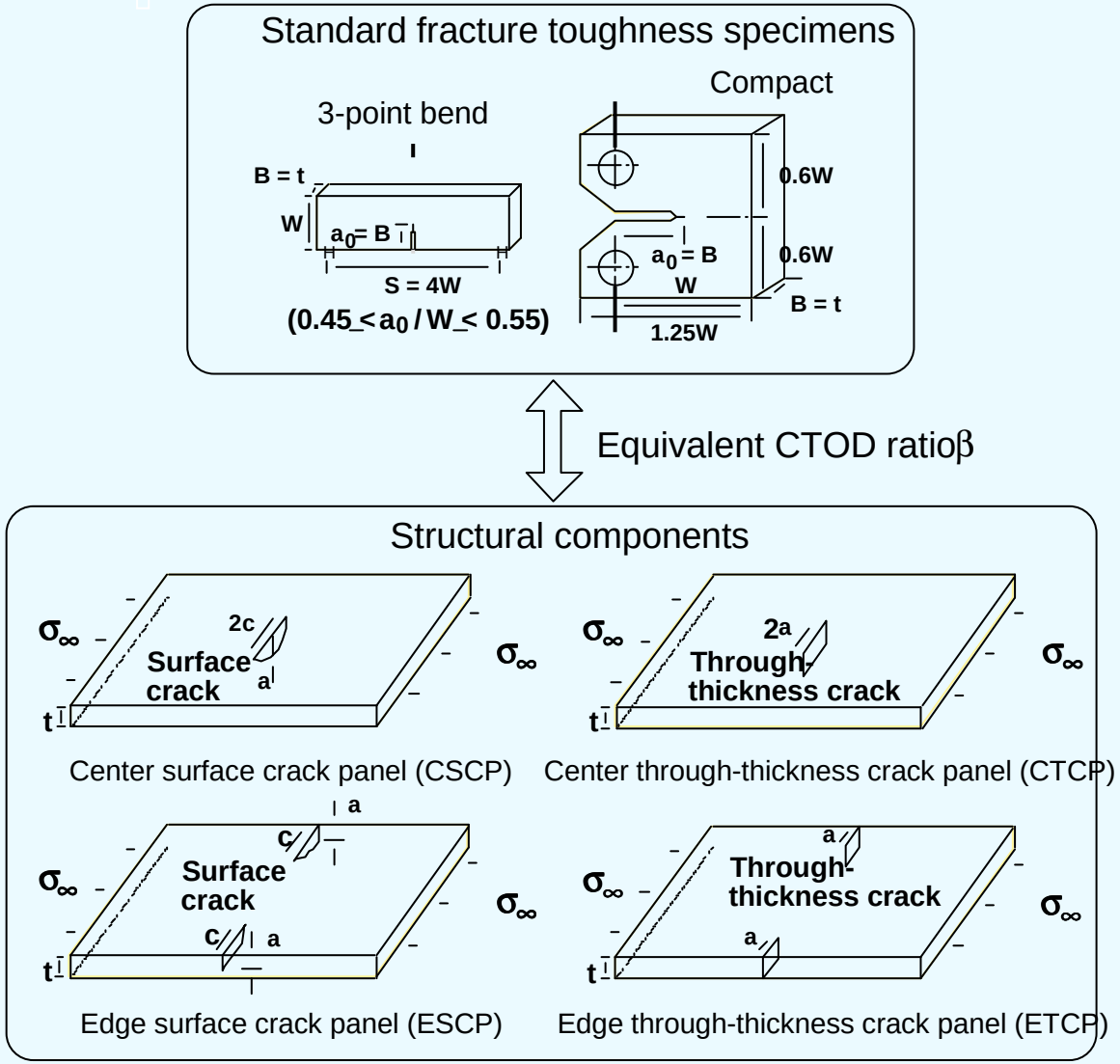
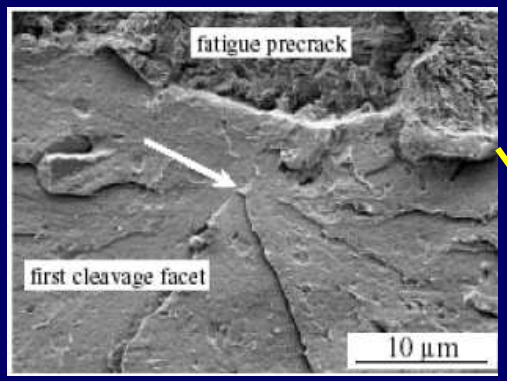

(m)
100
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
(µm)
(nm)
1000
100
10
1000
100
10
1
First Talk
Second Talk
10 µm
(a)
(b)
2 ¼ Cr – E. Bouyne, 1998
a)
b)
c)
d)
25 mm
A. Pineau, IJF, 2008
[Sharp 1967]
Lame mince dans le plan de la bande claire
Y. Bréchet, Mat. Nuc., 2008
Pareige, JNM, 2007
90 nm

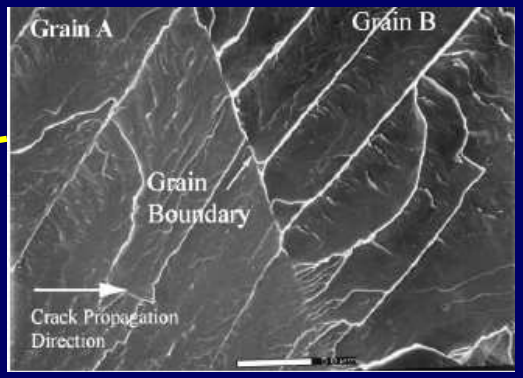


Standard Fracture Toughness specimens and wide plate components linked with the equivalent CTOD ratio β

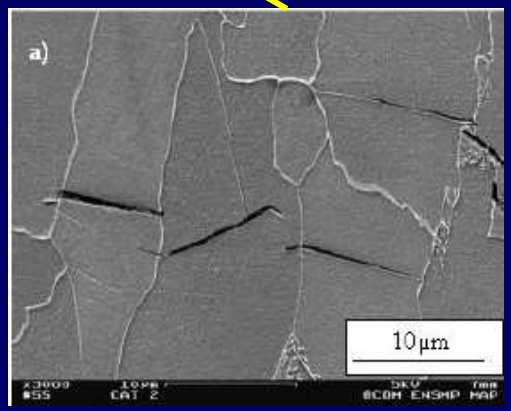
Bouchard,(NH),1978, R.M. Pelloux



A. Lambert-Perlade, 2001



Fe-3%Si- Qiao, Argon, 2003

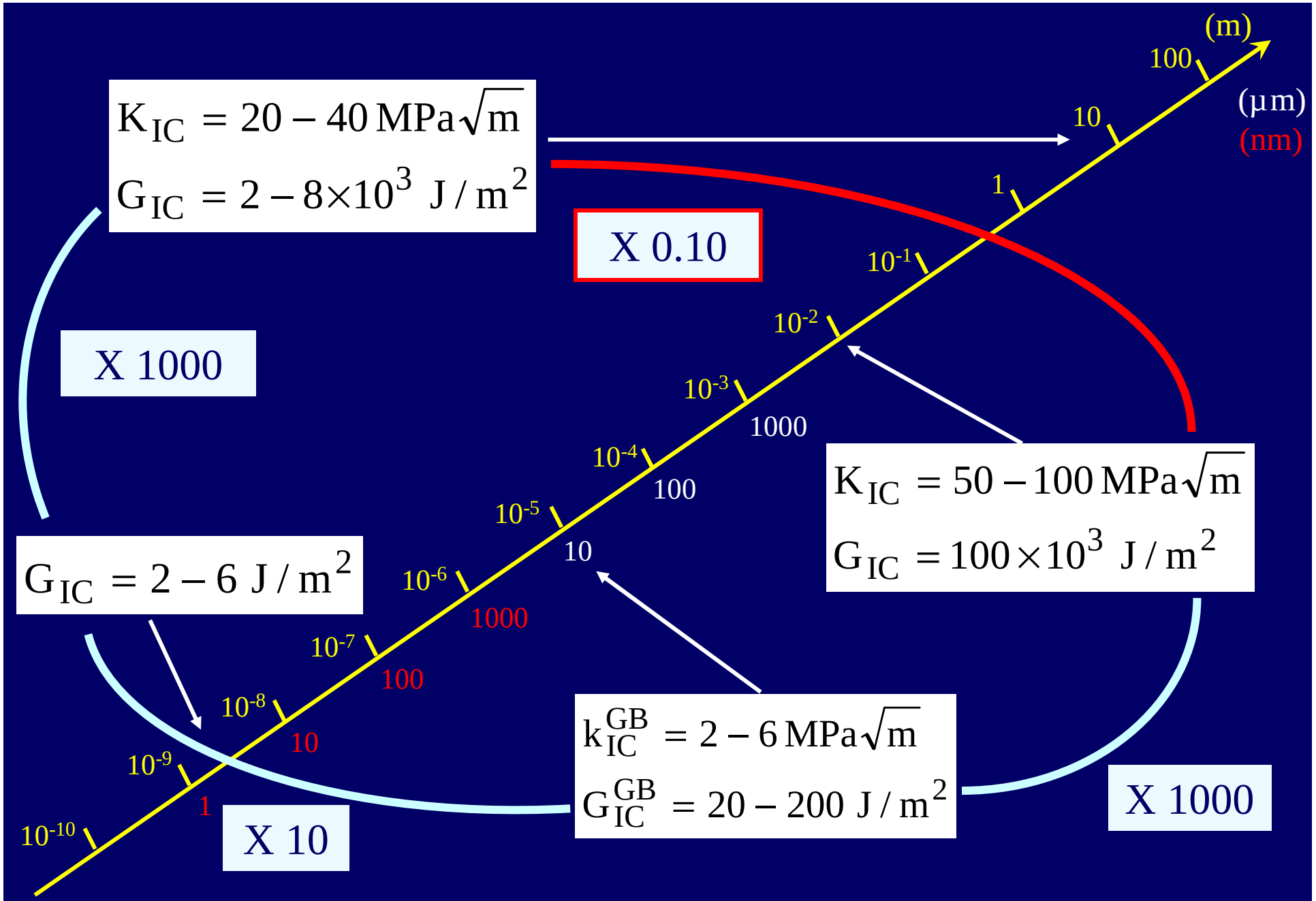


A. Lambert-Perlade, 2001

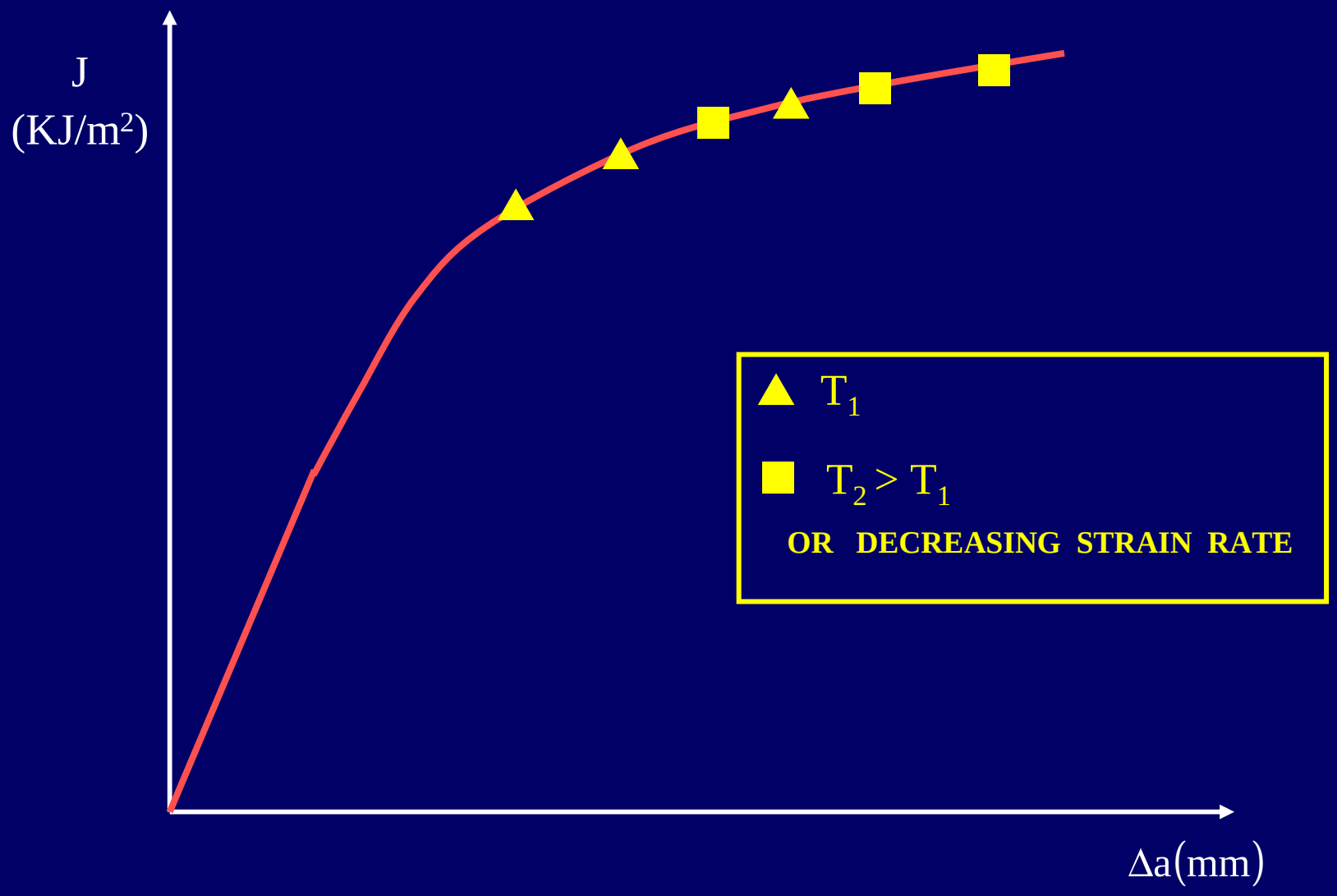
(m) 100 10 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10}

(µm) 1000 100 10

(nm) 1000 100 10 1

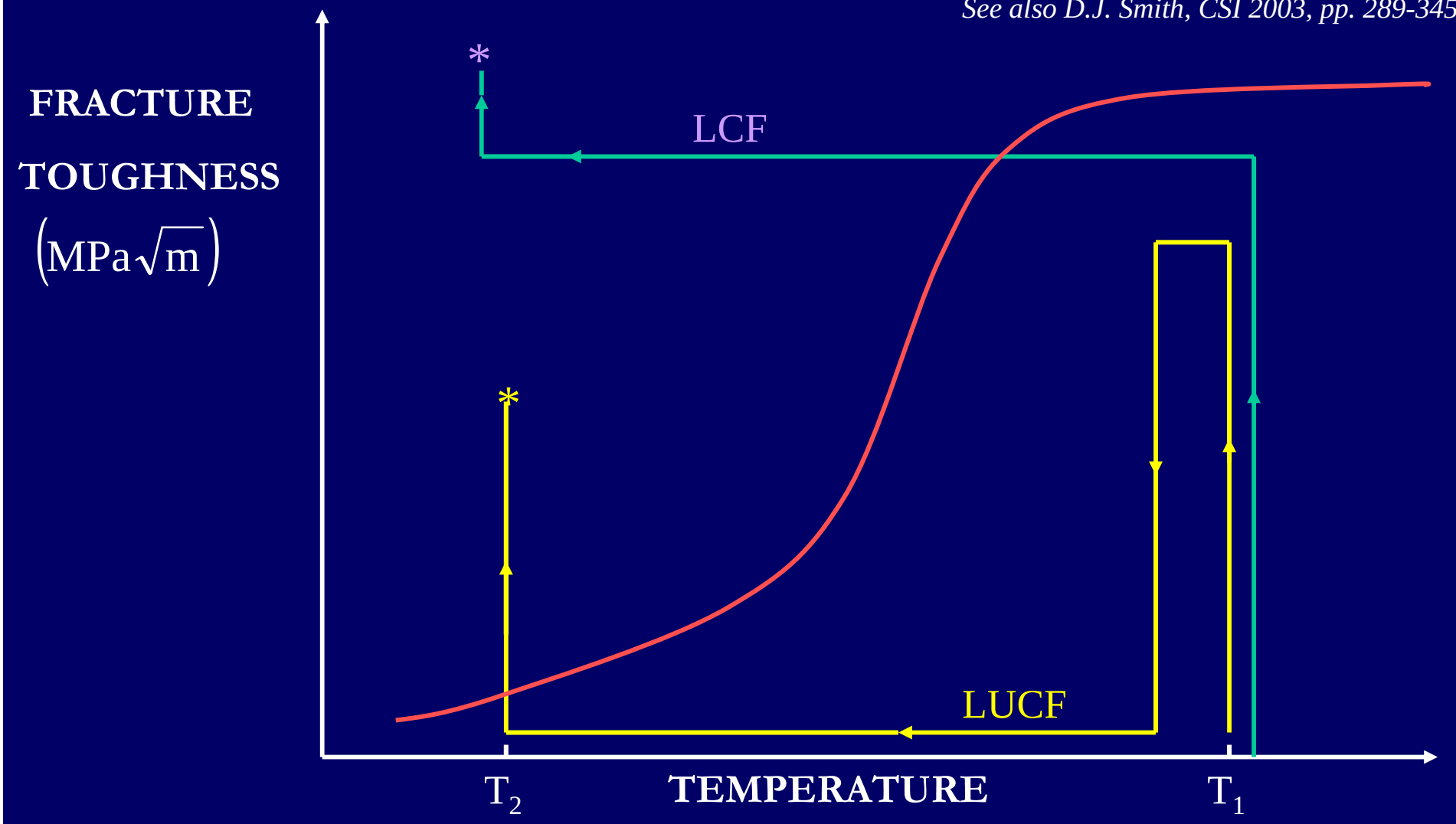

$K_{IC} = 20 - 40\ MPa\sqrt{m}$
$G_{IC} = 2 - 8\times10^{3}\ J/m^{2}$
X 0.10
X 1000
$G_{IC} = 2 - 6\ J/m^{2}$
$K_{IC} = 50 - 100\ MPa\sqrt{m}$
$G_{IC} = 100\times10^{3}\ J/m^{2}$
$k_{IC}^{GB} = 2 - 6\ MPa\sqrt{m}$
$G_{IC}^{GB} = 20 - 200\ J/m^{2}$
X 1000
X 10
(m)
(µm)
(nm)
100
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1000
100
10
1000
100
10
1

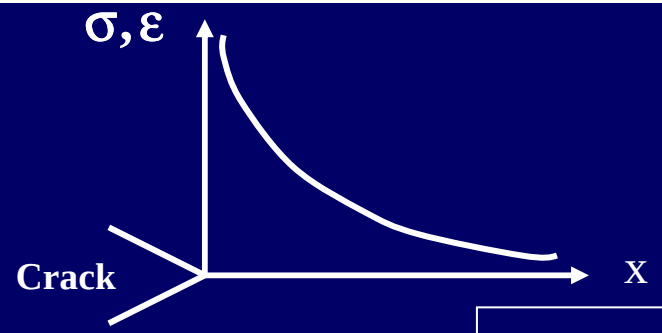
DUCTILE TO BRITTLE TRANSITION - DEFINITION



WARM-PRESTRESS EFFECT

See also D.J. Smith, CSI 2003, pp. 289-345





GLOBAL APPROACH

$\sigma - \varepsilon$ Field

- **Single parameter**
  K, J, CTOD
- **K-T; J-Q**
  Two parameters

LOCAL APPROACH

Crack Tip $\sigma - \varepsilon$ Field + Physically-based Fracture Criteria

→ COMPUTATIONAL FRACTURE MECHANICS

1960 1970 1980 1990 2000 2010

LEFM

EPFM

LAF

1981 ICF5 | 1986 1st Sem. | 1992 AIME Sem. | 1996 2nd Sem. | 2006 3st Sem.

I - EXPERIMENTS

- Mechanical Tests
- Microstructural Observations
- Micromechanisms

II - MODELS

- Constitutive Equations
- Damage Modelling

III - IDENTIFICATION

- Tuning of Models Parameters

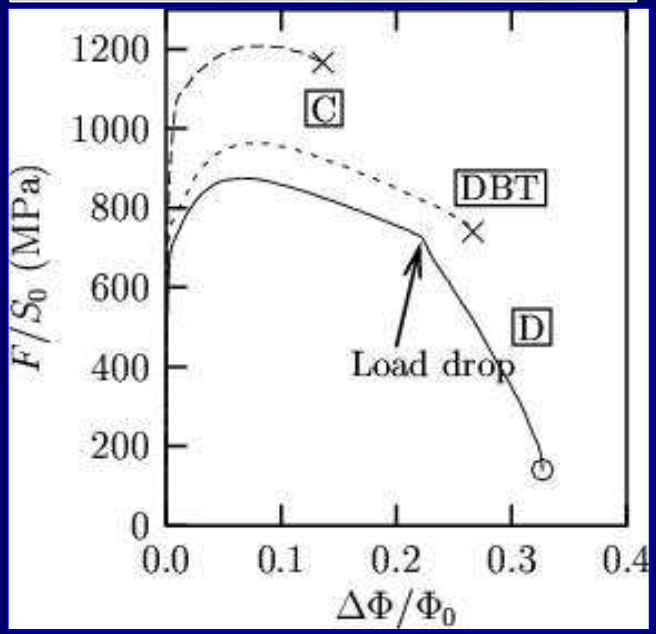
IV - SIMULATION

- Laboratory Tests

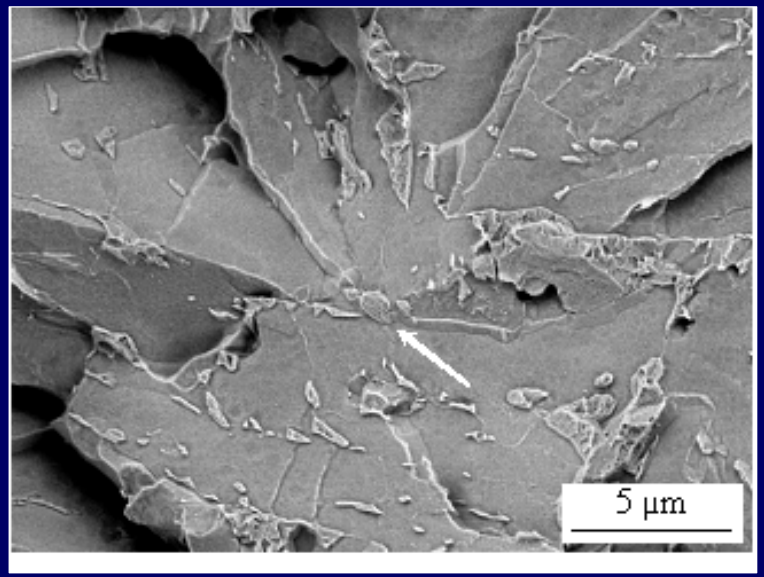
V - SIMULATION

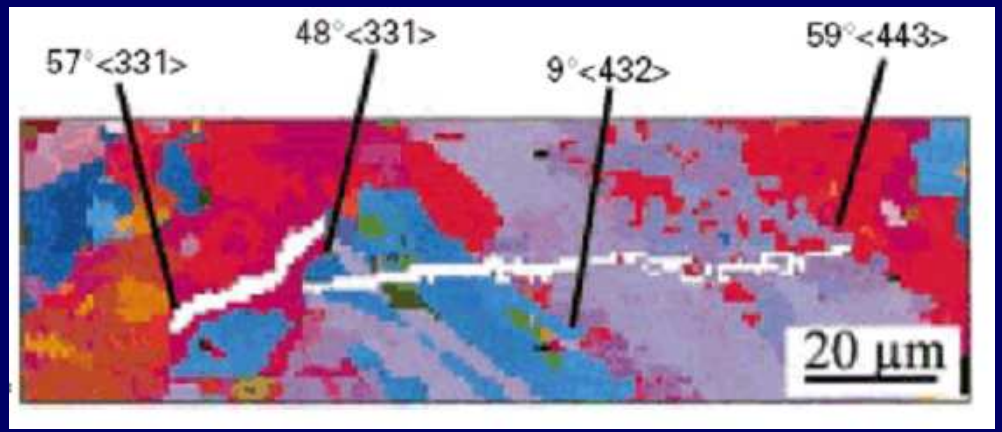
- Industrial Components
- Complex Loading Conditions

MECHANICAL TESTS



OBSERVATIONS



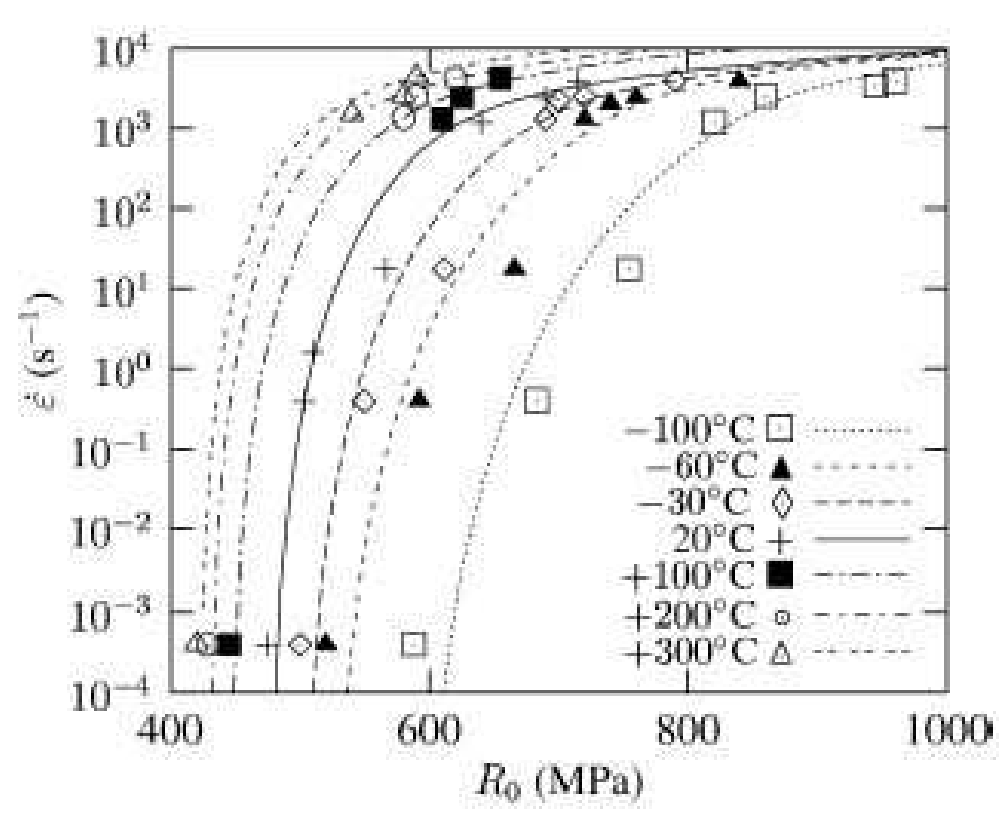


CONSTITUTIVE EQUATIONS

$$R(p,T) = R_0 + Q_1(1-\exp(-b_1 p)) + Q_2(1-\exp(-b_2 p))$$

$$\dot{p} = F(\sigma - R)$$

$$\frac{1}{\dot{p}} = \frac{1}{F} = \frac{1}{\dot{\varepsilon}_1} + \frac{1}{\dot{\varepsilon}_2} \qquad \dot{\varepsilon}_i = \left\langle \frac{\sigma - R}{K_i} \right\rangle^{n_i} ; \quad i = 1,2$$



DAMAGE MODELLING

- **CLEAVAGE FRACTURE**

WEIBULL STRESS

$$P_R = 1 - \exp - \left(\frac{\sigma_w}{\sigma_u} \right)^m$$

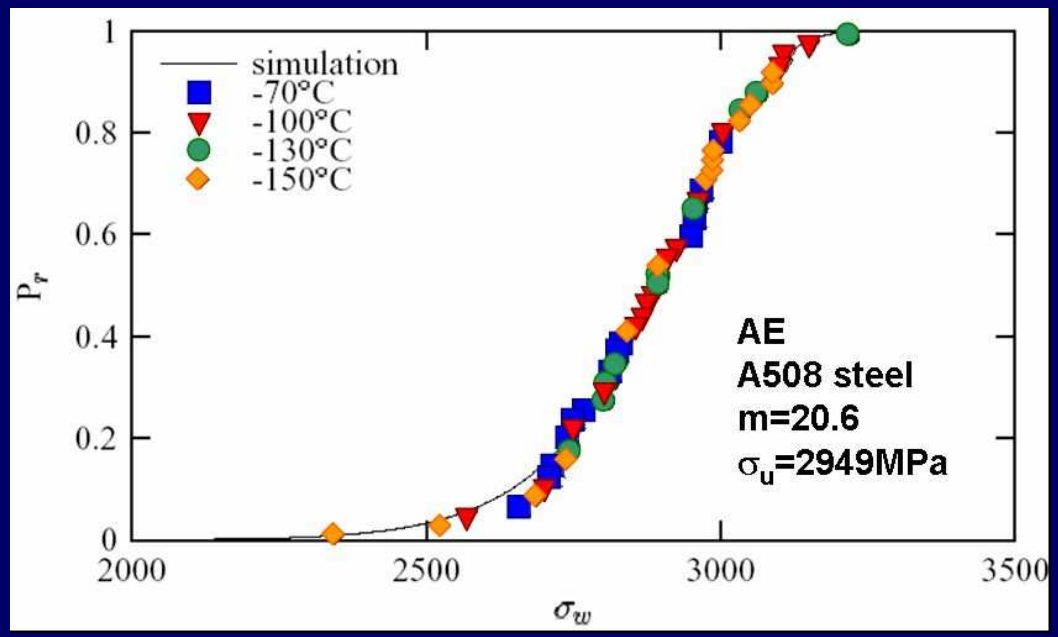
$$\sigma_w = \left[\frac{1}{V_u} \int \sigma_I^m \, dV \right]^{1/m}$$

- **DUCTILE RUPTURE**
  - Uncoupled models
  - Coupled models

CLEAVAGE FRACTURE

Probabilistic Model

Weibull Stress

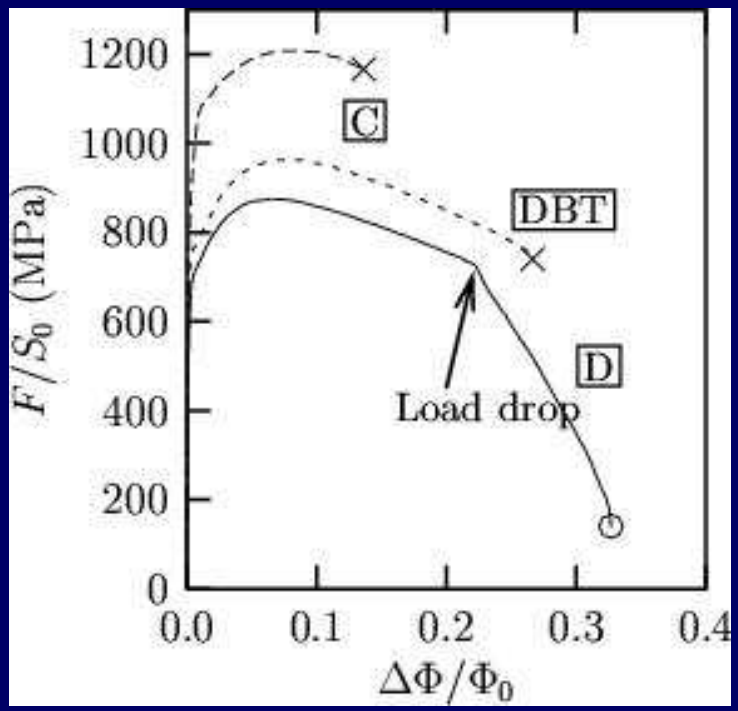


Charlotte Bouchet

DUCTILE RUPTURE

Coupled Models

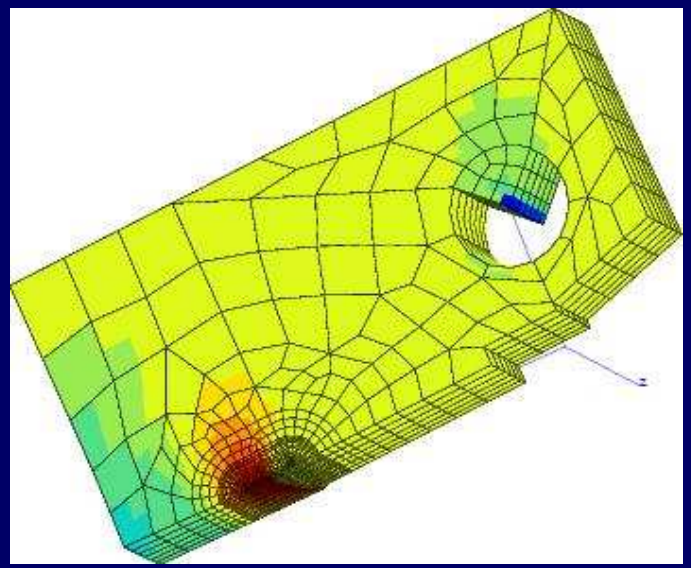
- **Gurson-Tvergaard-Needleman Potential with an accelerating function**
- **Rousselier Potential**
- **Statistical models in Duplex Stainless Steels**



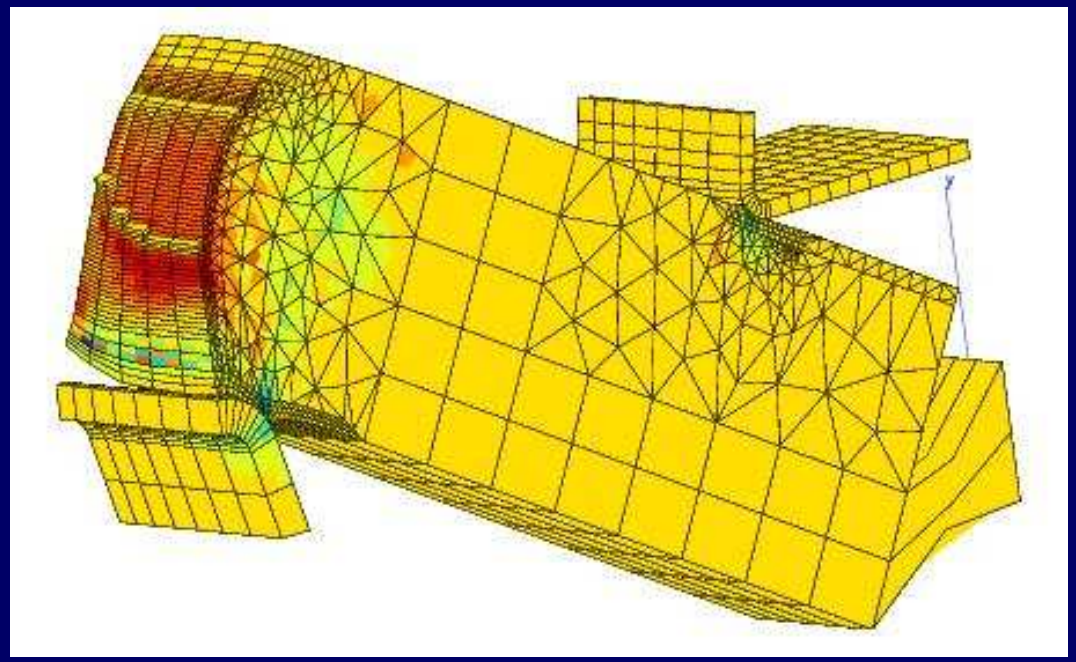
SIMULATION

NS (AE)

CT

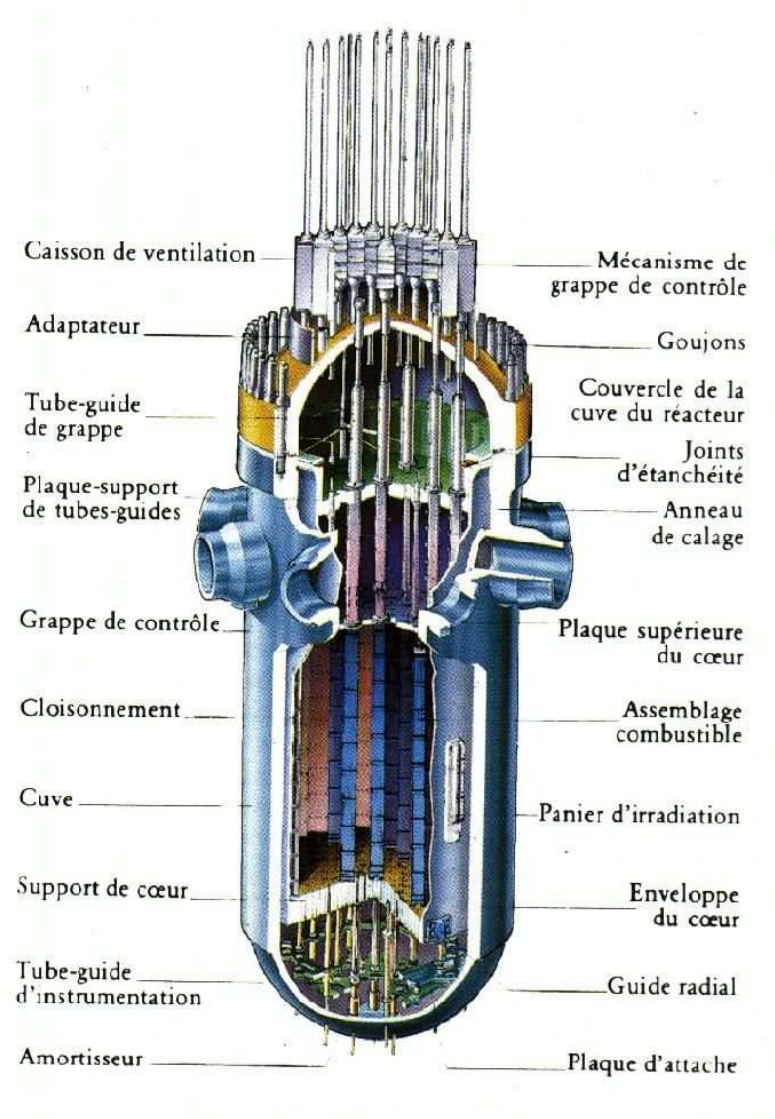


CHARPY V NOTCH



B. Tanguy & J. Besson

PRESSURE VESSEL



SIMULATION

ALOHA, 1988

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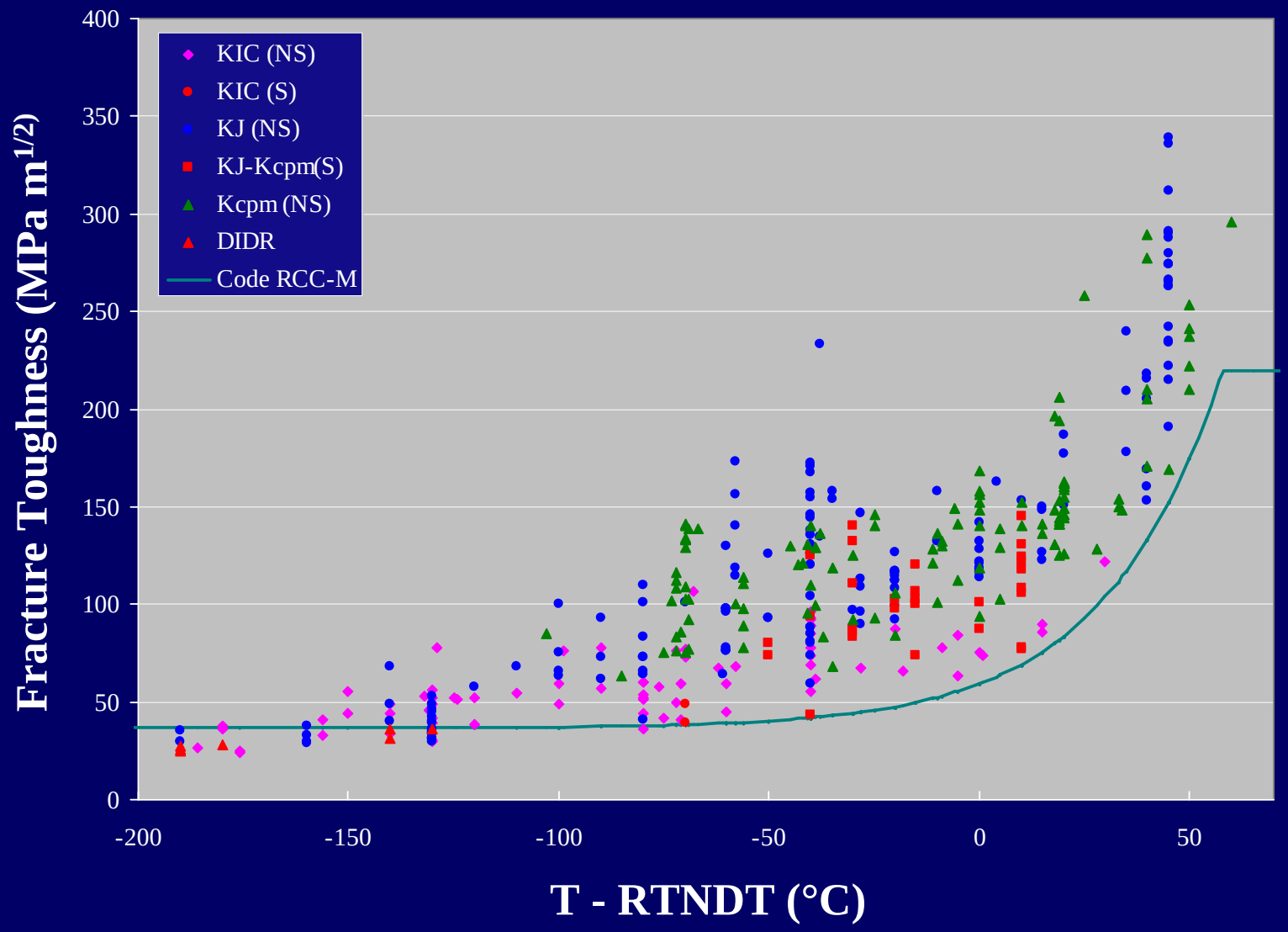
V. CONCLUSIONS

BRITTLE FRACTURE
MAIN CHARACTERISTICS

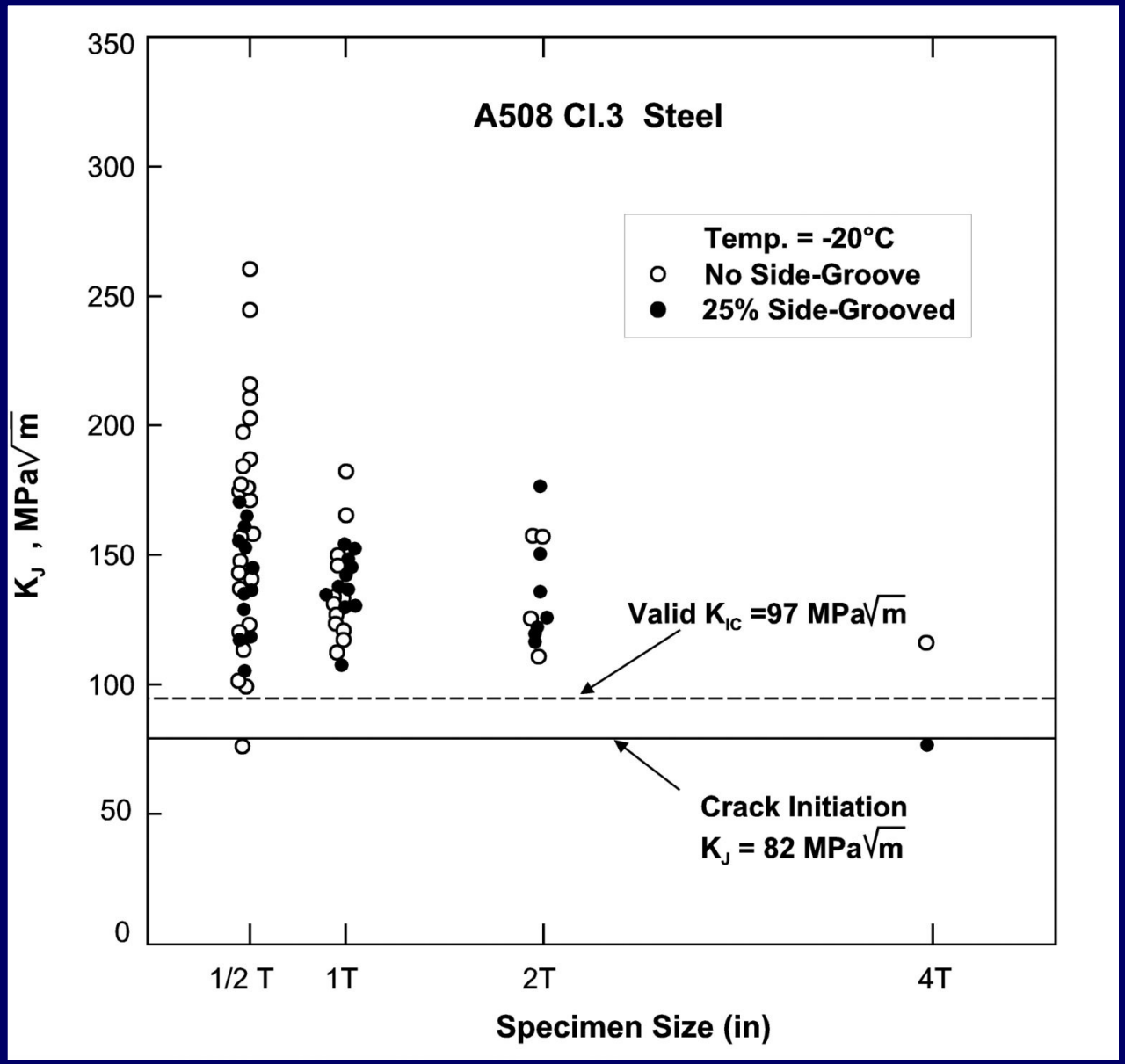
- SCATTER
- SIZE EFFECT
- GEOMETRICAL DEPENDENCE
- LOADING RATE EFFECT
- EFFECT OF METALLURGICAL VARIABLES & INHOMOGENEITIES

C. Naudin, A. Pineau and J.M. Frund (2001), 10th Conf. on environmental degradation



I. Iwadate et al., Nucl. Eng. Design (1985), Vol. 85, pp. 89-99

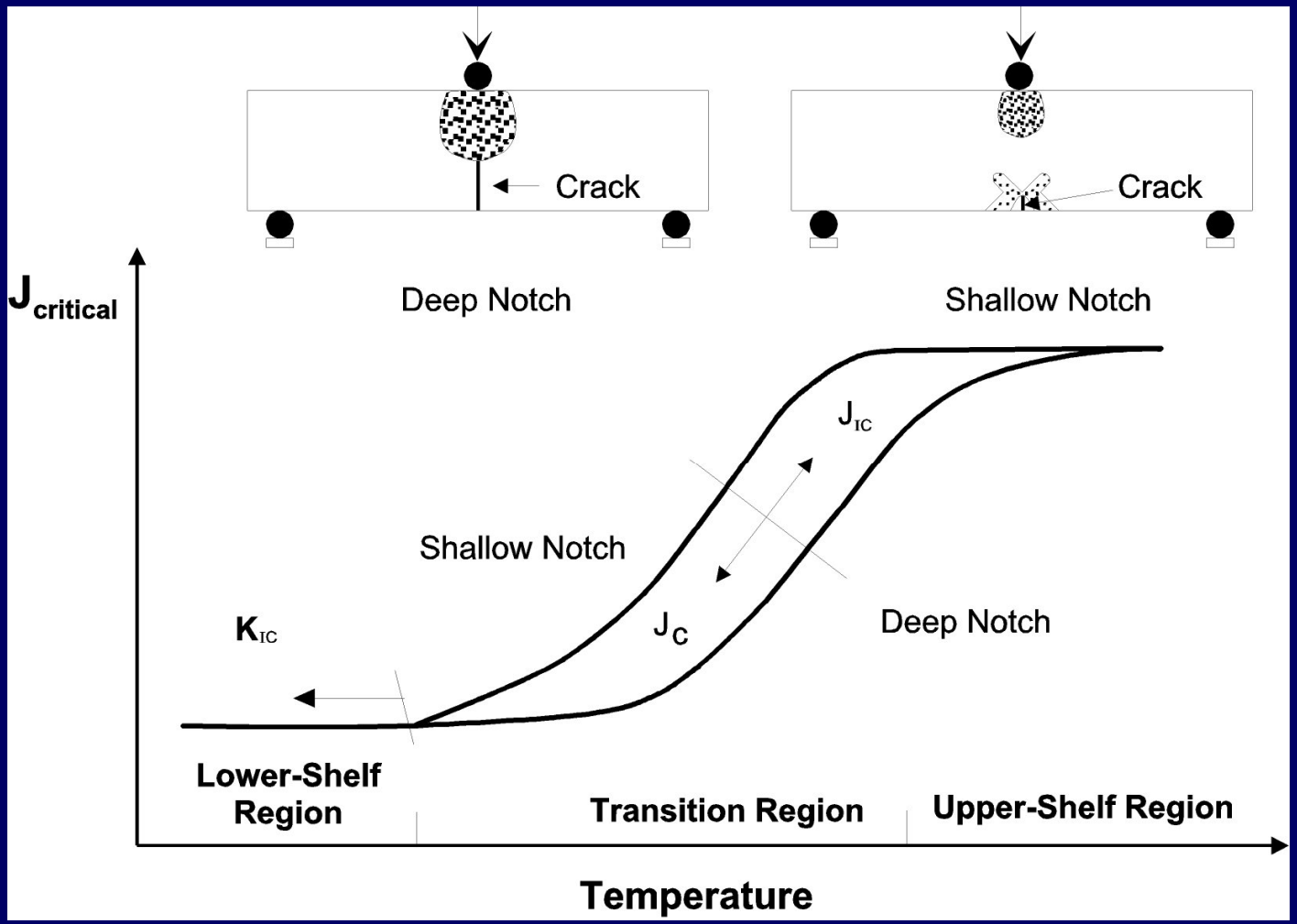
Size Effect



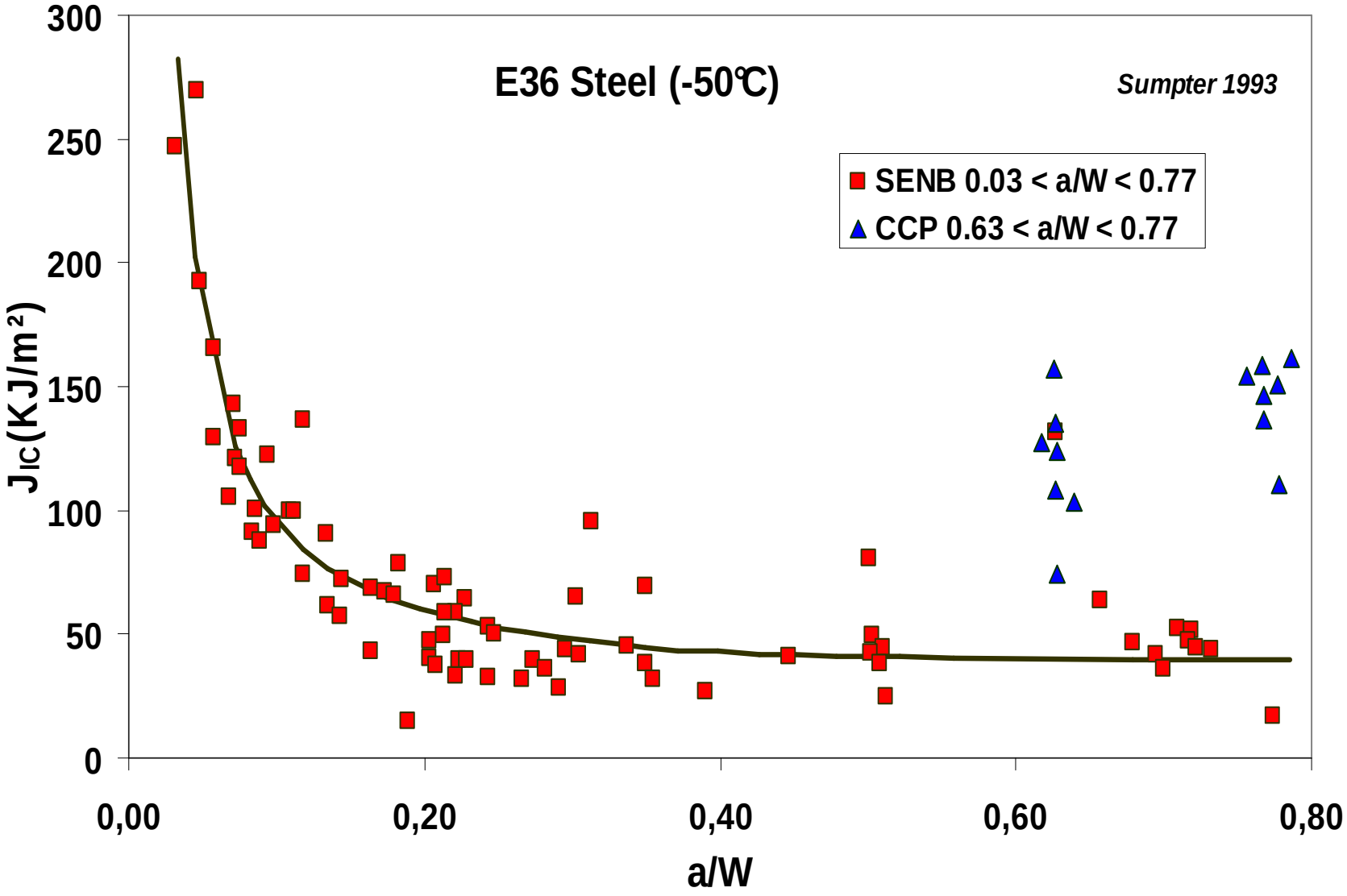
CONSTRAINT EFFECT

*- W.A. Sorem et al. Int. J. Fracture, (1991), **47**, 105-126*
*- D. Tigges et al. ECF 10, (1994), **1**, 637-646*

Short Crack Effect

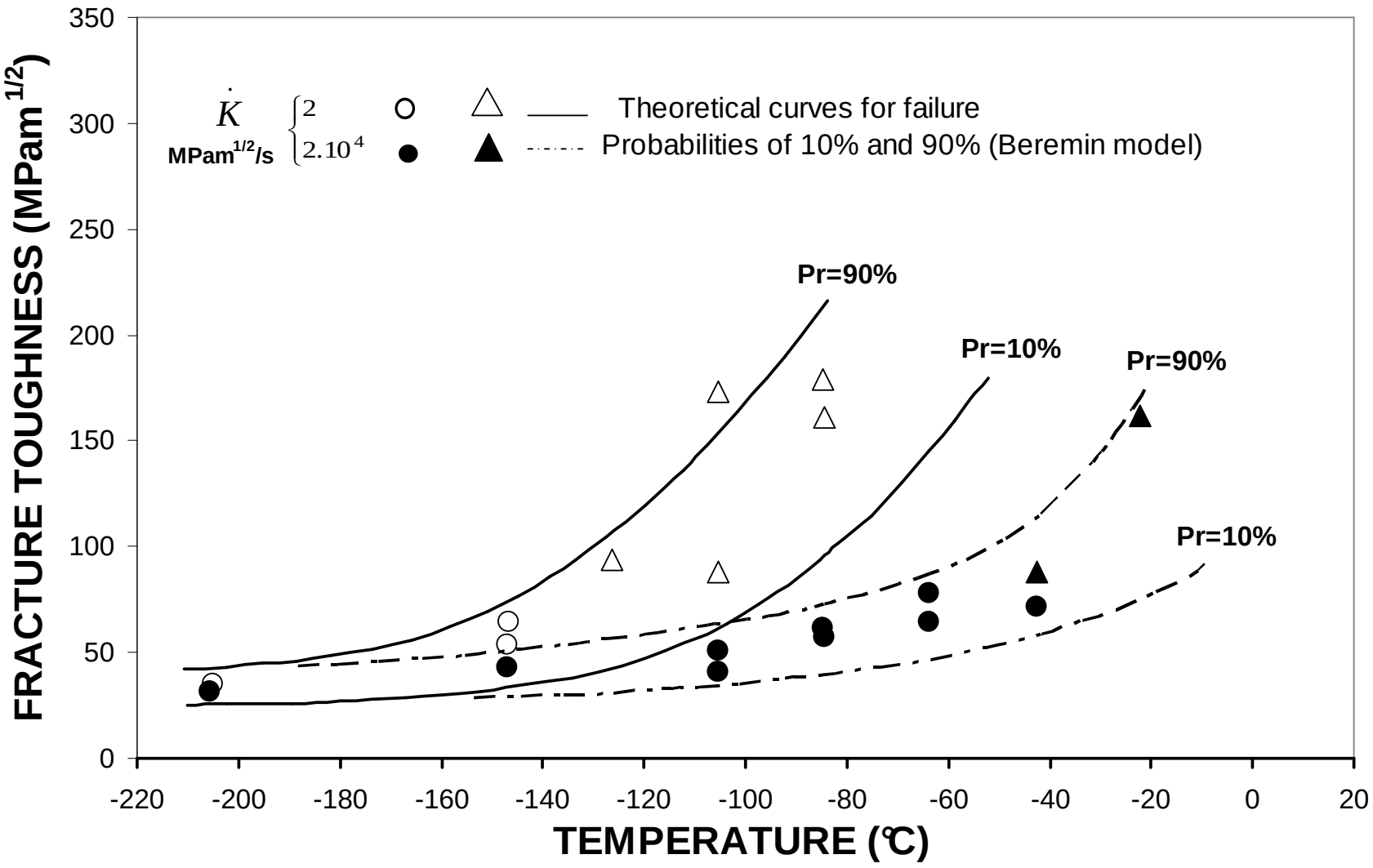


CONSTRAINT EFFECT



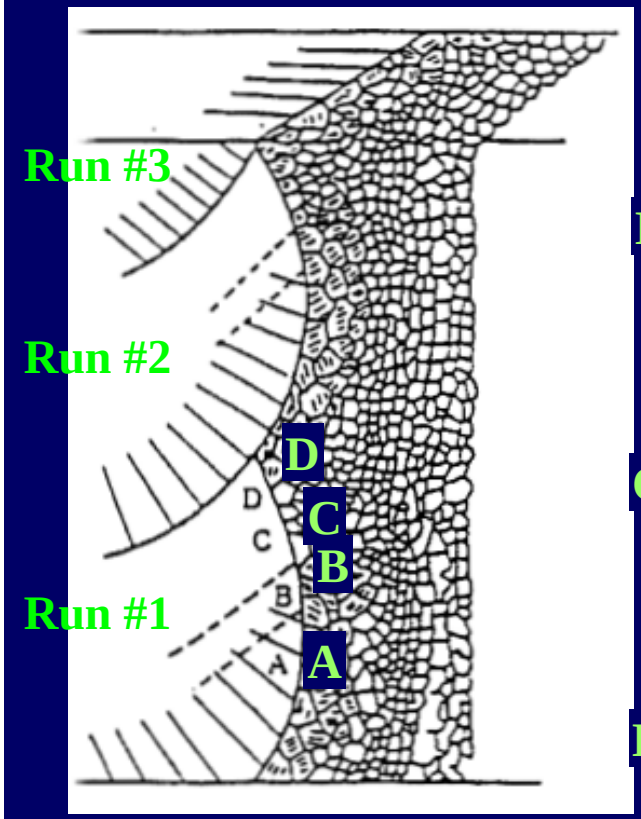
A 508 Steel

Henry et al., 1985

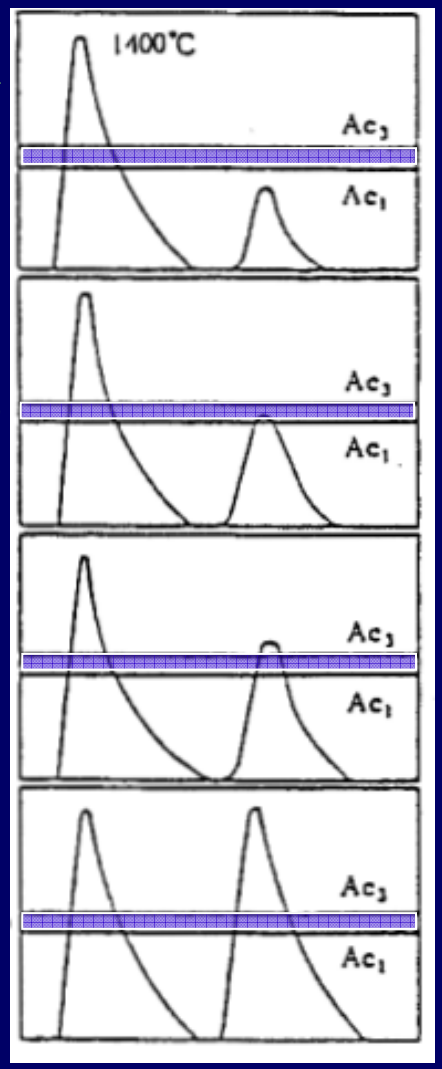


METALLURGICAL INHOMOGENEITIES

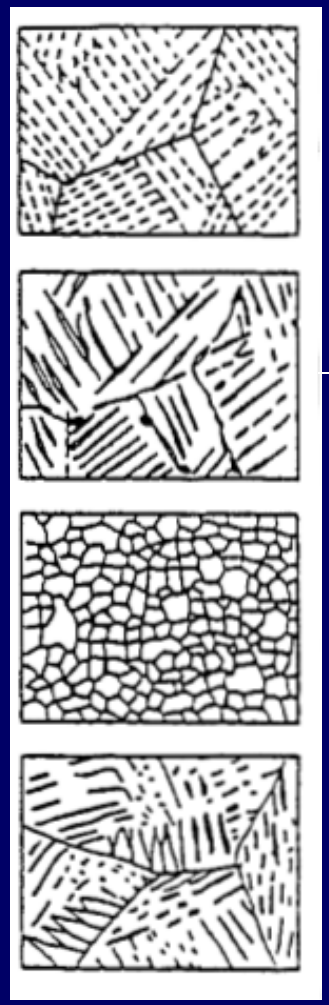
A. Lambert-Perlade et al., Metall. And Mater. Trans. A (2004), Vol. 35A, pp. 1039-1053



Weld structure



Corresponding thermal cycles



Coarse gained HAZ (CG HAZ)

Intercritically reheated CG HAZ

Supercritically reheated CG HAZ (fine grains)

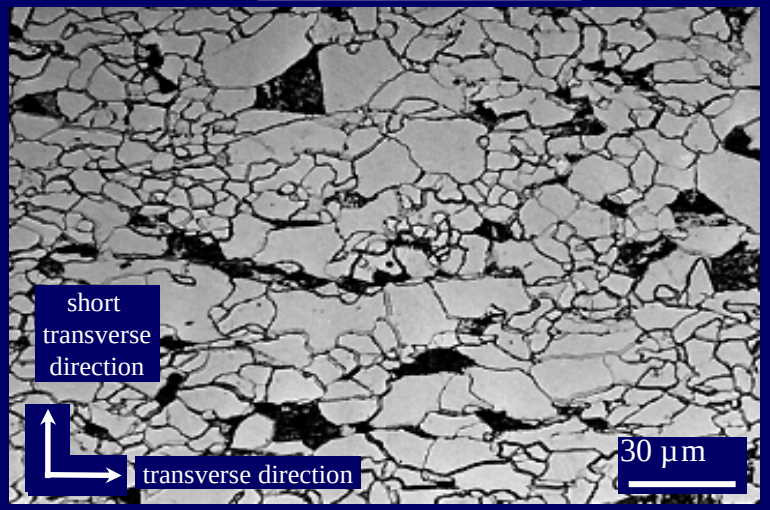
~ CG HAZ

Corresponding HAZ microstructures

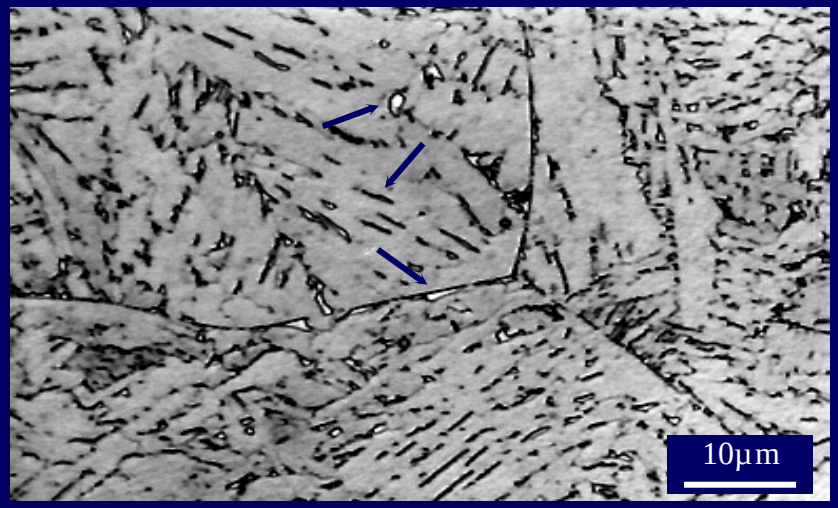
A. Lambert-Perlade et al., Metall and Mater. Trans. A, (2004), Vol. 35A, pp. 1039-1053

E 450

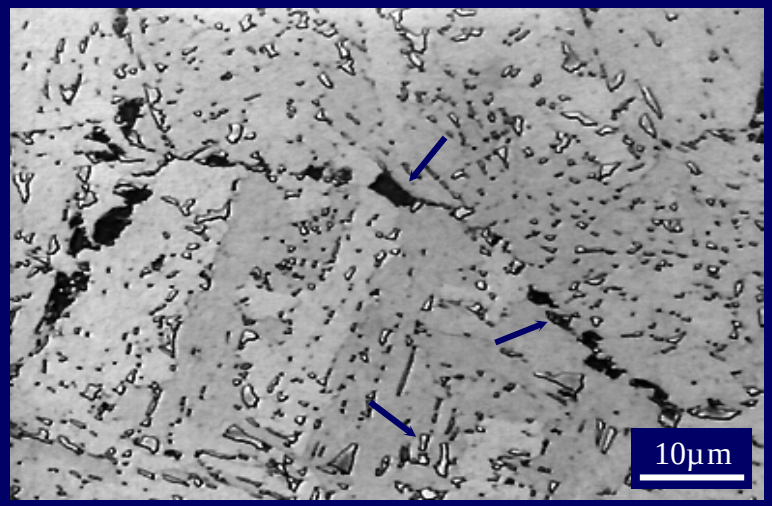
BASE METAL



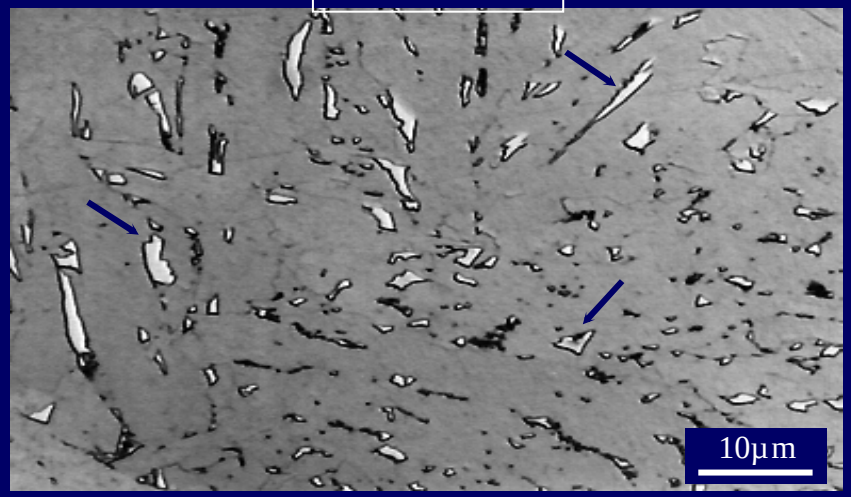
CGHAZ-25



ICCGHAZ-25



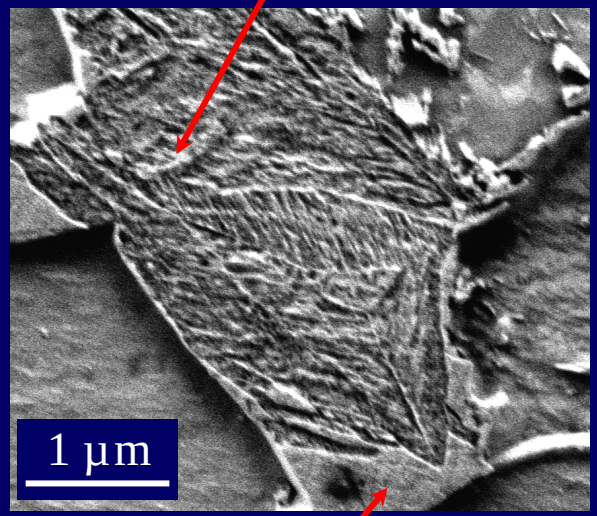
CGHAZ-120

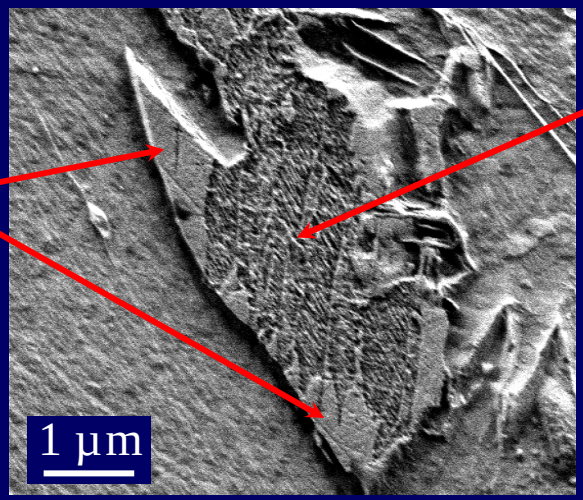


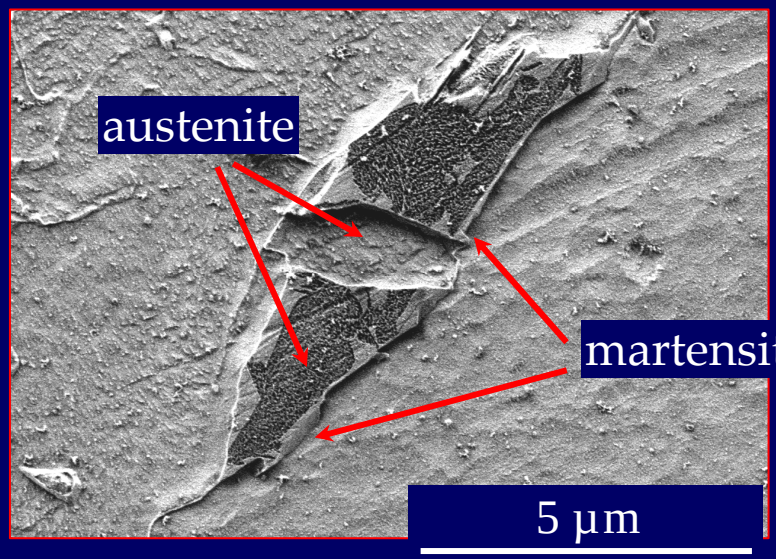
A. Lambert-Perlade et al., Metall. and Mater. Trans. A, (2004), Vol. 35 A, pp. 1039-1053

MARTENSITE - AUSTENITE CONSTITUENTS

E 450 STEEL

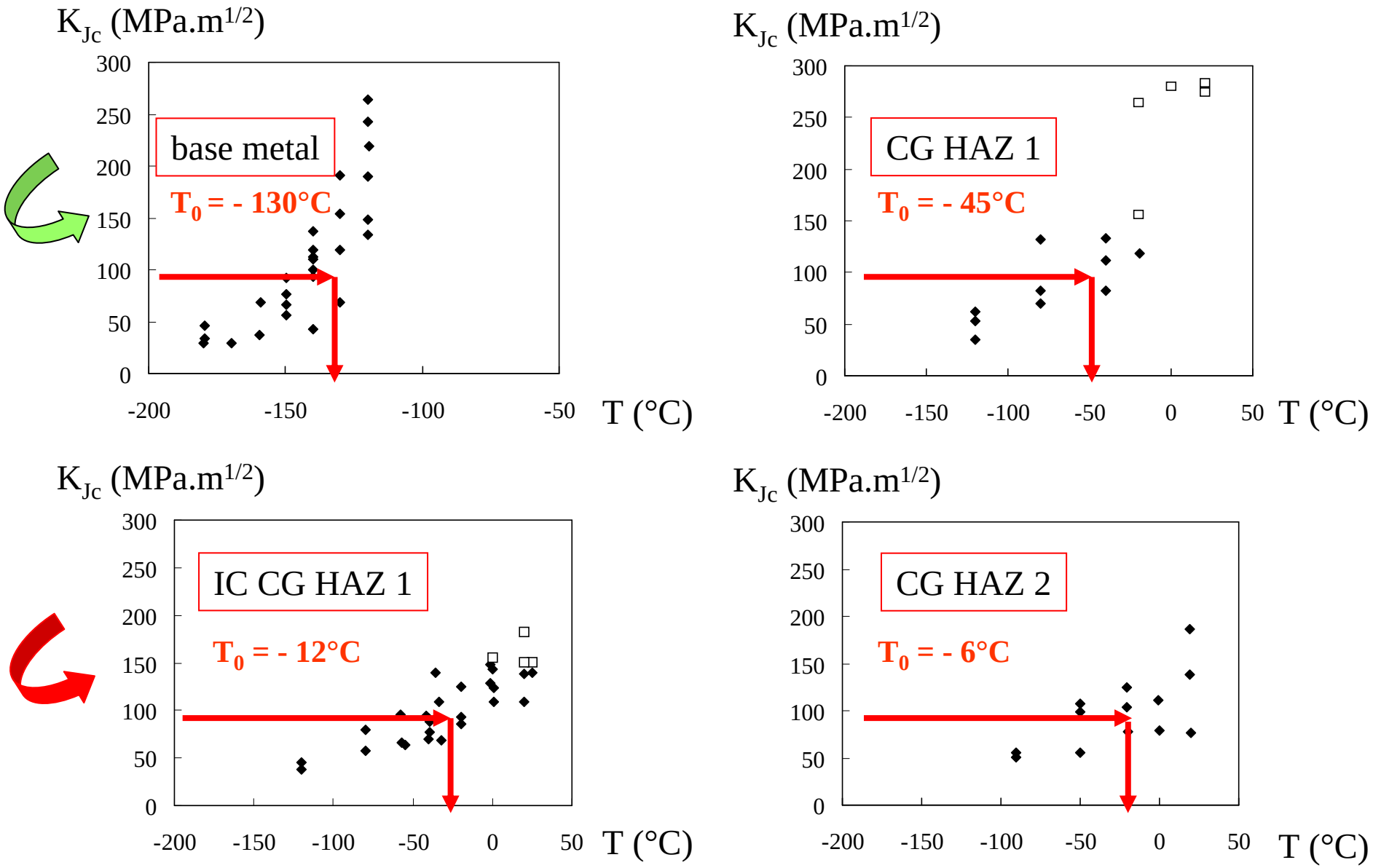






- ductile stable crack propagation over > 0.2 mm

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



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V. CONCLUSIONS

WEAKEST LINK THEORY. WEIBULL-BEREMIN MODEL

$$V_0 : p(l_0)dl_0 \rightarrow p(\sigma) = \int_{l_c}^{\infty} p(l_0)dl_0$$

$$\text{Griffith} \rightarrow l_c = \frac{\alpha}{\sigma^2}$$

$$V : P_R = 1 - \exp\left[-\int_{PZ} p(\sigma)\frac{dV}{V_0}\right]$$

Power Law

$$p(l_0) = \gamma / l_0^{\beta}$$

$$P_R = 1 - \exp\left[-\int_{PZ}\left(\frac{\sigma_1}{\sigma_u}\right)^m \frac{dV}{V_0}\right]$$

$$P_R = 1 - \exp\left[-\left(\frac{\sigma_w}{\sigma_u}\right)^m\right] \quad ; \quad \sigma_w = \left[\int_{PZ} \sigma_1^m \frac{dV}{V_0}\right]^{1/m}$$

$$m = 2\beta - 2$$

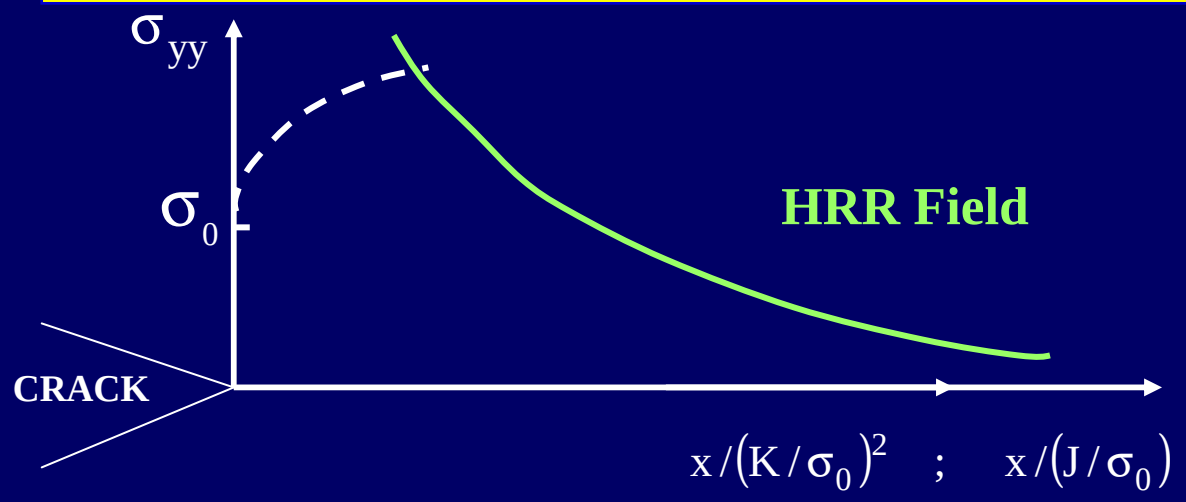
Exponential Law

$$p(\text{Size} > l) = \exp\left[-\left(\frac{l - l_u}{l_0}\right)^n\right]$$

$$P_R = 1 - \exp\left\{\int_{decoh} - \exp\left[-\left(\frac{1/\sigma_1^2 - 1/\sigma_u^2}{1/\sigma_0^2}\right)^n\right]\frac{dV}{V_0}\right\}$$

See also Kroon & Faleskog in Inter. Journal of Fract. Vol. 118, (2002), pp.99-118 & Eng. Fract. Mechanics, Vol. 71, (2004), pp. 57-79.

BEREMIN MODEL (83) (S.S.Y.)



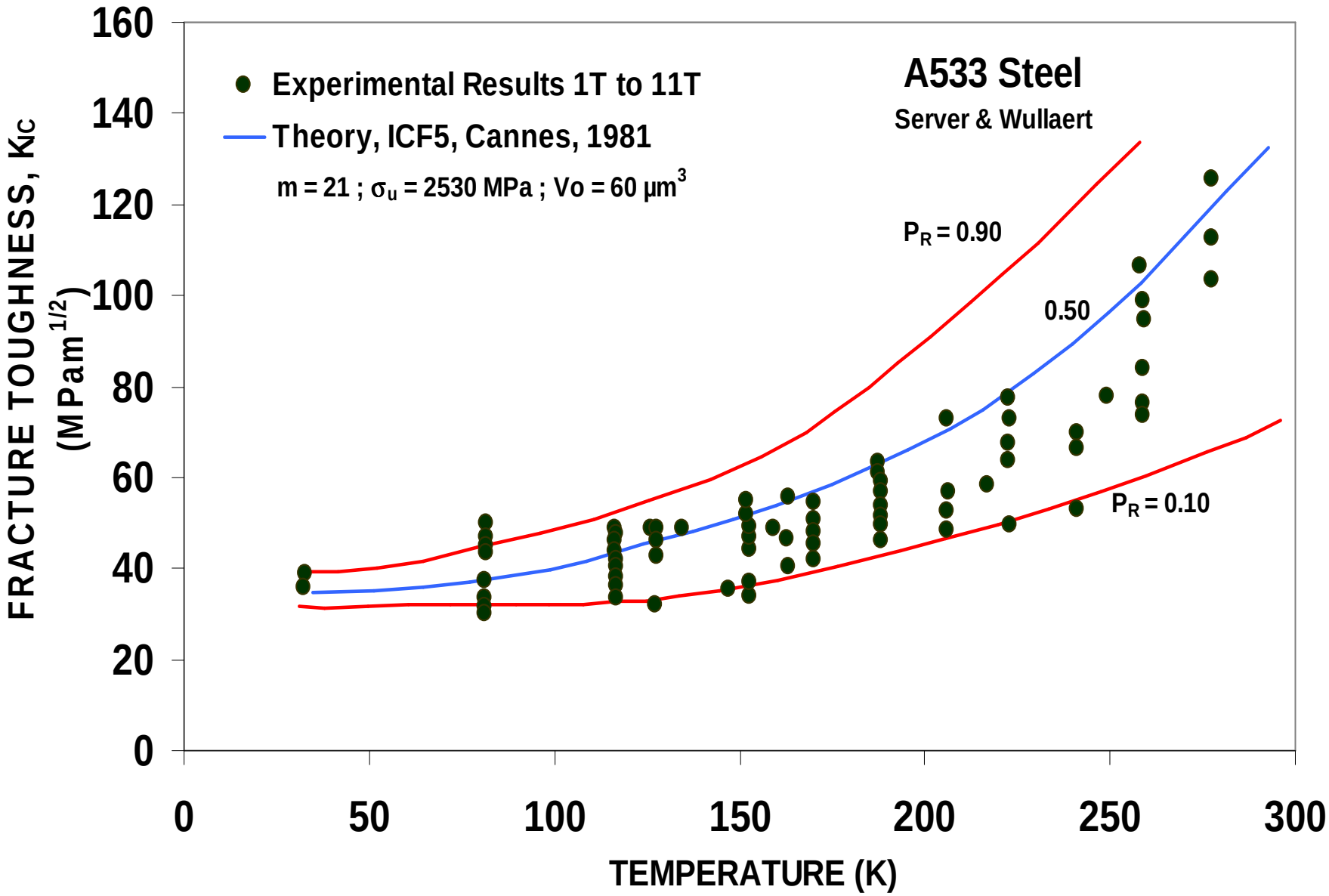
HRR $$\sigma_{YY} = \sigma_0 \, f\left(\frac{x}{(K/\sigma_0)^2}\right) = \sigma_0 \, g\left(\frac{x}{J/\sigma_0}\right)$$

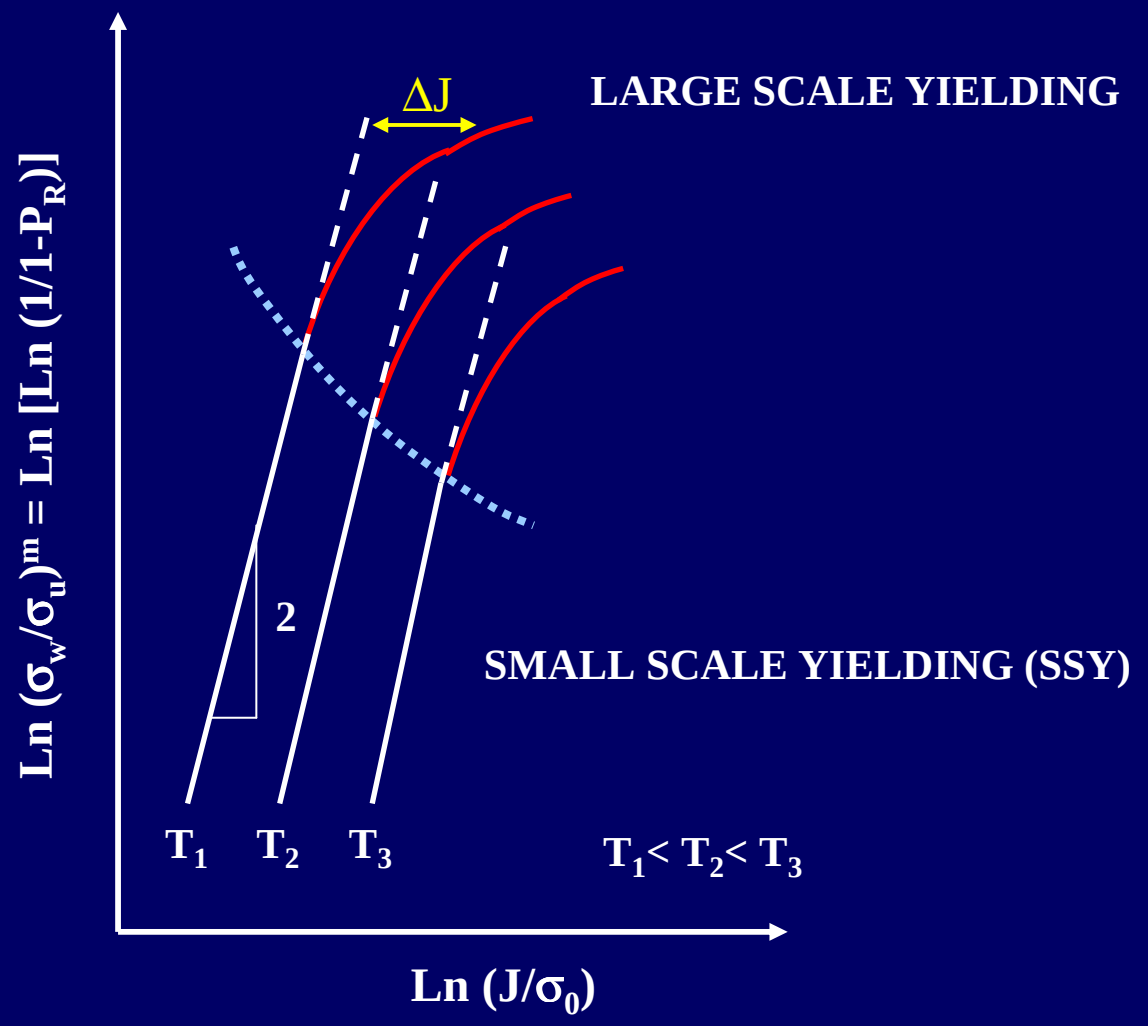
B : Specimen Thickness
C_m (n) : constant

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

$$J_{IC} = \frac{K_{IC}^2}{E}\left(1 - \nu^2\right)$$

$$P_R = 1 - \exp - \left\{ \frac{J_{IC}^2 \, E^2 \, \sigma_0^{m-4} \, B C_m}{\left(1-\nu^2\right)^2 V_0 \, \sigma_u^m} \right\}$$


A533 Steel
Server & Wullaert
Experimental Results 1T to 11T
Theory, ICF5, Cannes, 1981
m = 21 ; σu = 2530 MPa ; Vo = 60 µm3
PR = 0.90
0.50
PR = 0.10
FRACTURE TOUGHNESS, KIC (MPam1/2)
TEMPERATURE (K)
0
20
40
60
80
100
120
140
160
0
50
100
150
200
250
300


ΔJ
LARGE SCALE YIELDING
Ln (σw/σu)m = Ln [Ln (1/1-PR)]
2
SMALL SCALE YIELDING (SSY)
T1 T2 T3
T1< T2< T3
Ln (J/σ0)

BEREMIN MODEL & MASTER CURVE

BEREMIN MODEL

$$P_R = 1 - \exp\left[-\frac{K_{IC}^4\ B\ \sigma^{m-4}\ C_m}{V_u\ \sigma_u^m}\right]$$

MASTER CURVE

$$P_R = 1 - \exp\left[-\frac{B}{B_o}\left(\frac{K_{IC} - K_I\,\min}{K_o - K_I\,\min}\right)^4\right]$$

BOTH MODELS PREDICT THE SAME TEMPERATURE DEPENDENCE

– if $K_{IC}, K_{JC} >> K_I\,\min$

– when $K_{JC}(\text{medium})/(\sigma_o(T))^{1-m/4} = \text{Cst}$

– $K_I\,\min \approx 20\ \text{MPa}\sqrt{m}$

– $K_o \Rightarrow P_R = 0.63$

– $K_{JC}(\text{medium}) = 30 + 70\exp[0.019(T - T_o)]$

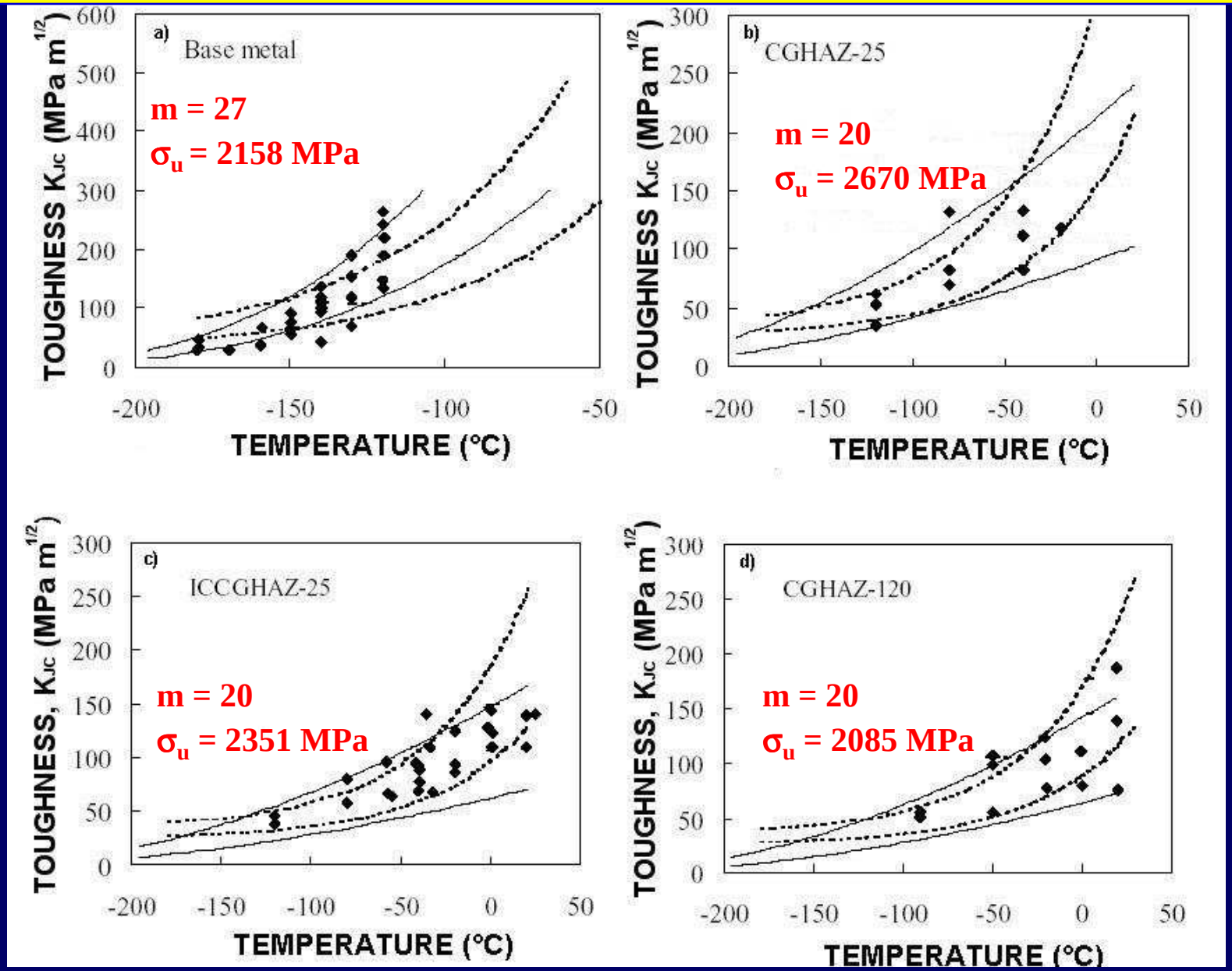
$(K \text{ in MPa}\sqrt{m};\ T \text{ in } °C)$

$T_o \rightarrow K_{JC}(\text{median}) = 100\ \text{MPa}\sqrt{m}$

for $B = 25$ mm

A. Lambert-Perlade, PhD Thesis, 2001

COMPARISON OF BEREMIN (——) & MASTER CURVE (····) (P_R = 0.10 - 0.90)



BEREMIN MODEL - LIMITATIONS

(1) • THRESHOLD WEIBULL STRESS ?

(2) • STRAIN and/or TEMPERATURE DEPENDENCE OF MODEL PARAMETERS $(m \text{ and } \sigma_u)$?

(3) • EXISTENCE OF DIFFERENT MICROSTRUCTURAL BARRIERS FOR A PROPAGATING CRACK $\Rightarrow$ MULTIPLE BARRIER MODELS

BRITTLE FRACTURE & BRITTLE to DUCTILE FRACTURE TRANSITION MICROMECHANISMS

André PINEAU
Centre des Matériaux - Ecole des Mines de Paris. ParisTech
UMR CNRS 7633
andre.pineau@ensmp.fr

I. INTRODUCTION : Various Scales / History of Fracture Mechaniscs

II. BRITTLE CLEAVAGE FRACTURE – THEORY
II.1. Main characteristics of Brittle Cleavage Fracture
II.2. Weibull – Beremin Theory
II.3. Multiple barrier models
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IV-1. Qualitative explanations for the existence of DBT
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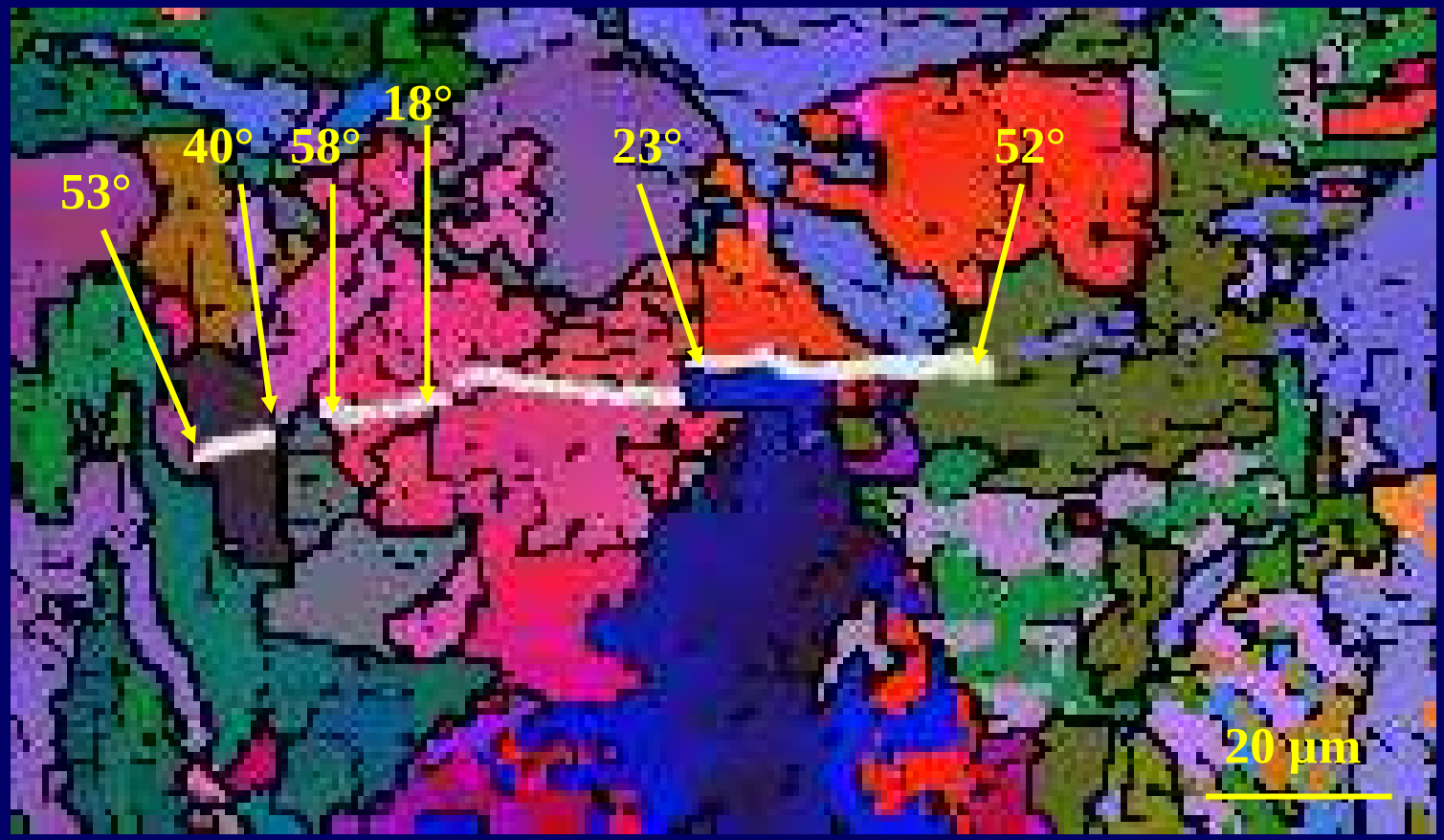
IV-3. Impact Charpy test

V. CONCLUSIONS

MULTIPLE BARRIER MODELS

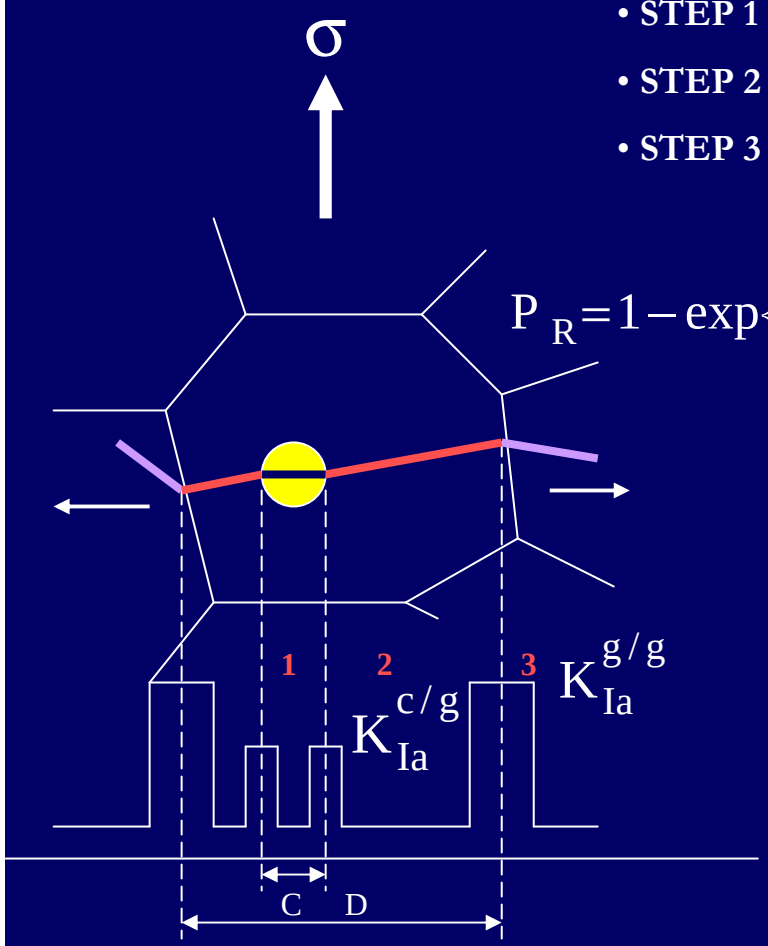


A. Lambert-Perlade & A.-F. Gourgues

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.**



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

F_g & F_c Determined by Metallography

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

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

Table 3. Parameters of Multiple Barriers Models.

Parameter	Present Study Value	Literature Data		
		Value	Microstructural Unit	Reference
σ_d (MPa)	2112	-	-	Lambert-Perlade *et al.*, (2004)
$K_{Ia}^{c/f}$ (MPa m$^{1/2}$)	7.8	2.5 to 5.0	Carbides	Martin-Meizoso *et al.*(1994)
		2.5	Globular carbides	Hahn (1984)
		1.8	TiN particles	Rodrigues-Ibabe (1998)
$K_{Ia}^{f/f}$ (MPa m$^{1/2}$)	CGHAZ-25	5.0 to 7.0	Bainite packets	Martin-Meizoso *et al.*(1994)
	28	7.0	Bainite packets	Martin-Meizoso *et al.*(1994)
		7.5	Ferrite grains	Hahn (1984)
	ICCGHAZ-25	4.8	Bainite packets	Rodrigues-Ibabe (1998)
	18	15.2	Bainite packets	Rodrigues-Ibabe (1998)

CRACKS AT GRAIN BOUNDARIES (1)

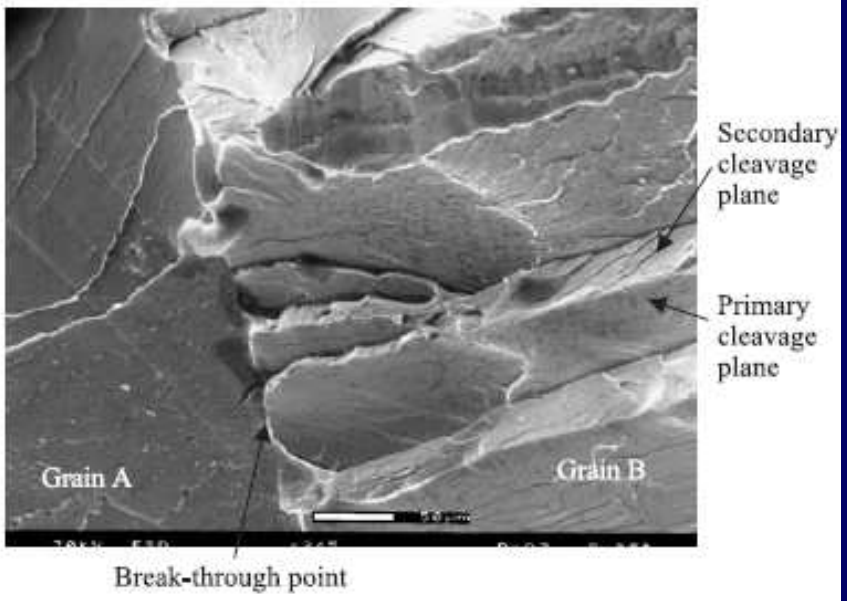


Fig. 1. SEM fractography of a high-angle grain boundary in a Fe–3%S bicrystal.

Qiao, Argon, Mat. Letters, vol.54, 2008, pp.3156-3160

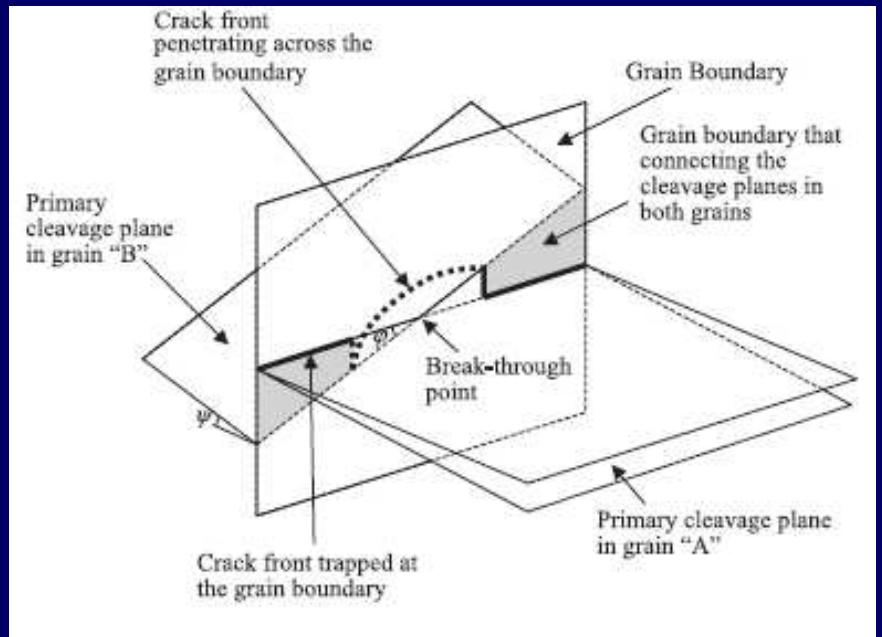
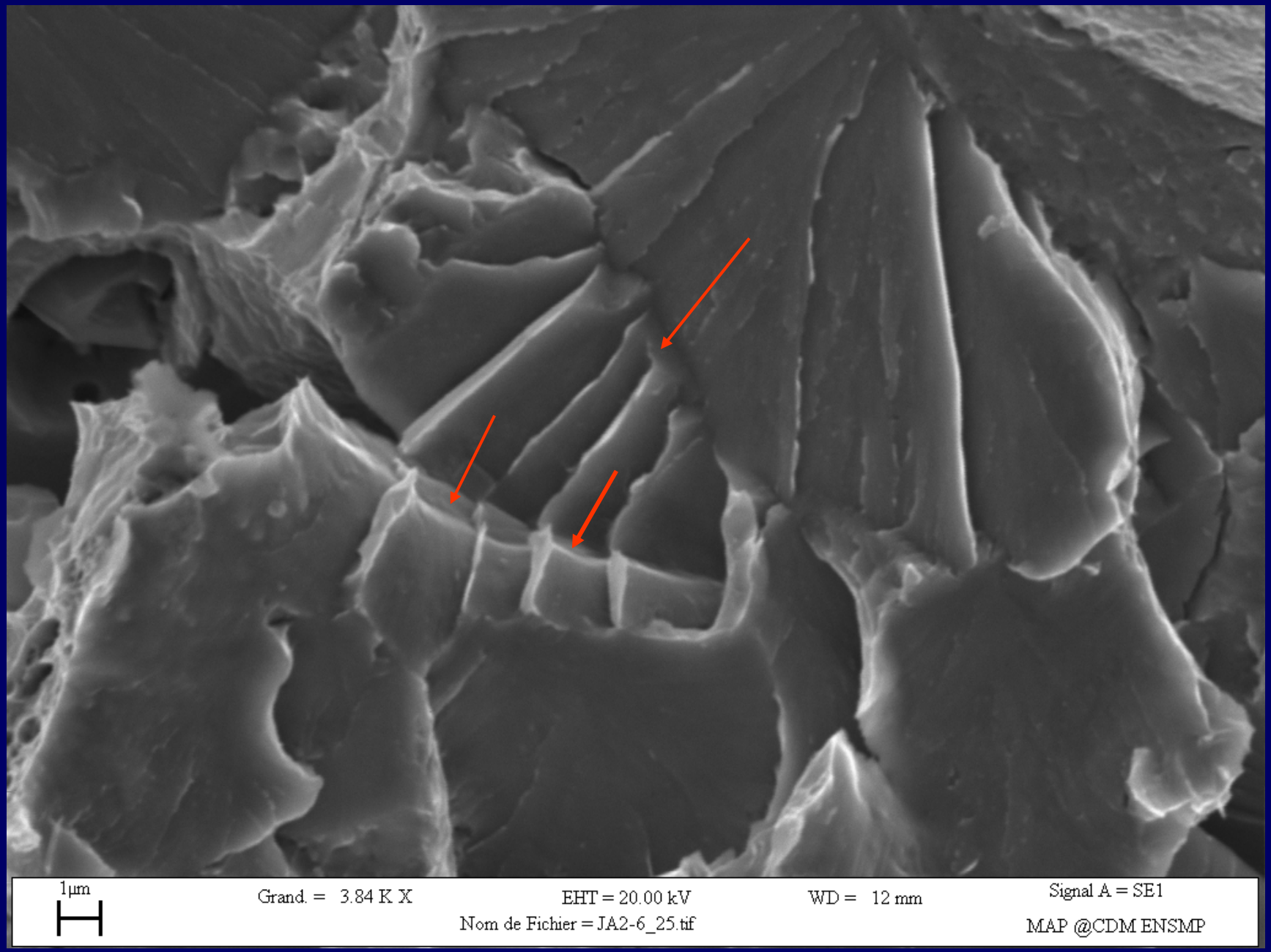
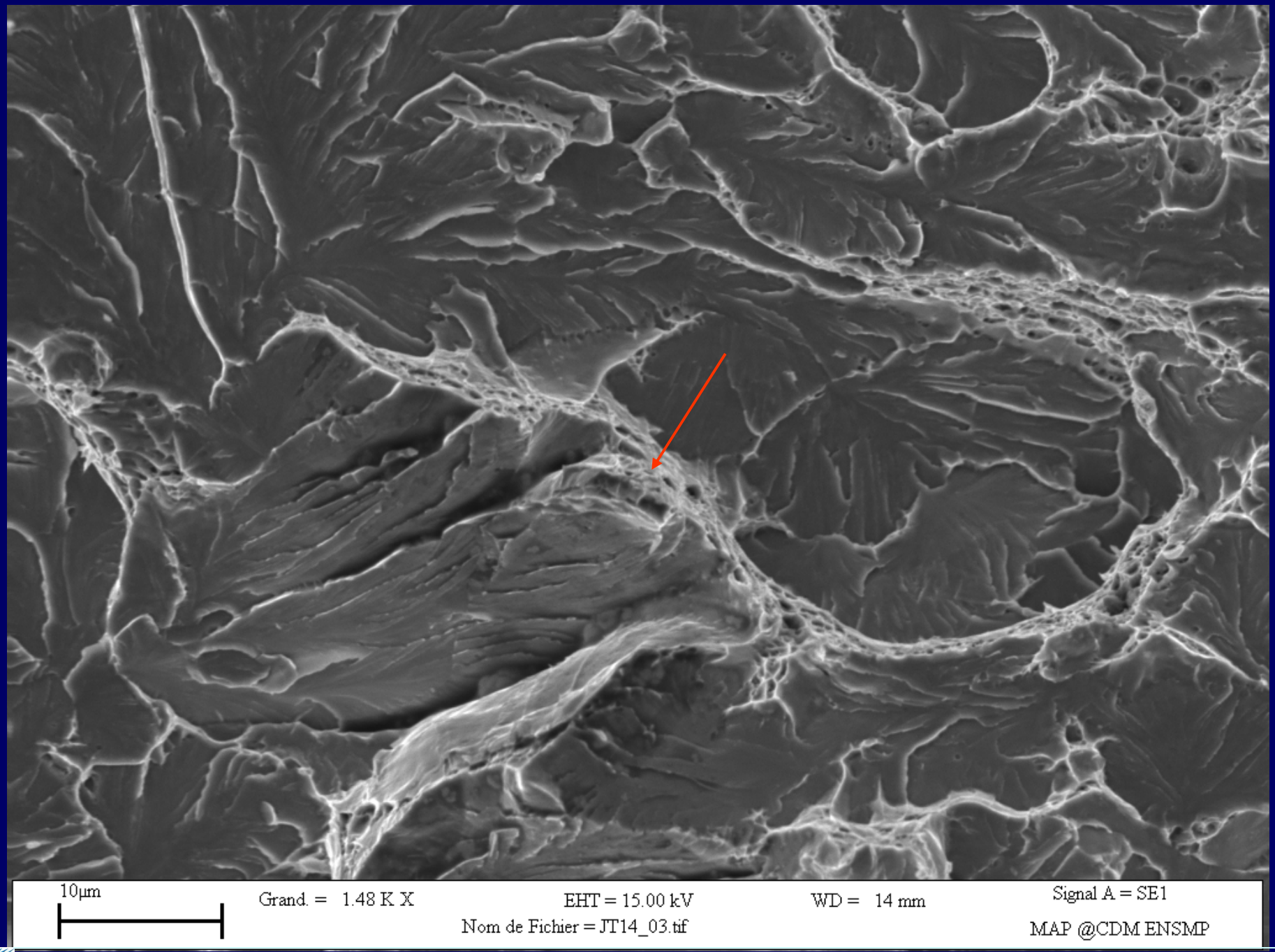


Fig. 2. A schematic diagram of the cleavage cracking across a high-angle grain boundary around a breakthrough point.

See also Qiao , Argon, Mech. Materials, vol.35, 2003, pp.129-154 and pp.313-331


1µm
Grand. = 3.84 K X
EHT = 20.00 kV
Nom de Fichier = JA2-6_25.tif
WD = 12 mm
Signal A = SE1
MAP @CDM ENSMP


10µm
Grand. = 1.48 K X
EHT = 15.00 kV
Nom de Fichier = JT14_03.tif
WD = 14 mm
Signal A = SE1
MAP @CDM ENSMP

CRACKS AT GRAIN BOUNDARIES (2)

Qiao, Argon, Mat. Letters, vol.54, 2008, pp.3156-3160

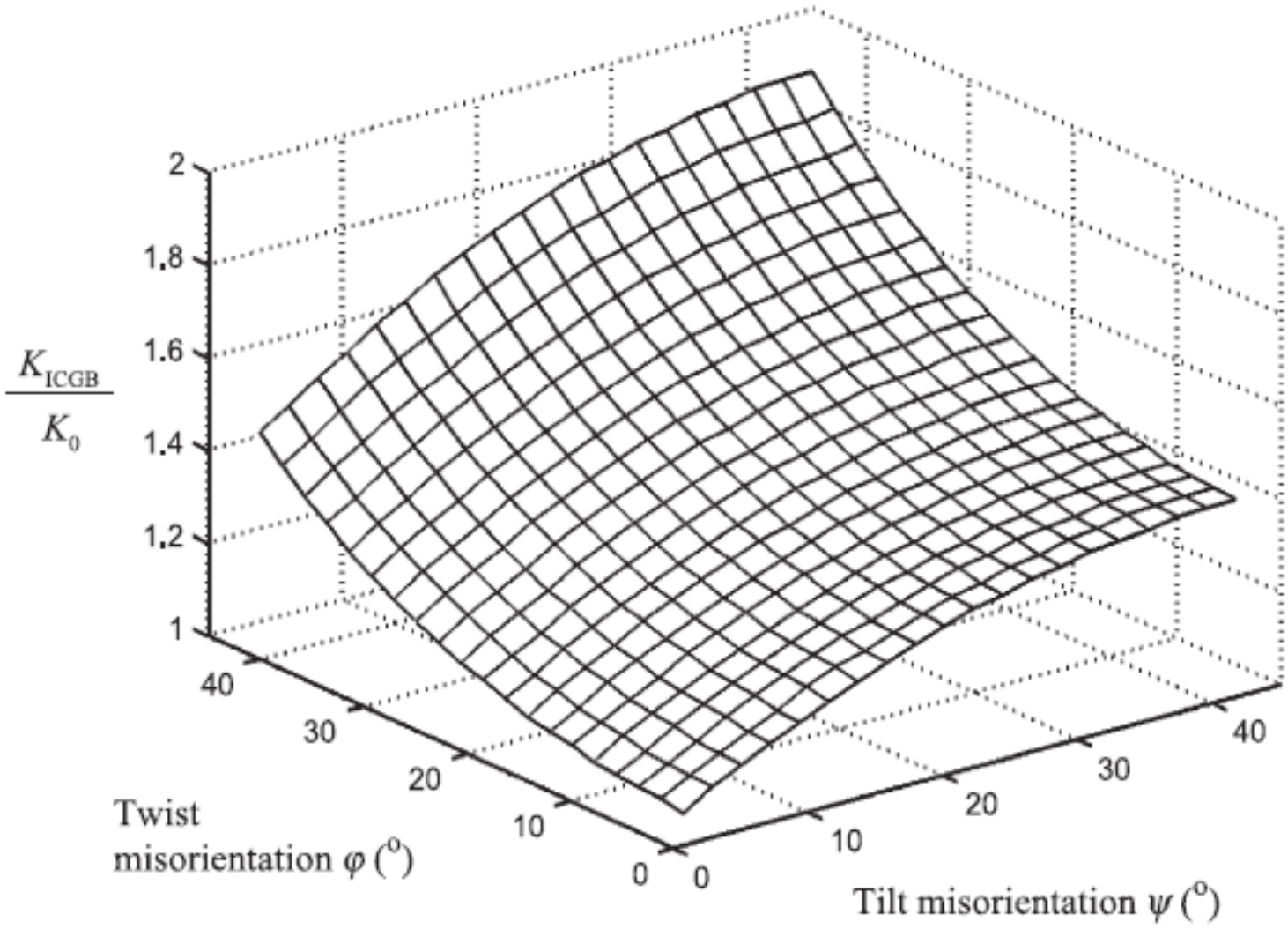


Fig. 6. The relationship between the grain boundary toughness and the crystal misorientation.

BRITTLE FRACTURE & BRITTLE to DUCTILE FRACTURE TRANSITION MICROMECHANISMS

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V. CONCLUSIONS

A SIMPLIFIED THEORY

BEREMIN MODEL (1983)

+

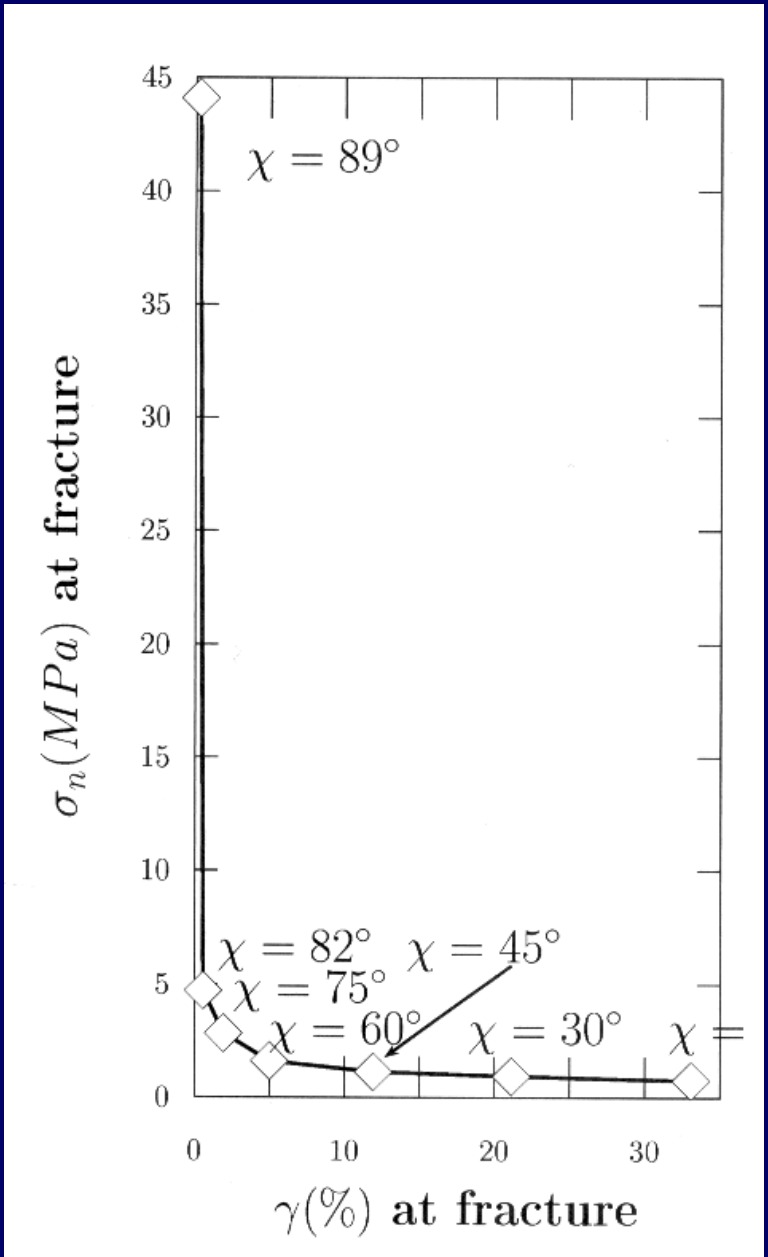
S. BORDET (2005)

Second Order Approximation

- The cleavage stress depends on plastic strain
- This dependence remains deterministic

J.-J.Gilman, (1958)

ZINC SINGLE CRYSTALS



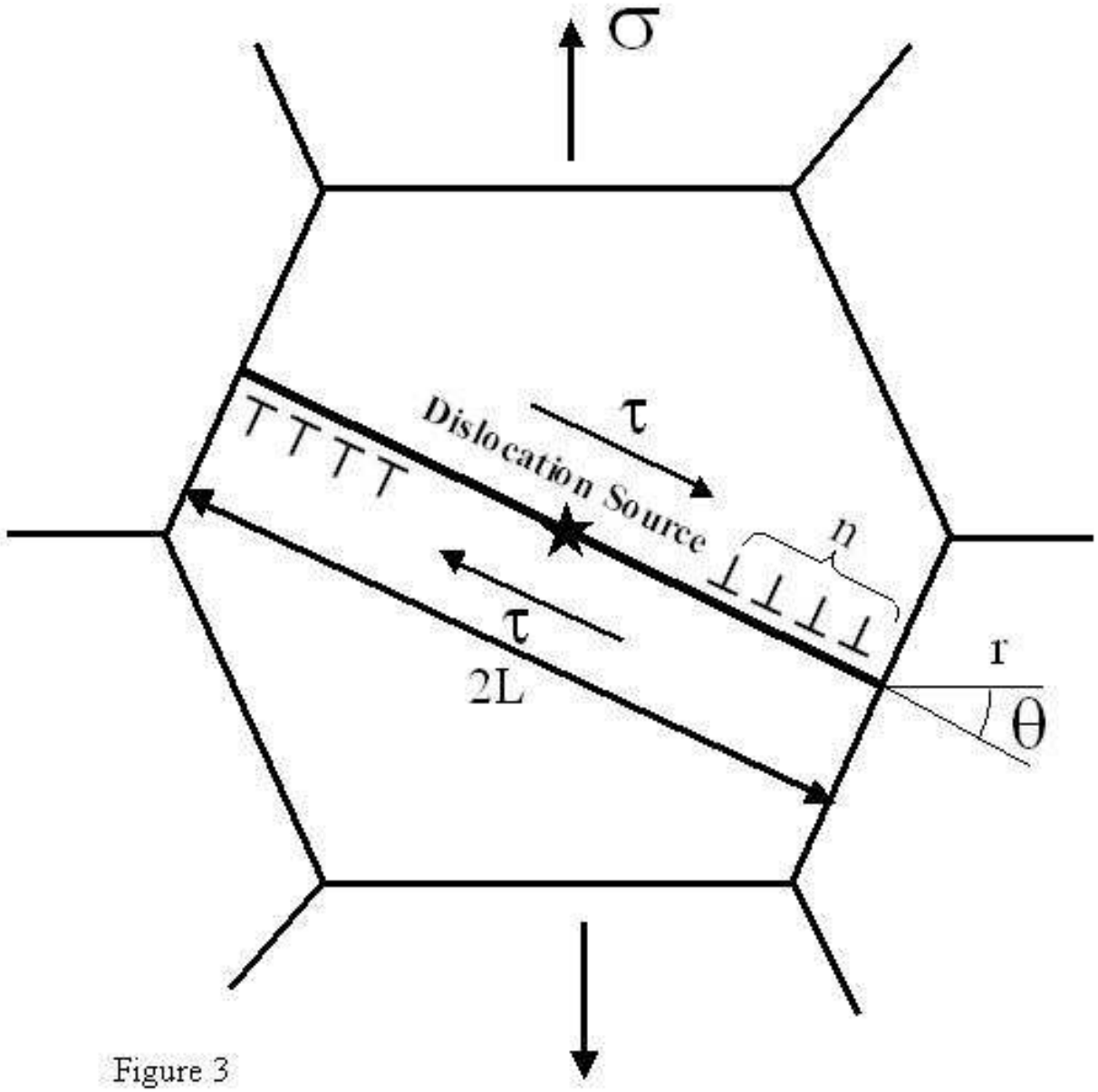
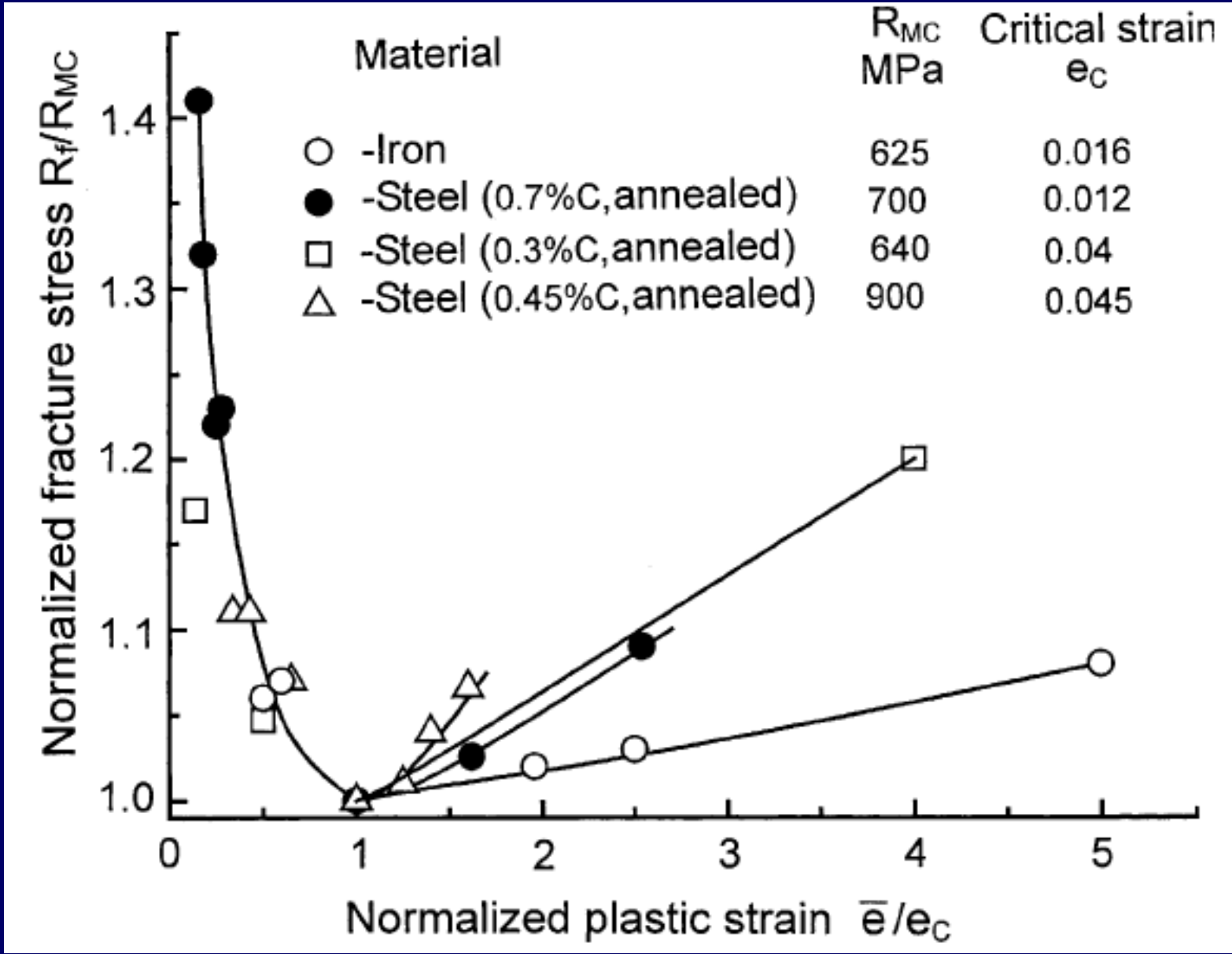


Figure 3

*S. Kotrechko, Theoretical & Applied Fracture Mechanics, **40,** (2003), 271-277*



EFFECT OF PLASTIC STRAIN

- Strong Effect in Zn single crystals
- **CLEAVAGE INITIATED FROM PARTICLES**

→ Nucleation TiN in IN718 (F. Alexandre, 2005)

$$P_{nucl} = 1 - \exp - \left[\frac{\sigma_1 + \lambda(\sigma_{eq} - \sigma_0)}{\sigma_{uN}} \right]^{Na} \quad \text{(Bere min, 1981)}$$

→ Bordet et al. (2005) (EFM, Part I, 435-452; Part II, 453-474)

$$P_{cleav}(t) = \int_0^t P_{prop}\, \delta P_{nucl}$$

$$\delta P_{nucl} = N_0 (1 - P_{nucl}) \sigma_0\, d\varepsilon_{eq} \Rightarrow P_{nucl} = 1 - \exp - \left[\frac{\sigma_0}{\sigma_{Y0}} \frac{\varepsilon_{eq}}{\varepsilon_{eq0}} \right]$$

$$P_R = 1 - \exp\left[- \int_{PZ} \int_0^t P_{prop}\, \delta N_{nucl}\, dV \right] = 1 - \exp\left[- \left(\frac{\sigma_w^*}{\sigma_u^*} \right)^m \right]$$

$$(\sigma_w^*)^m = \int_{PZ} \left[\int_0^{\varepsilon_{eq}} \frac{\sigma_0}{\sigma_{Y0}} (\sigma_1^m - \sigma_{th}^m)(1 - P_{nucl}(t)) \frac{d\varepsilon_{eq}}{\varepsilon_{eq0}} \right] \frac{dV}{V_u}$$

A SOPHISTICATED THEORY TO BE DEVELOPED !

Third Order Approximation

- The local stresses are no longer uniform

  - Random distribution due to elastic anisotropy *(S. Kotrechko + S. Pommier)*

  - Crystalline plasticity *(Ecole des Mines)*

- "Self organisation" of the local stresses :
  Arching type effect *(S. Pommier)*

INHOMOGENEITY IN LOCAL STRESS DISTRIBUTION (ELASTICITY)

- S. KOTRECHKO (Theoretical and Applied Fracture Mechanics, 47, (2007), 171-181)

$$D\sigma_{11} = D_I \Sigma_1^2 + D_{II}(\Sigma_2 + \Sigma_3)^2 + 2\left[\mu_I(\Sigma_1\Sigma_2 + \Sigma_1\Sigma_3) + \mu_{II}\Sigma_2\Sigma_3\right]$$

$$D\sigma_{22} = D_I \Sigma_2^2 + D_{II}(\Sigma_1 + \Sigma_3)^2 + 2\left[\mu_I(\Sigma_2\Sigma_1 + \Sigma_2\Sigma_3) + \mu_{II}\Sigma_1\Sigma_3\right]$$

$$D\sigma_{33} = D_I \Sigma_3^2 + D_{II}(\Sigma_1 + \Sigma_2)^2 + 2\left[\mu_I(\Sigma_3\Sigma_1 + \Sigma_3\Sigma_2) + \mu_{II}\Sigma_1\Sigma_2\right]$$

$D\sigma_{ii}$: Variance of the local stresses

$D_I, D_{II}, \mu_I, \mu_{II}$: coefficients functions of the elastic anisotropy

Ex : Fe (Random distribution of grains)

$D_I = 1.7\,x10^{-2}$; $\mu_I = 0.72\,x10^{-2}$; $D_{II} = \mu_{II} = 0.66\,x10^{-2}$

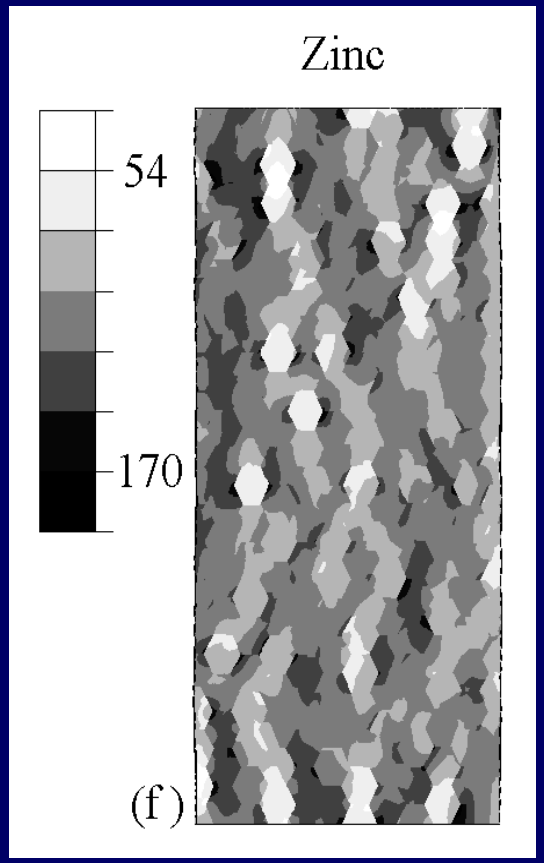
Uniaxial Tension for 3 St. dev. $\sigma_{11}[0.60\,\Sigma_1 - 1.40\,\Sigma_1]$

σ_{22} and $\sigma_{33}[-0.24\,\Sigma_1 - 0.24\,\Sigma_1]$

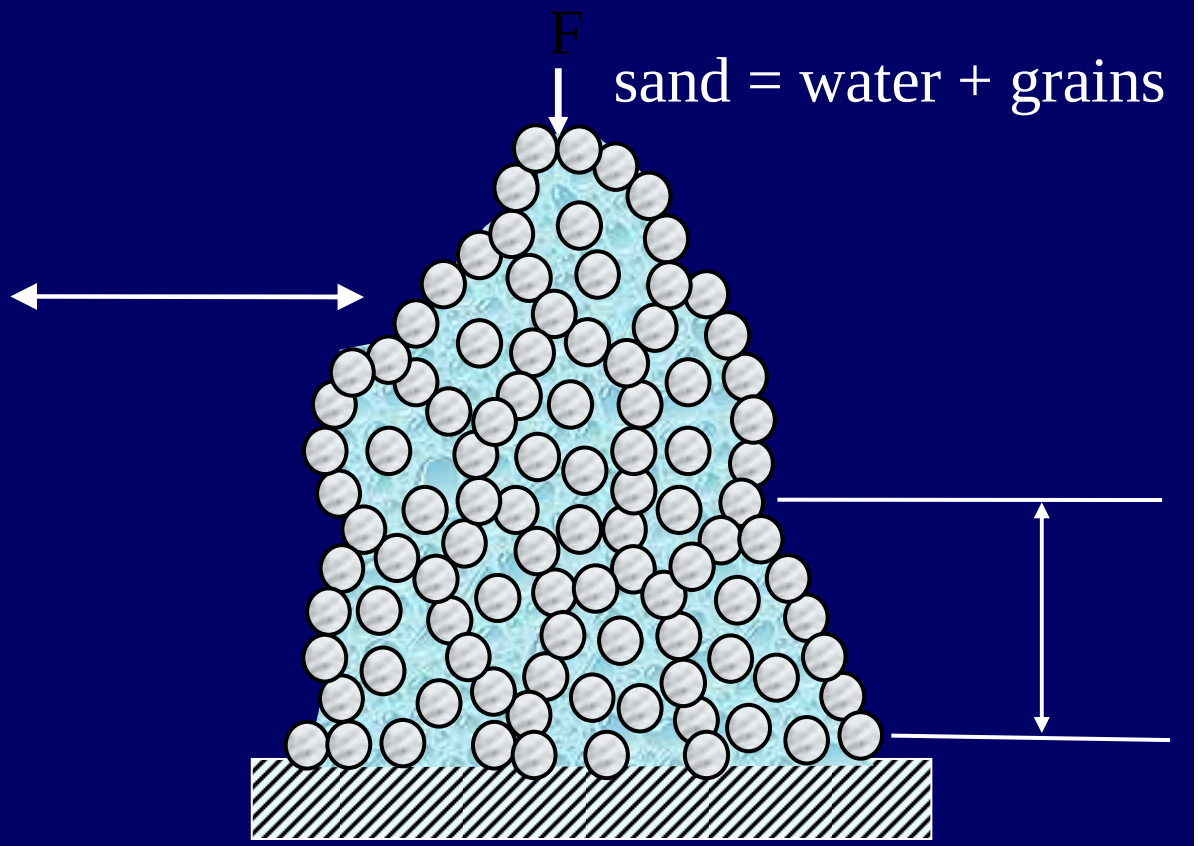
- *See also : S. POMMIER (Fatigue & Fracture of Engineering Materials & Structures, **25**, (2002), 331-348.*

*S. Pommier, FFEMS, (2002), **25**, 331*

Analogy with Granular Materials [Dantu, Radjai, Roux, Evesque …]



Distribution of maximum principal stress (FEM)

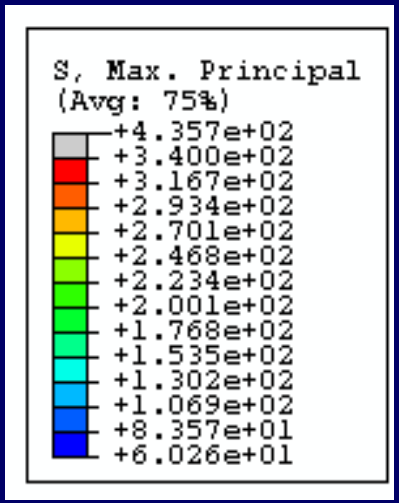


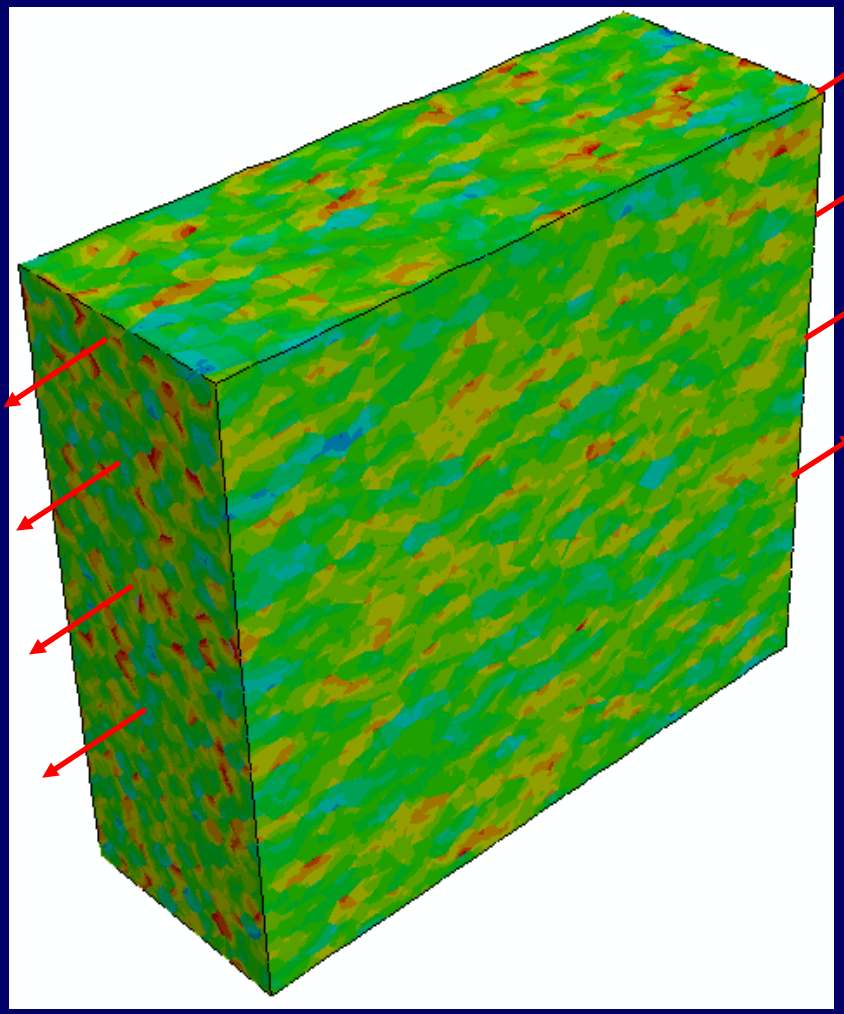
Characteristic length > grain = arch dimension

LOCAL STRESS HETEROGENEITY : 3D

S. Pommier

Tensile loading





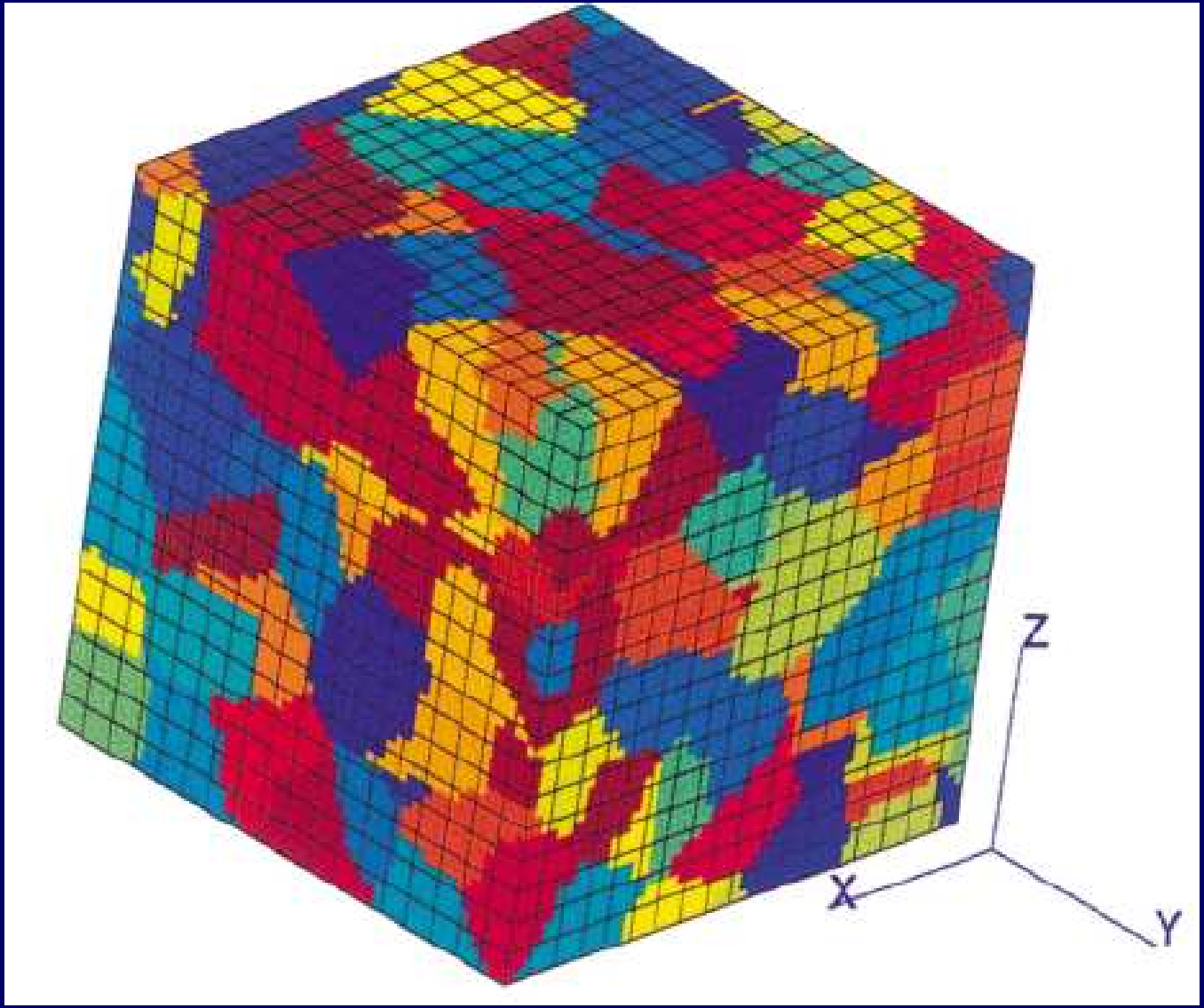
Copper

Max. principal stress

*S. Pommier (FFEMS, **25**, (2002, 331-348)*

Distribution calculated from the results of 70 calculations	Zirconium	Titanium	Zinc	Copper	Iron	Aluminum
Minimum value (MPa) Maximum value (MPa) Mean value (MPa)	926 1046 976	1058 1225 1141	792 1269 1036	679 1283 1018	1379 2107 1799	640 726 681
Standard Deviation (MPa)	27	35	123	121	144	16
3 times the standard deviation in percentage of the mean value	**8.5%**	**9.25%**	**35%**	**35%**	**24%**	**7%**

*F. Barbe, S. Forest, G. Cailletaud, Int. J. Plasticity, **17**, (2001), 537-563*



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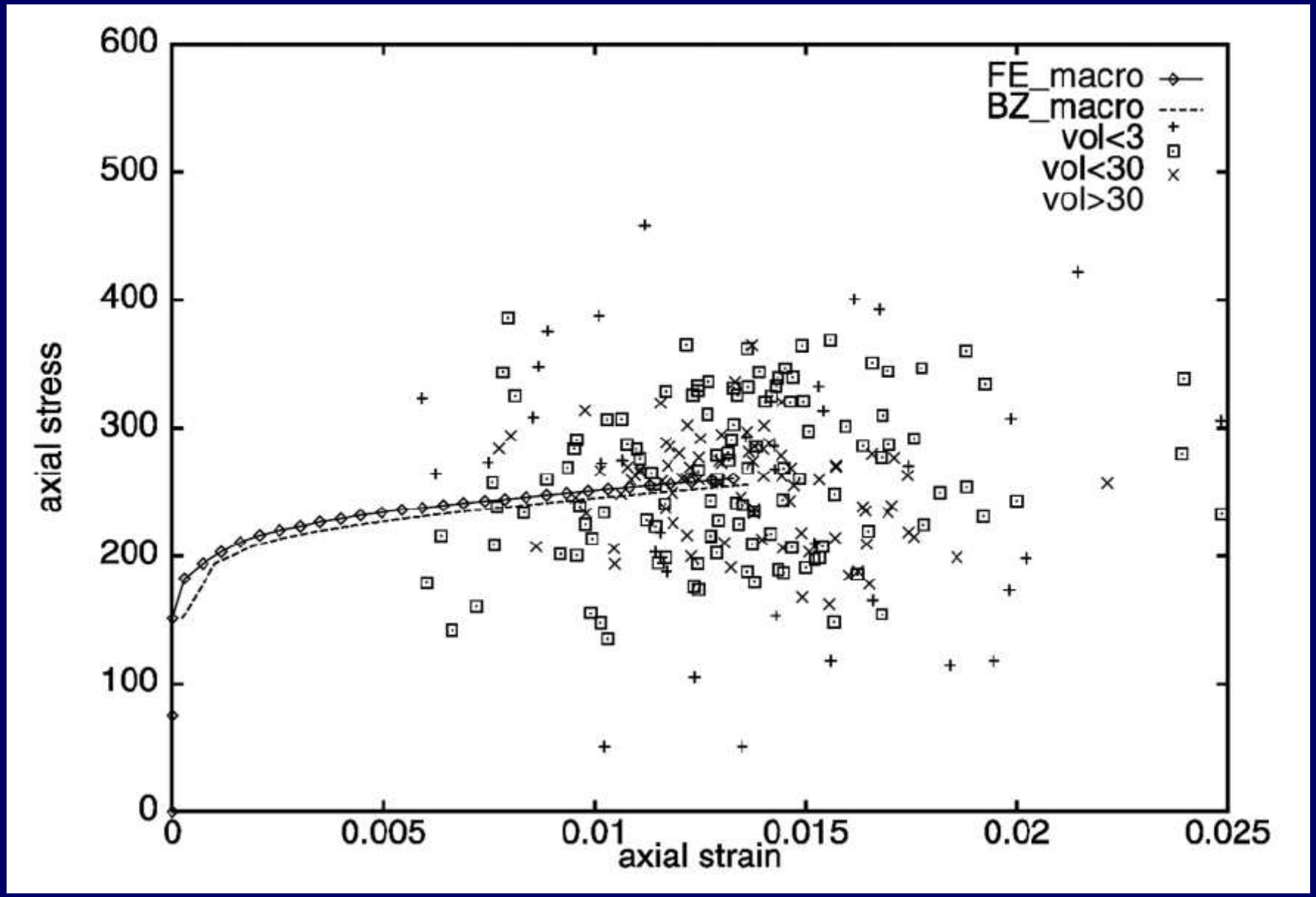
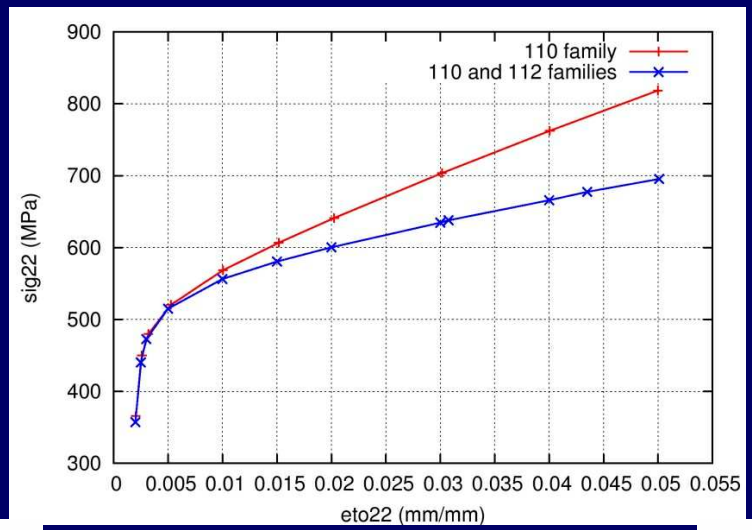


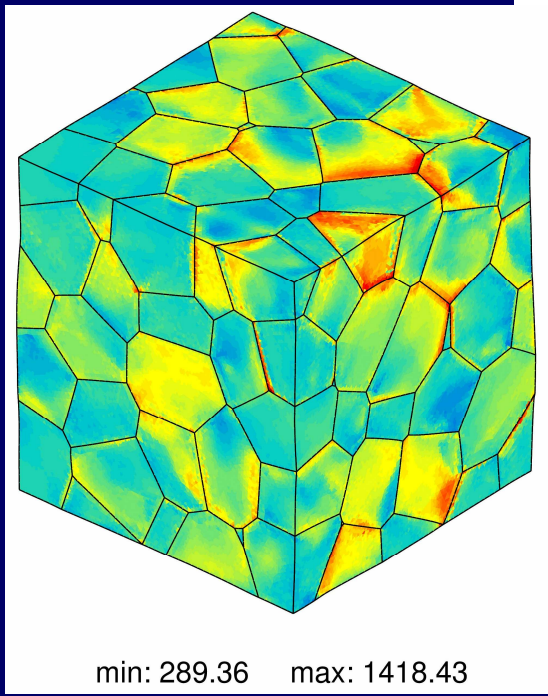
BAINITIC STEEL

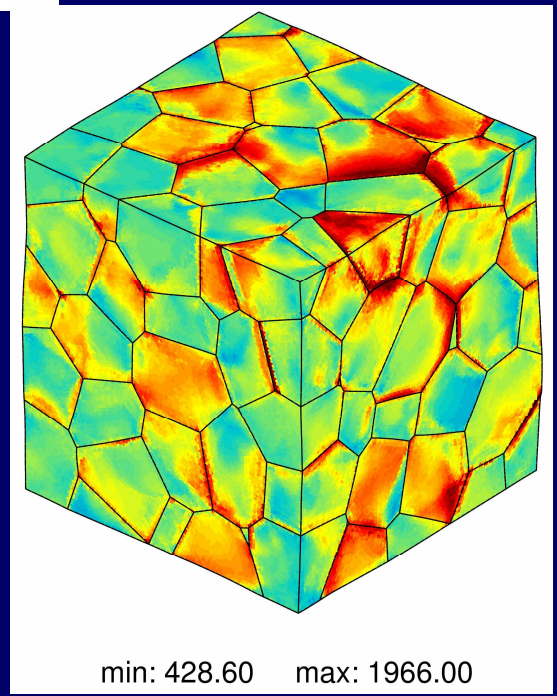


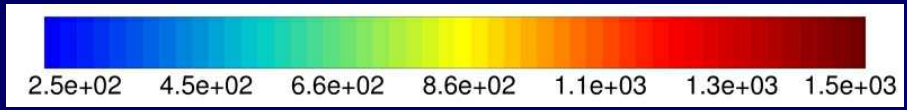
N. Osipov

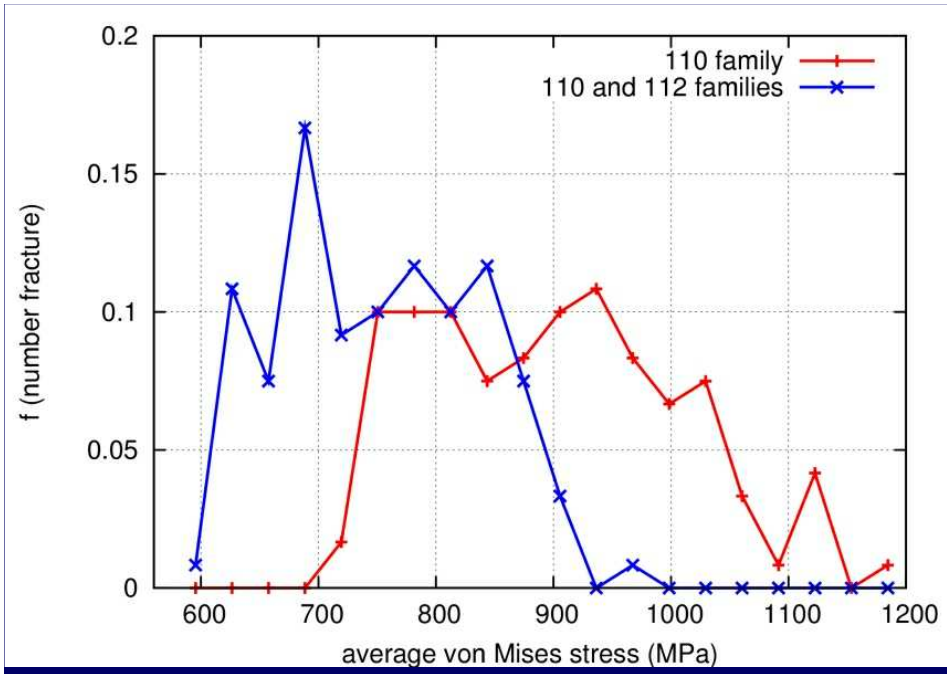
G. Cailletaud

A.F. Gourgues







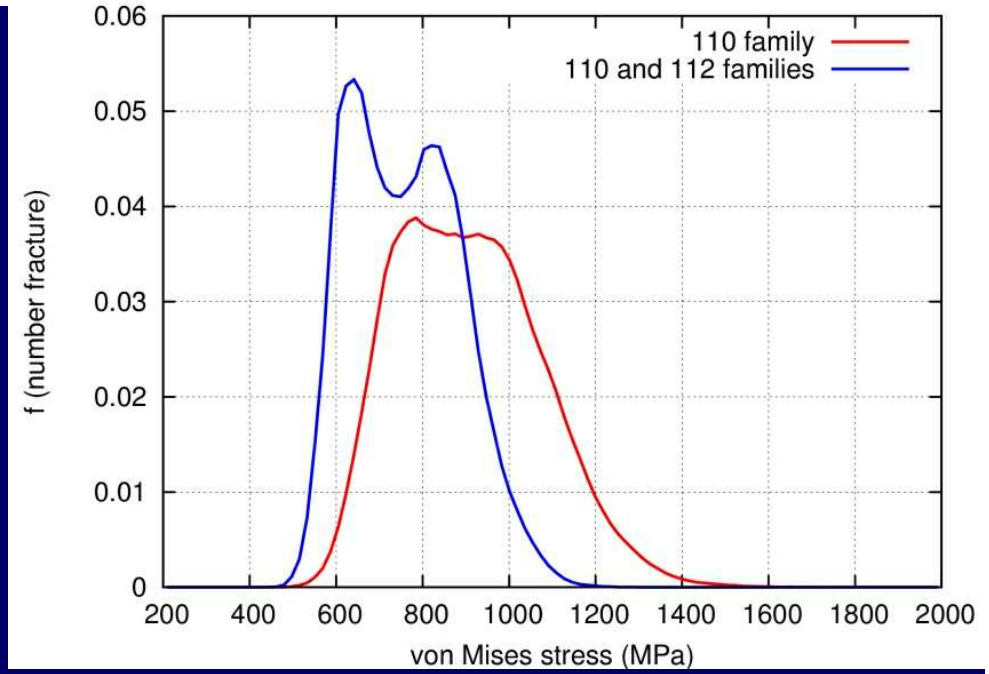


BAINITIC STEEL

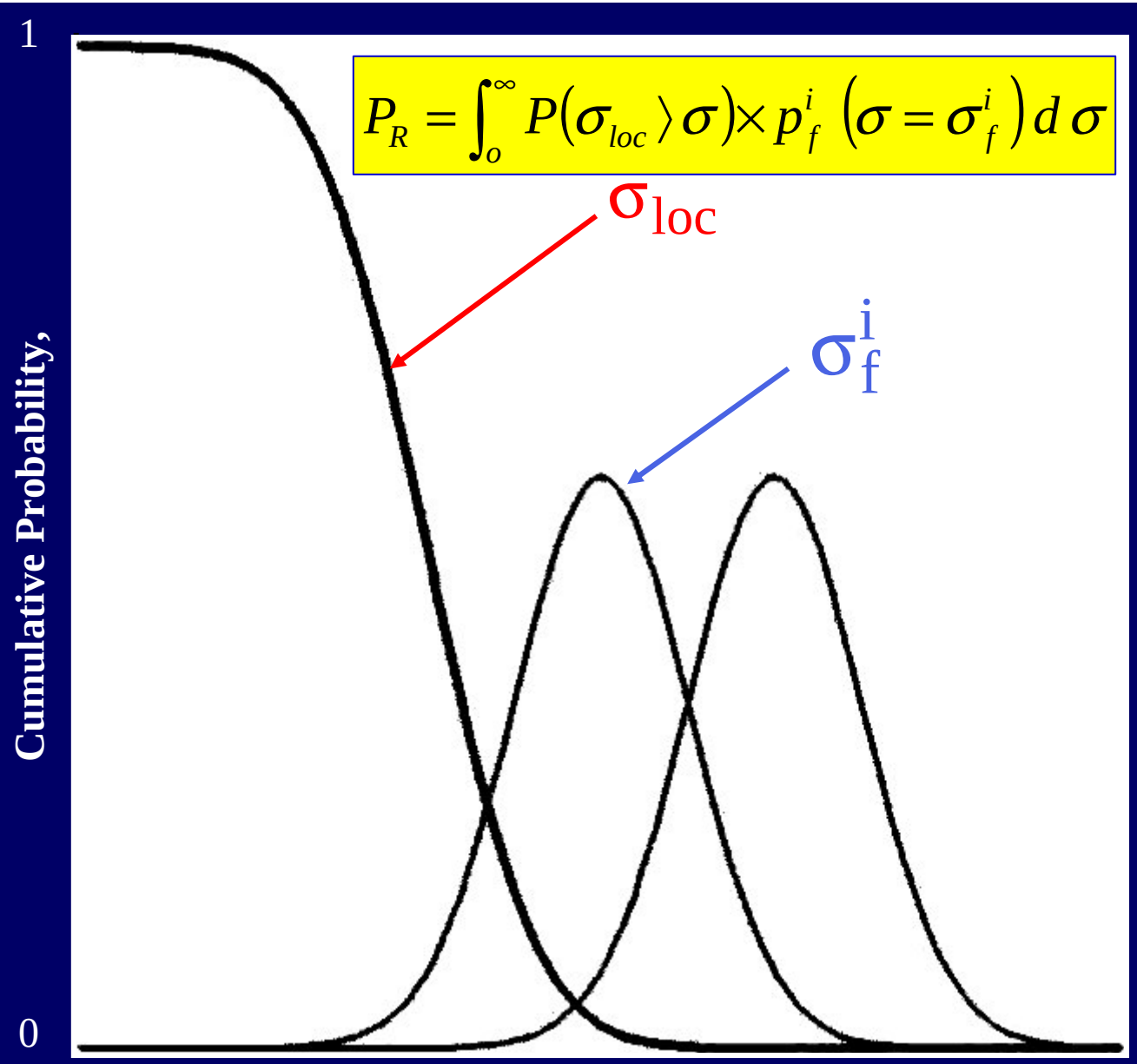
N. Osipov

G. Cailletaud

A.F. Gourgues



$$P_R = \int_o^{\infty} P(\sigma_{loc} \rangle \sigma) \times p_f^i \left(\sigma = \sigma_f^i\right) d\sigma$$



N. Osipov

G. Cailletaud

A.F. Gourgues

STATISTICAL ASPECTS OF CLEAVAGE FRACTURE - CONCLUSIONS

- Various sources of scatter for cleavage fracture
- This scatter has strong practical implications. Threshold stress ? Size effect
- Modelling. Three approximations :

  - Engineering purposes. 1st Order Approximation will remain largely used

    However attempts made to consider that in the master curve approach,
    T_0 is statistically distributed

  - Most urgent problem : Strain and Temperature dependence of σ_u

- Many metallurgical means to develop microstructure with improved fracture toughness

→ A 508 steel / 2 1/4 - 1 Mo steel

BRITTLE FRACTURE & BRITTLE to DUCTILE FRACTURE TRANSITION MICROMECHANISMS

André PINEAU
Centre des Matériaux - Ecole des Mines de Paris. ParisTech
UMR CNRS 7633
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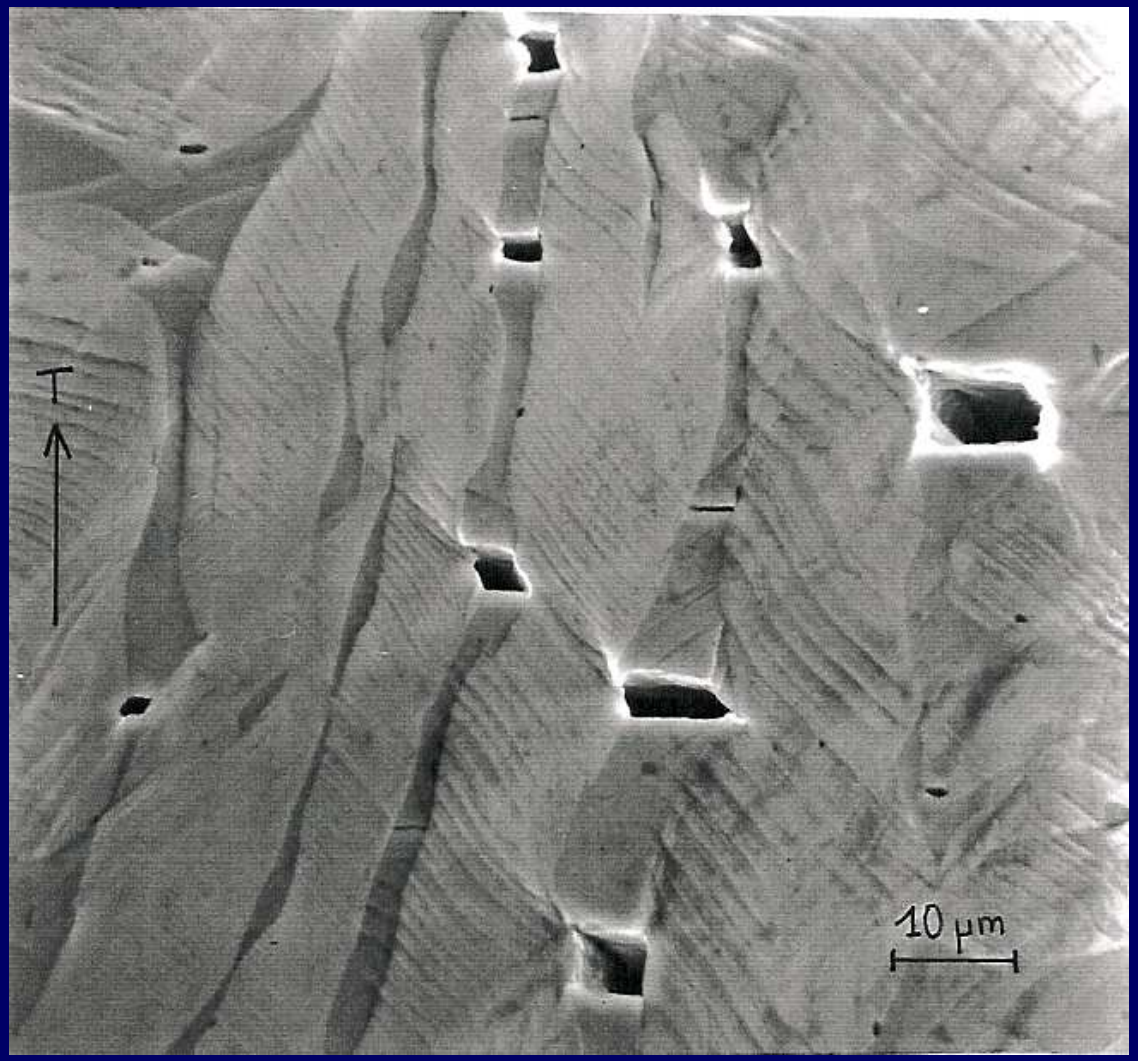
DUCTILE FRACTURE MICROMECHANISMS

DUPLEX STAINLESS STEEL

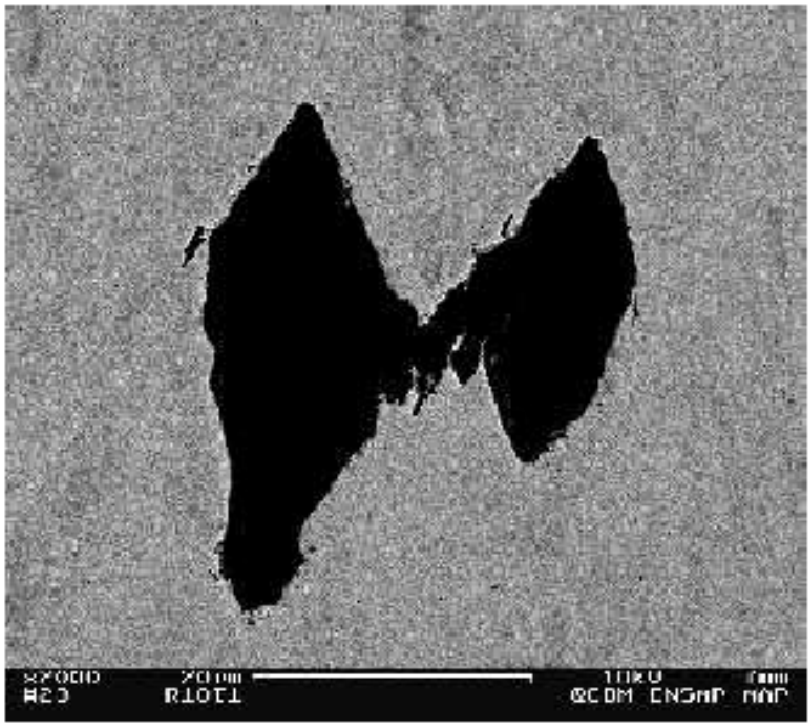
L. Devillers-Guerville, 1998

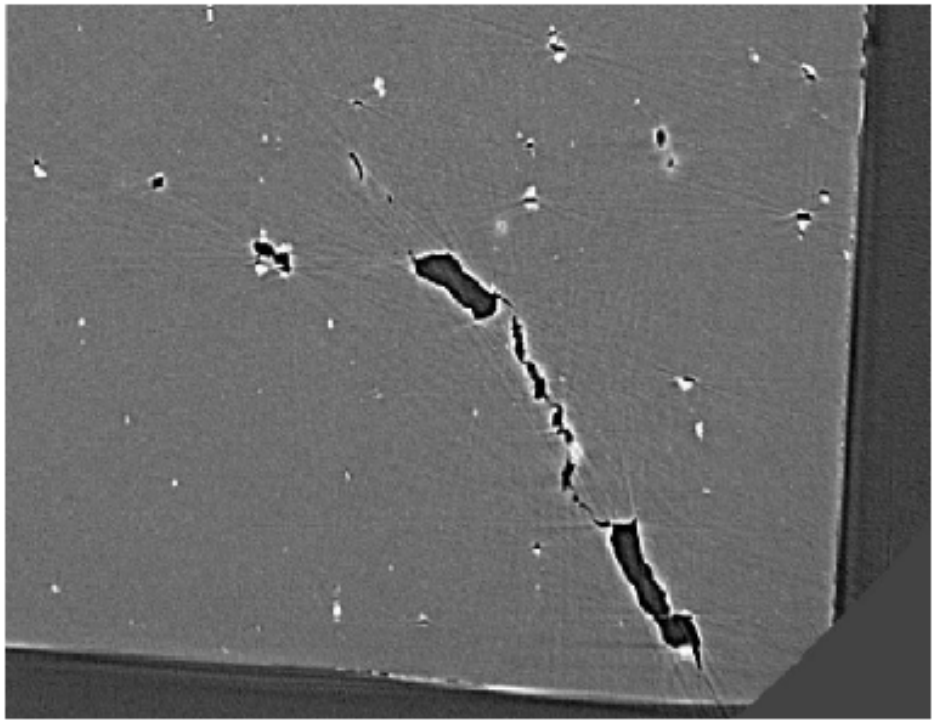
Cavity nucleation & growth from embrittled ferrite



DUCTILE FRACTURE MICROMECHANISMS

CAVITY COALESCENCE





Steel C-Mn

Aluminium 6156

GTN Model (Growth)

- Isotropic hardening $\sigma_y(p)$ + Elasticity

- Comparison with calculations on elementary cells (cavity + matrix)

See Koplik & Needleman, 1988

- "New" Yield Surface $\boxed{\phi = \frac{\sigma_{eq}^2}{\sigma_y^2} + 2\, q_1 f \cosh\left(\frac{q_2}{2}\frac{\sigma_{kk}}{\sigma_y}\right) - 1 - q_1^2 f^2}$

Most often : $q_1 = 3/2,\ q_2 = 1$

But new calculations *(Faleskog et al., 1998)* showed that q_1 and q_2 depend on σ_y / E and work hardening exponent, n

GTN Model (Cavity Nucleation)

$$\dot{f} = (1-f)\,\mathrm{tr}\,\dot{\varepsilon}_p + A_n \dot{p}$$

Growth Nucleation

- Phenomelogical Approach
  - Fitting of A_n on macroscopic tests
  - *See e.g. (Chu & Needleman, 1980)*

$$A_n = \frac{f_n}{\sqrt{2\pi}\ s_n} \exp\left(-\frac{(p-\varepsilon_n)^2}{2\ s_n^2}\right)$$

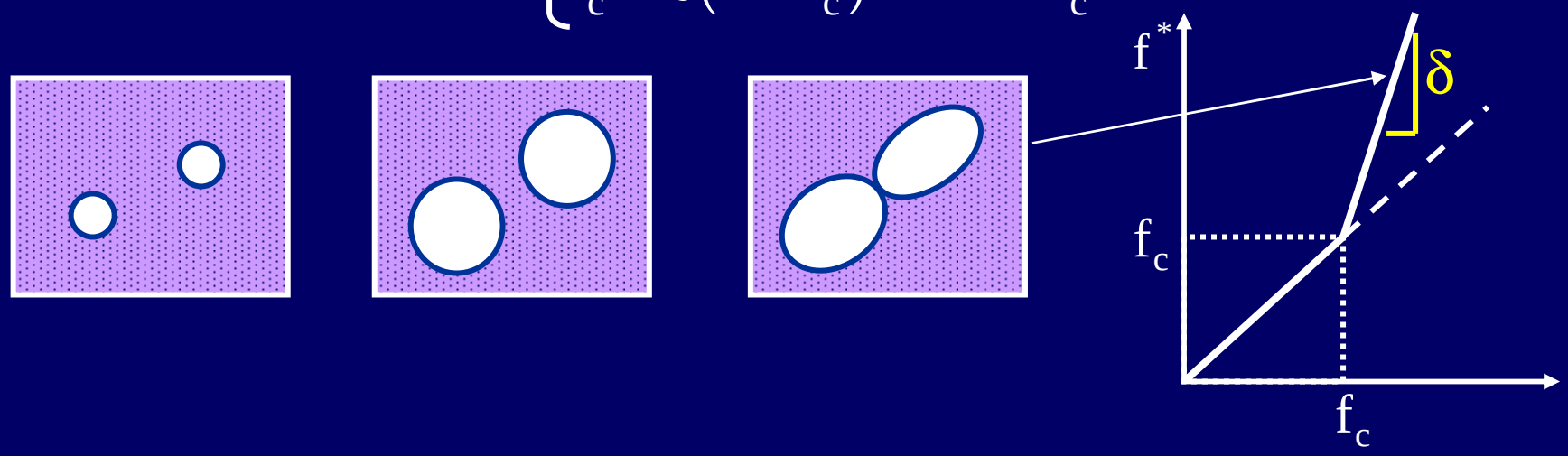
- Experimental Approach
  - *See e.g. Duplex Stainless Steels (Devillers-Guerville et al., 1997)*

GTN Model (Coalescence)

Definition of an effective cavity volume fraction, f^*

$$\phi = \frac{\sigma_{eq}^2}{\sigma_y^2} + 2 q_1 f^* \cosh\left(\frac{q_2}{2}\frac{\sigma_{kk}}{\sigma_y}\right) - 1 - q_1^2 f^{*2} = 0$$

where $f^* = \begin{cases} f & \text{if } f < f_c \\ f_c + \delta(f - f_c) & \text{if } f > f_c \end{cases}$



Not necessary to introduce δ accelerating factor, when statistical cavity distribution is taken into account *(Devillers-Guerville et al., 1997; Decamp et al., 1997)*

GTN MODEL - EXTENSIONS

- Plastic Anisotropy (Bron - Besson, 2004)
- Cavity Shape (Gologanu - Leblond, 1993, 1997)

COALESCENCE THOMASON MODEL

- Thomason, (1985, 1990)
- Pardoen and Hutchinson (2000)
- Benzerga (2000)

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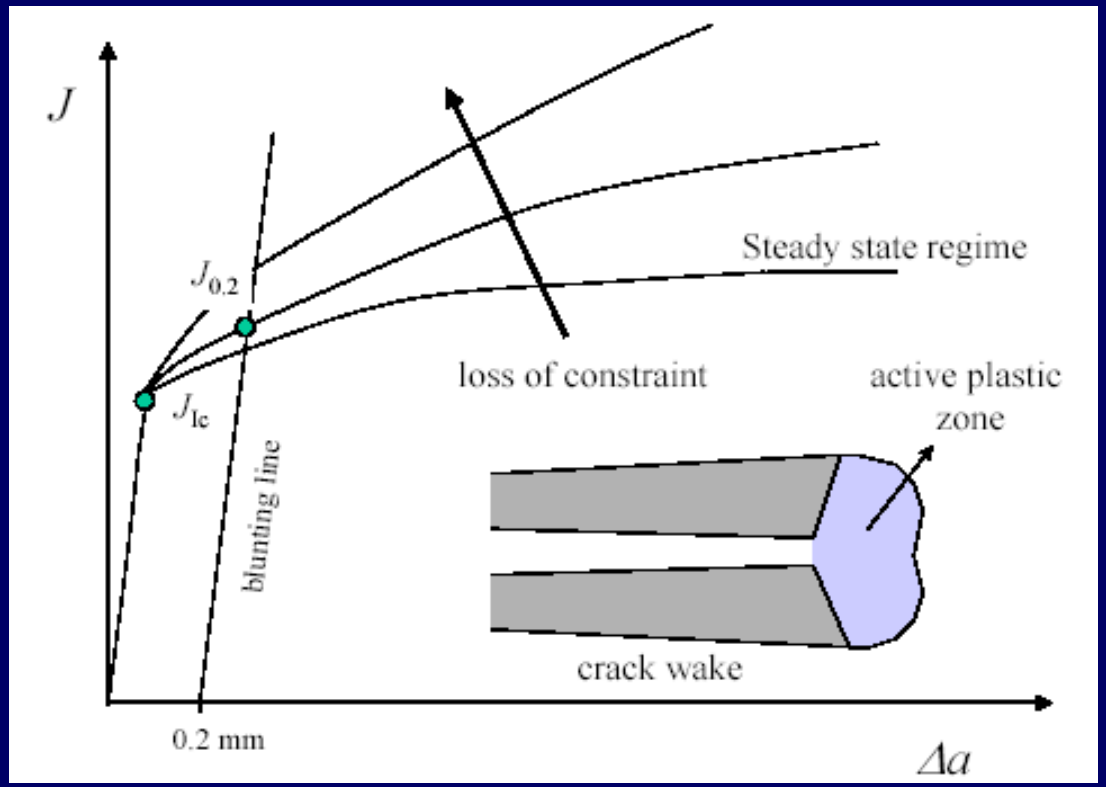
COMPUTATIONAL STRATEGIES TO SIMULATE DUCTILE CRACK GROWTH

STRATEGY 1

- Use of the void Nucleation, Growth and Coalescence laws
- Integrate them using solutions of elastoplastic crack problems
- Neglect coupling effects between mechanical fields and Damage

See e.g. d'Escatha and Devaux, 1979

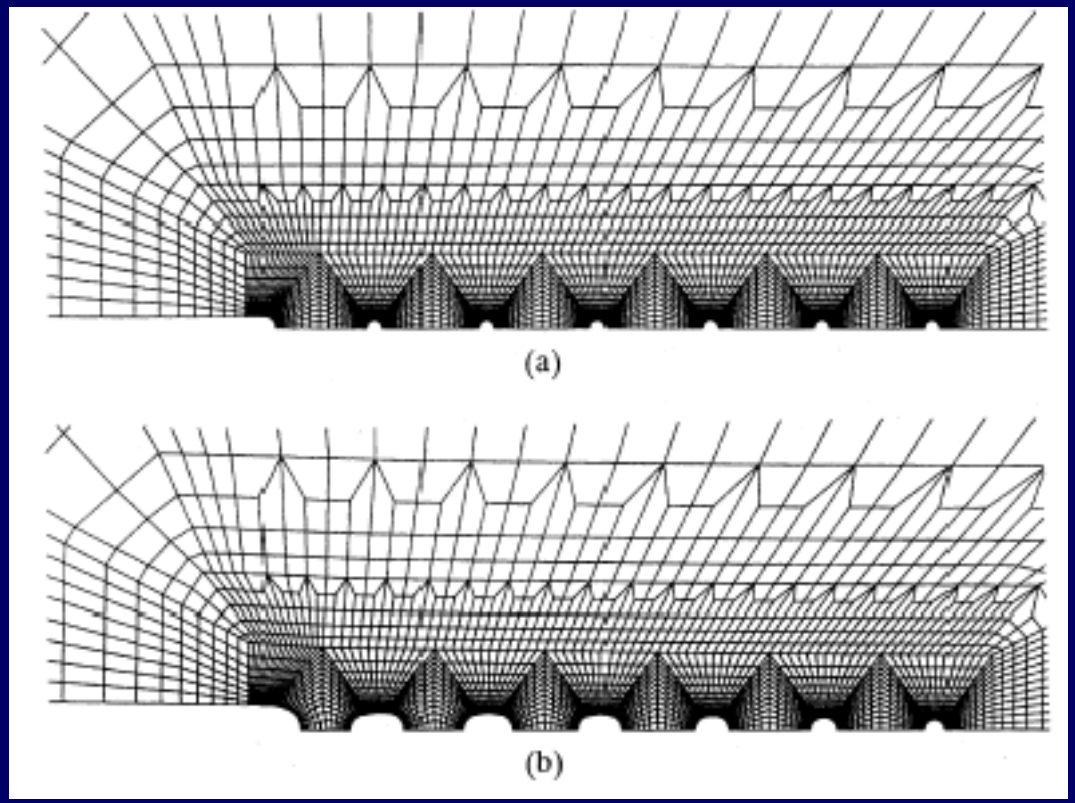


COMPUTATIONAL STRATEGIES TO SIMULATE DUCTILE CRACK GROWTH

STRATEGY 2

- Explicit modeling of the cavities using refined finite element mesh
- Requires a criterion for void coalescence
- Limitation to small crack extension and simple void geometry

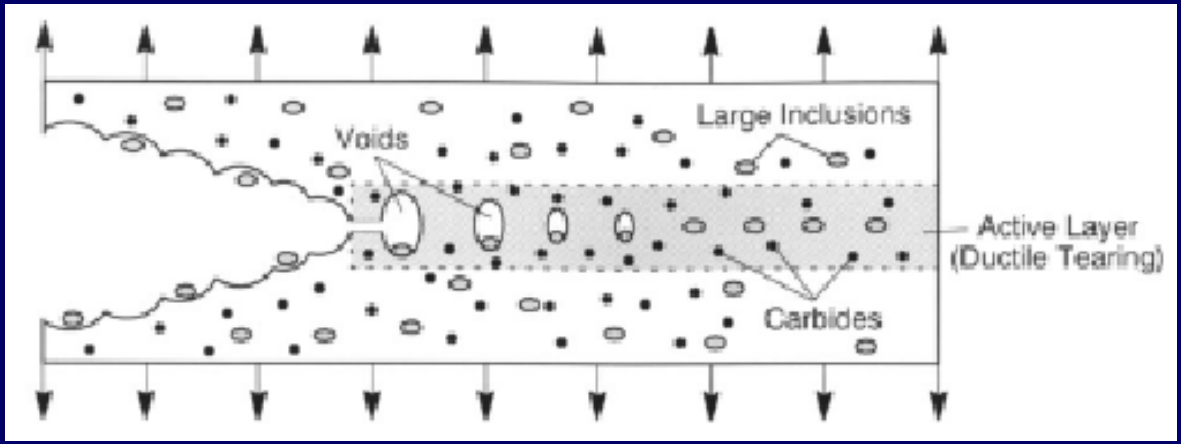
See e.g. Aravas, McMeeking, 1985. Tvergaard, Hutchinson, 2002



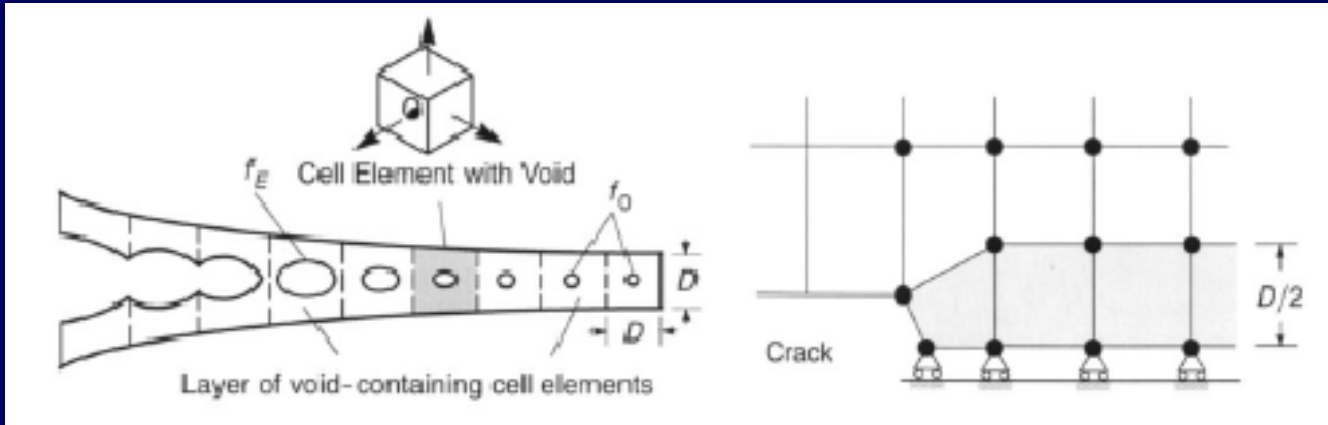
COMPUTATIONAL STRATEGIES TO SIMULATE DUCTILE CRACK GROWTH

STRATEGY 3

- **Pursued mainly by groups in France, Germany, U.K. and U.S.**
- **Constitutive model (Gurson or Rousselier) with damage-induced softening**
- **Averaging over a critical distance**
- **Introduction of an internal length** *(e.g. Mudry et al., 1989. Rivalin et al., 2001)*



COMPUTATIONAL CELLS

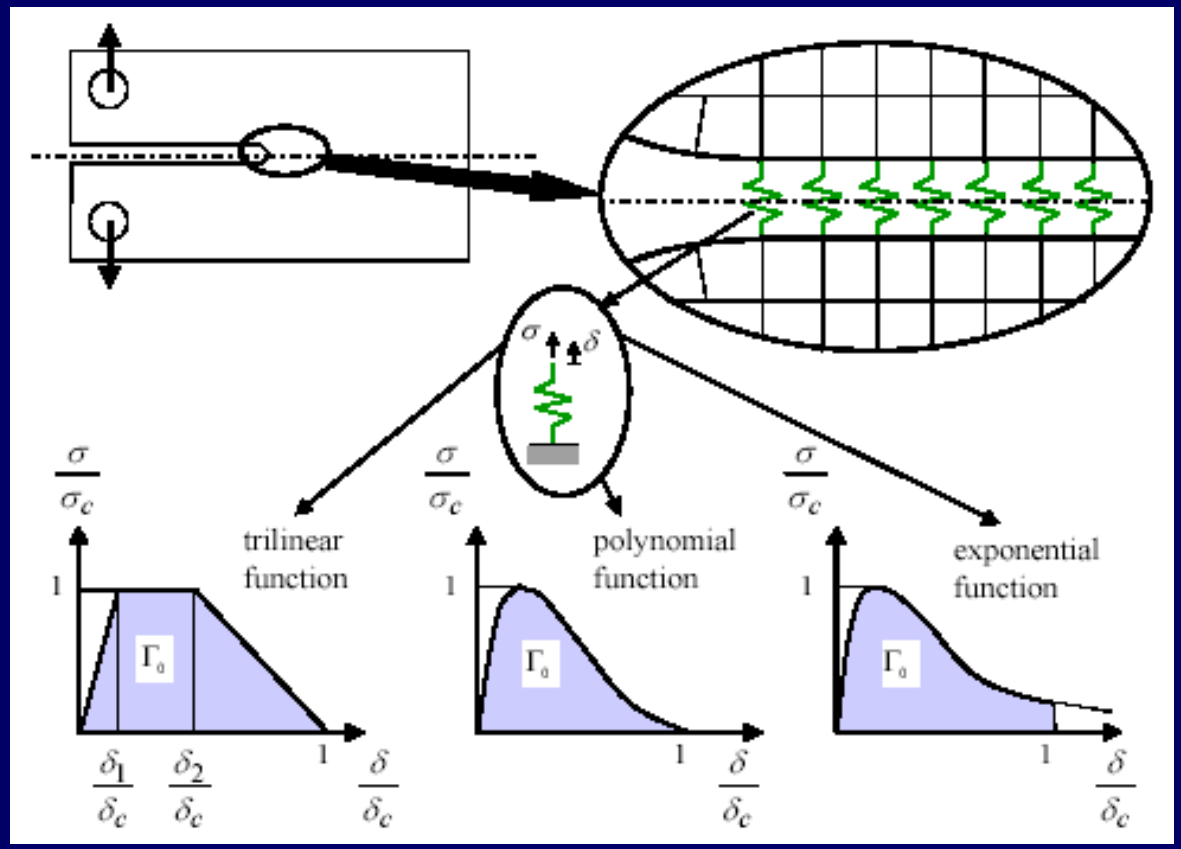


COMPUTATIONAL STRATEGIES TO SIMULATE DUCTILE CRACK GROWTH

STRATEGY 4

- Introduction of the Cohesive Zone Model
- CZM parameters depend on constraint effects
- Crack path must be prescribed in advance

See e.g. Tvergaard and Hutchinson, 1992. Brocks et al., 2003



SIMULATION OF DUCTILE CRACK GROWTH RESISTANCE CURVES

SUMMARY

- Considerable success of the so-called "local approach" *(Pineau, CSI, 2003)* or "top-down" approach to ductile fracture *(Hutchinson and Evans, 2000)*

- Assessment of the fracture integrity of structural components under large scale yielding conditions

- Main interest : microstructural parameters (void volume fraction, void spacing, etc…) must be set such that the model reproduces experiments on specific specimens

- 3D aspects of crack initiation and growth have been simulated
  Comparison with experiments scarce *(Gao et al., 1998; Rivalin et al., 2001)*

Very much remains to be done : flat/slant fracture in these sheets

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WHY DOES A TRANSITION EXIST ?

1 - PROBABILISTIC ASPECT

Volume of sampled material increases with crack growth

⇨ ***Sketch***

2 - MESO-MECHANICAL ASPECT

Maximum stress increases with crack growth

⇨ ***B. Tanguy***

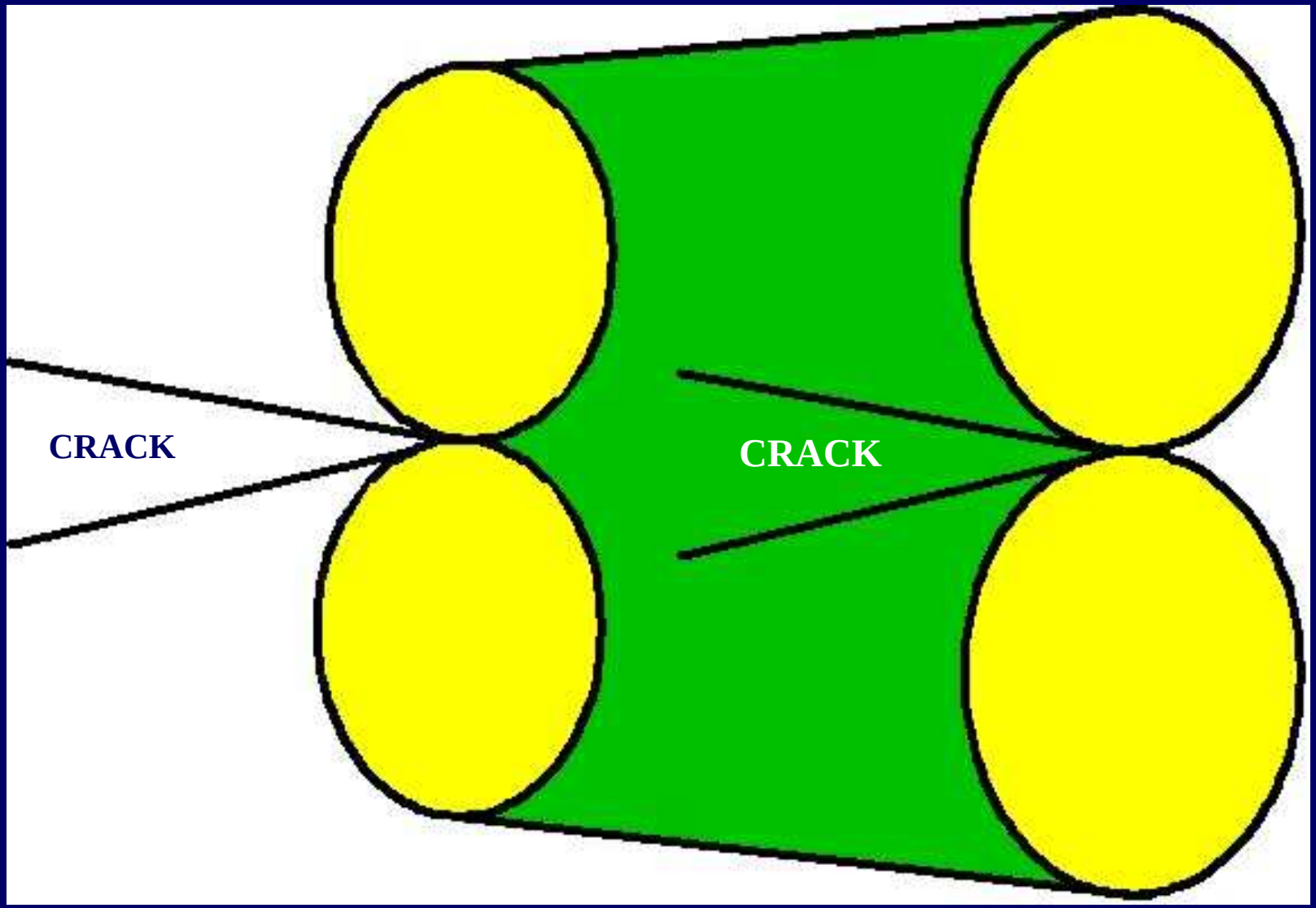
3 - MICRO-MECHANICAL ASPECT

Local stresses amplified by cavity growth

(Petti & Dodds, IJSS (2005), p. 3655)

⇨ ***J.C. Lautridou***

PROPAGATING CRACK



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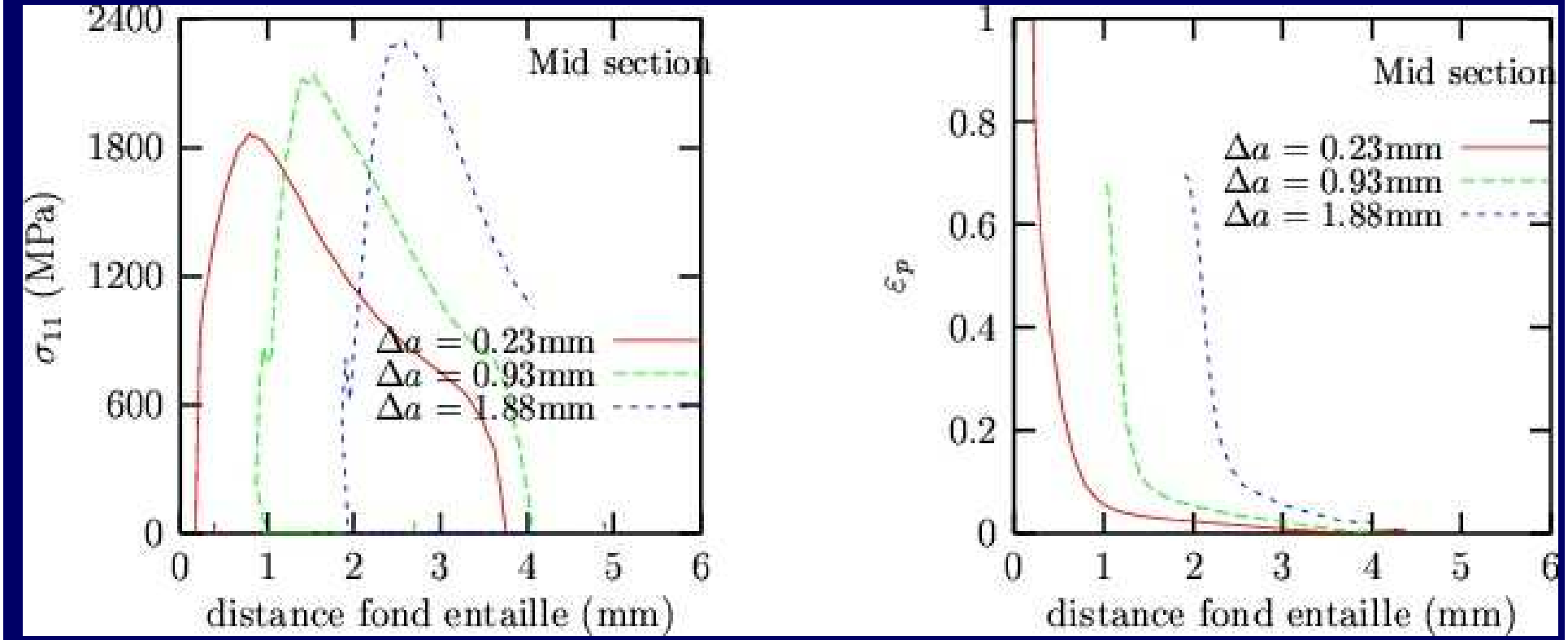
Local stresses amplified by cavity growth

(Petti & Dodds, IJSS (2005), p. 3655)

⇨ ***J.C. Lautridou***

MAXIMUM STRESS AHEAD OF A PROPAGATING CRACK

CHARPY V SPECIMEN



B. Tanguy, 2001

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Steel 16 MND5

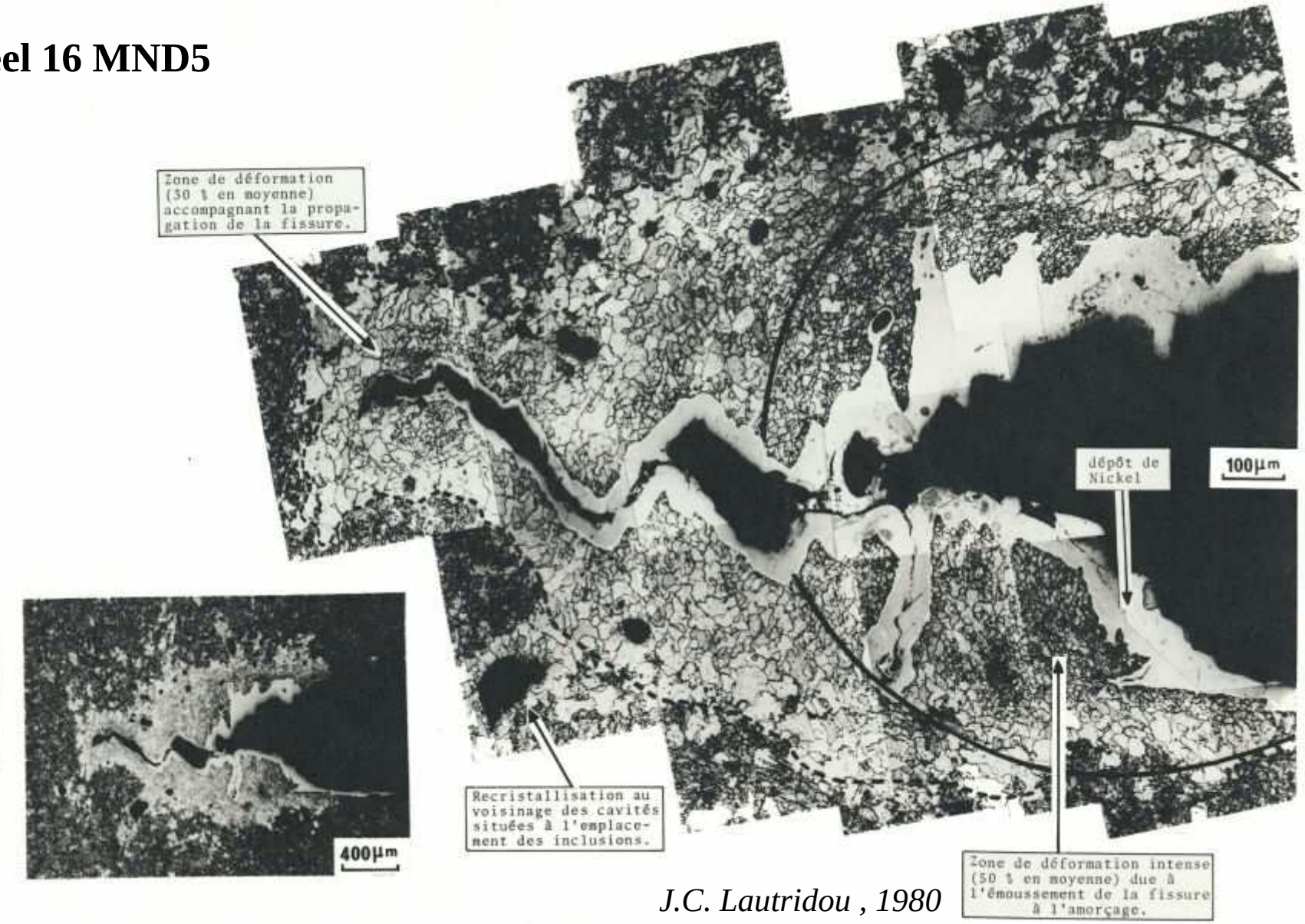


Figure IV-24 Recristallisation des régions fortement déformées au voisinage d'une fissure en cours de propagation. Virole sens long.

J.C. Lautridou , 1980

SAMPLING EFFECT DUE TO CRACK GROWTH

- **WALLIN (1989)**
  - **Assumes that the "effective" volume continues to grow as** $\left(K_I^2\right)^2$

$$\mathrm{Ln}\frac{1}{1-P_R}=\frac{\left(f(\Delta a)\right)^4}{K_0^4}+\frac{2\sigma_f^2}{K_0^4\,B}\int_0^{\Delta a}\left(f(\Delta a)\right)^2\,da$$

$K_I = f(\Delta a)$; K_0 = normalizing value for K easily calculated under SSY

σ_f = cleavage stress; B = specimen thickness

- **BRUCKNER & MUNZ (1984)**
  - **Assumes that the size of the active volume is constant during crack extension**

$$\mathrm{Ln}\frac{1}{1-P_R}=\left(\frac{K_i}{K_0}\right)^4+\frac{1}{K_0^4 W_i}\int_0^{\Delta a}\left(f(\Delta a)\right)^4\,da$$

K_i = value of K at crack initiation; W_i : constant describing the size of the active volume

➢ **In both cases, $K(\Delta a)$ or R curve must be known**

⇒ Simplified expression of the DCG correction proposed by Wallin (1993)

$$\left(\mathrm{Ln}\left(\frac{1}{1-P_R}\right)\right)^{1/4}=\frac{K_i}{K_0}\left(1+\frac{2\Delta a\,\sigma_f^2}{K_i^2\,\beta}\right)$$ where $\beta \approx x/\left(K_i/\sigma_f\right)^2$ cleavage process zone size

ELIMINATION OF ELIGIBLE NUCLEATION SITES

$$\sigma_w = \left[\Sigma_{i=1}^{n} \left(1 - P_{void}^{i}\right) \left(\sigma_I^i\right)^n \frac{V_i}{V_0} \right]^{1/m}$$

P_{void}^{i} = Probability to nucleate a microvoid from a particle in the volume V_i of the ith element

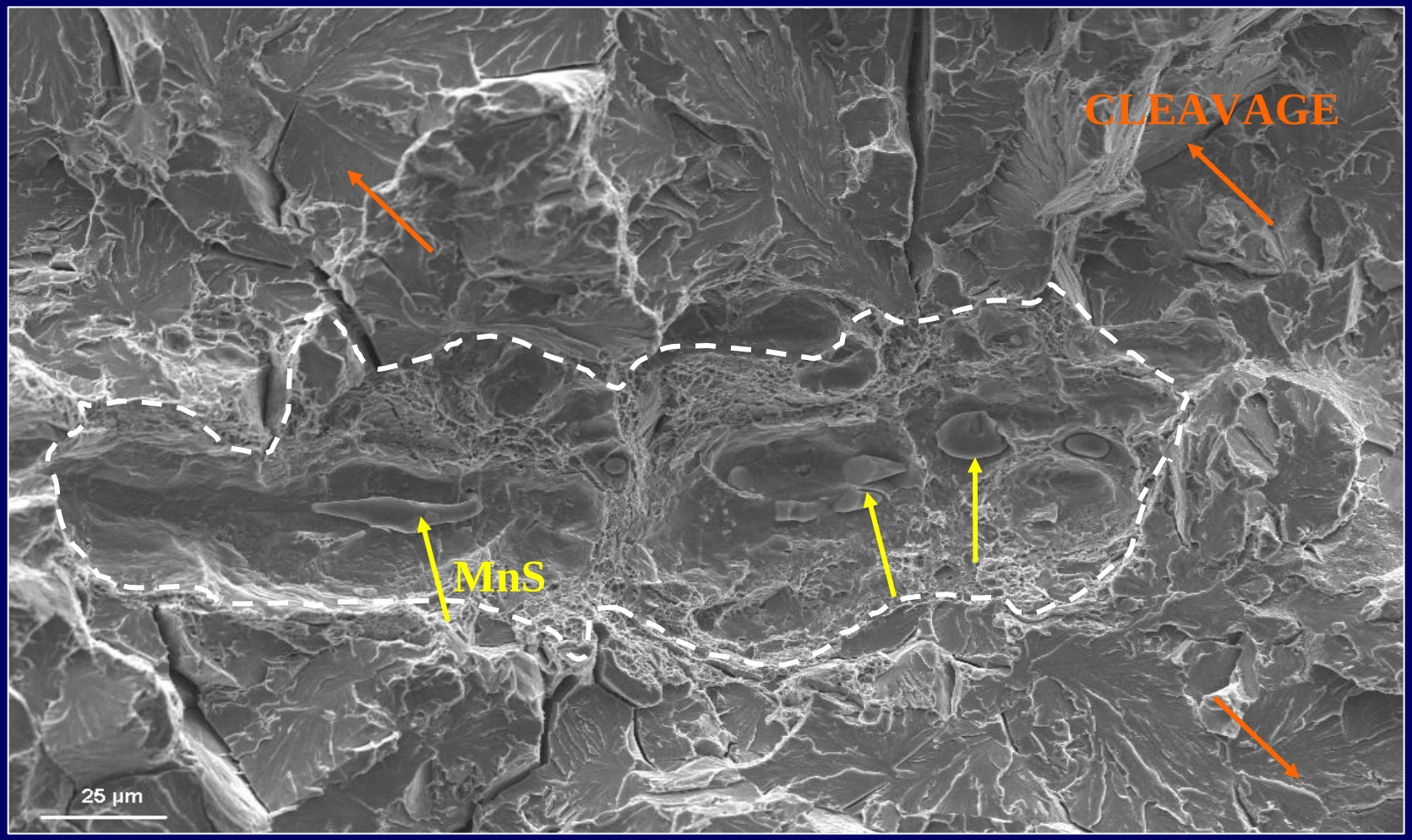
See e.g. Koers et al. (1995)

- Very few results in the literature
- This effect is usually neglected

A 508 Steel Notched Specimen T = - 150°C

CLEAVAGE INITIATED FROM MnS INCLUSIONS

Tanguy, 2007



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A SIMPLIFIED APPROACH TO DB TRANSITION

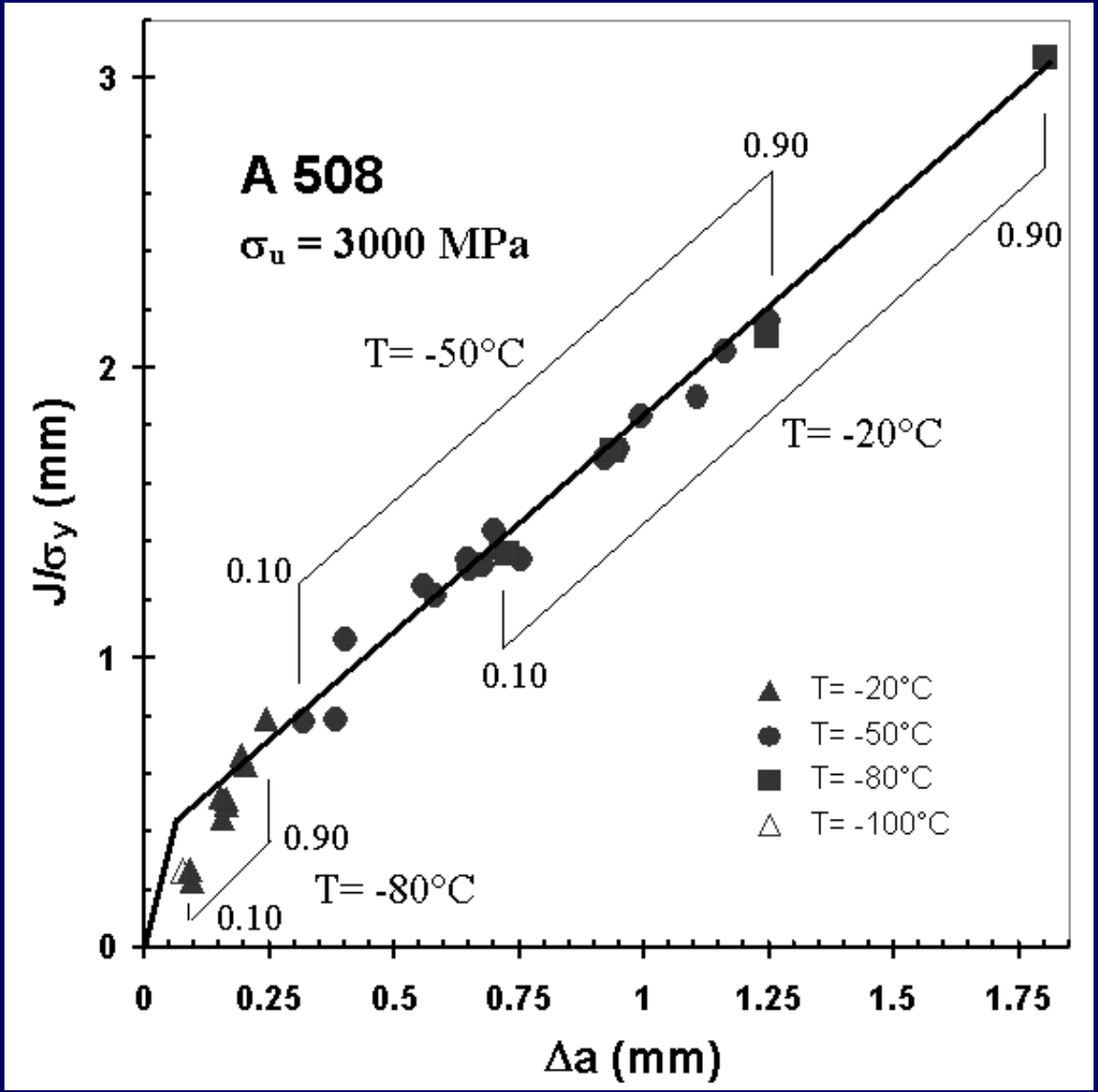
- Based on the assumption that the stress-strain field is not modified by crack extension except the loading parameter, J

See e.g. Amar, Pineau, 1987; Koers et al., 1995

- Strong limitations to this approach

→ Does not account for modifications in the stress field of a propagating crack

→ Does not rely on a possible change in micromechanisms



Amar & Pineau, 1987

See also Koers et al., 1995. Fe 510 Nb

MORE ADVANCED MODELS FOR DB TRANSITION

OBJECTIVES

(i) • Stress Profiles ahead of a growing crack

⟶ Strongly dependent on geometry (bend vs tension)

(ii) • Introduction of damage ahead of the crack tip produces a macroscopic reduction of the "local" stresses (GTN model). At metallurgical scales ductile damage amplify local stress *(See Petti & Dodds, 2005)*

(iii) • Sampling effect due to crack growth

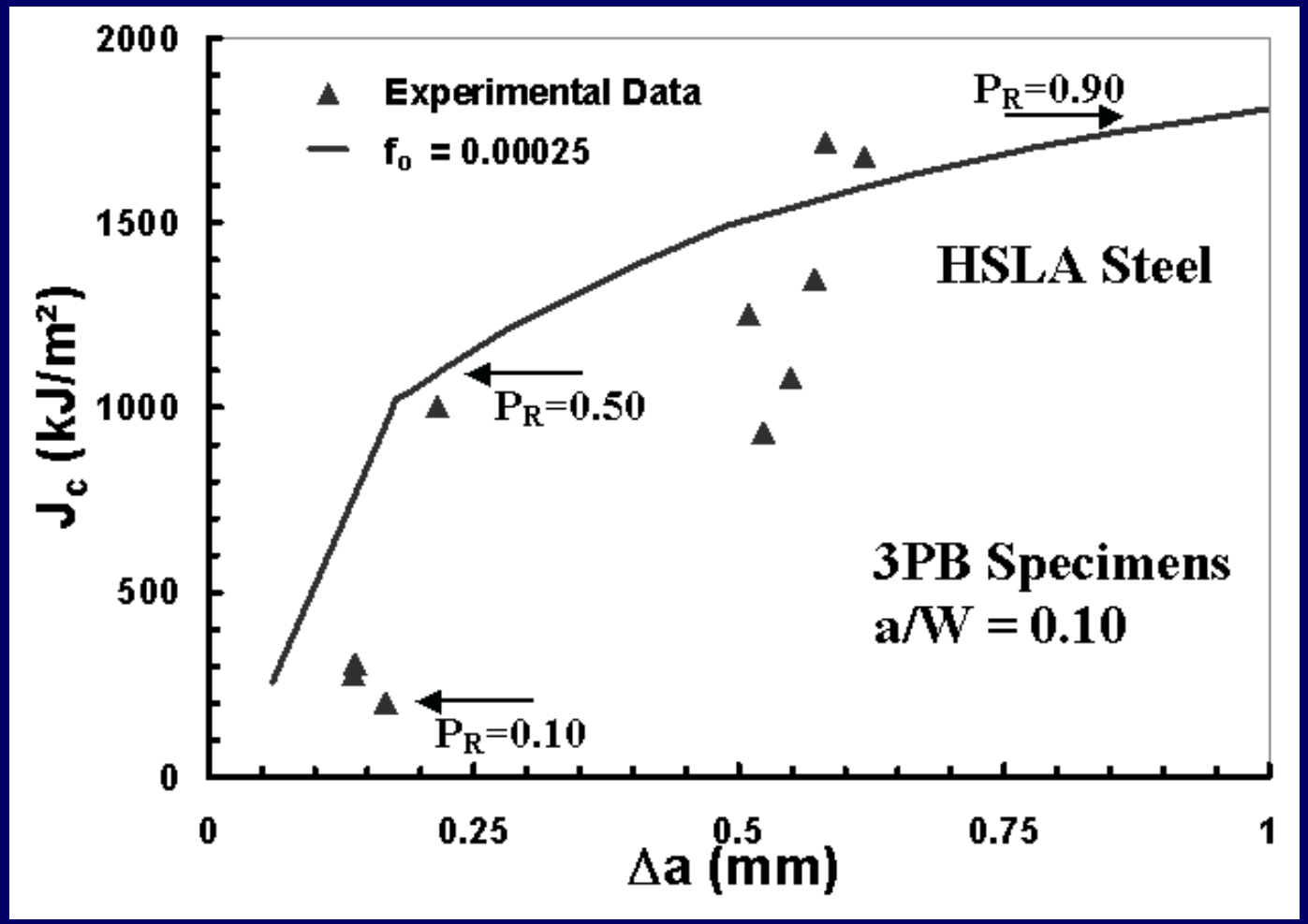
(iv) • Elimination of eligible particles (or nucleation sites)

(v) • Effect of plastic strain on cleavage stress

(See above, Beremin, 1983, Bordet et al., 2005)

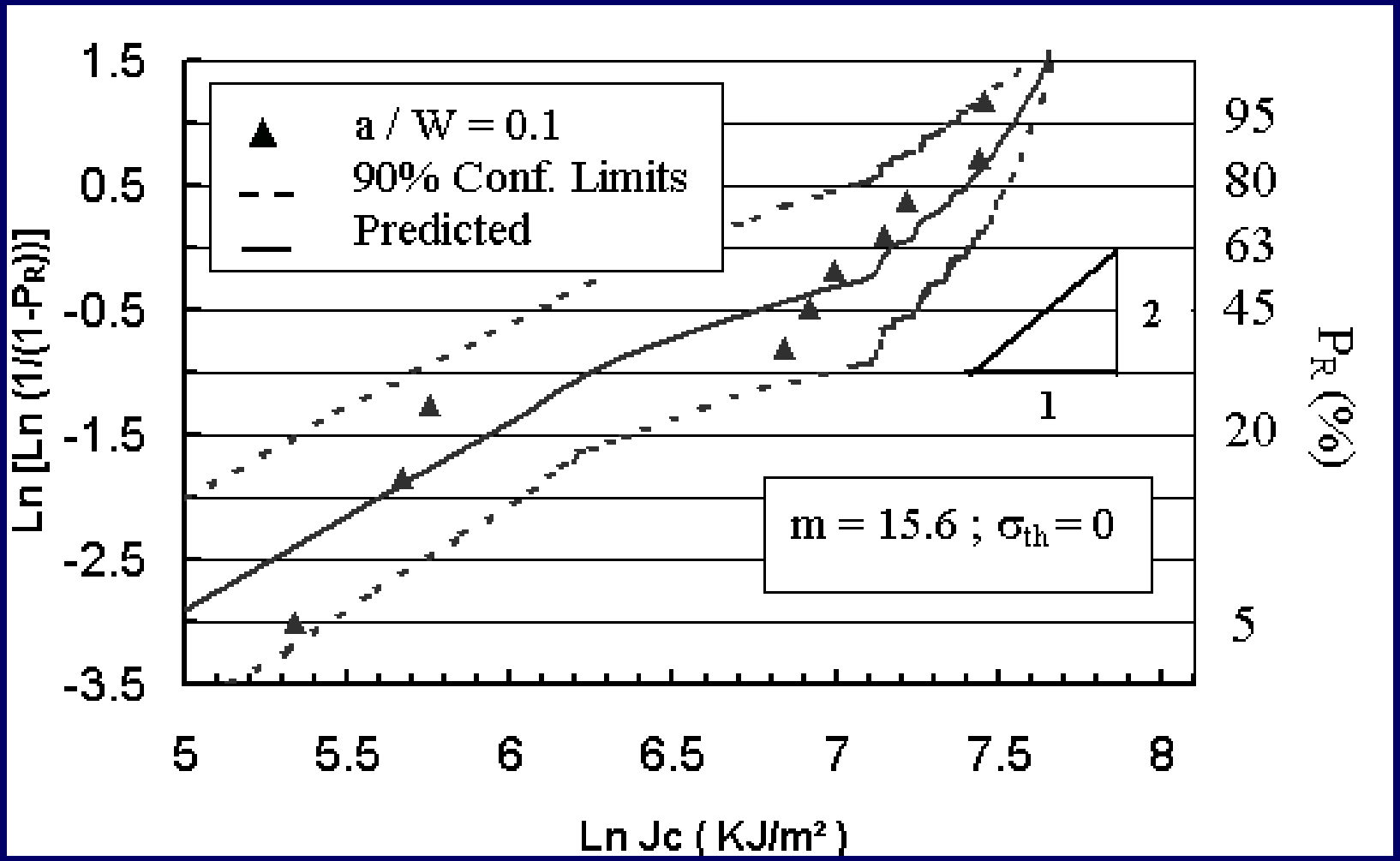
HSLA Steel

Toyoda et al., 1991; Ruggieri & Dodds, 1996



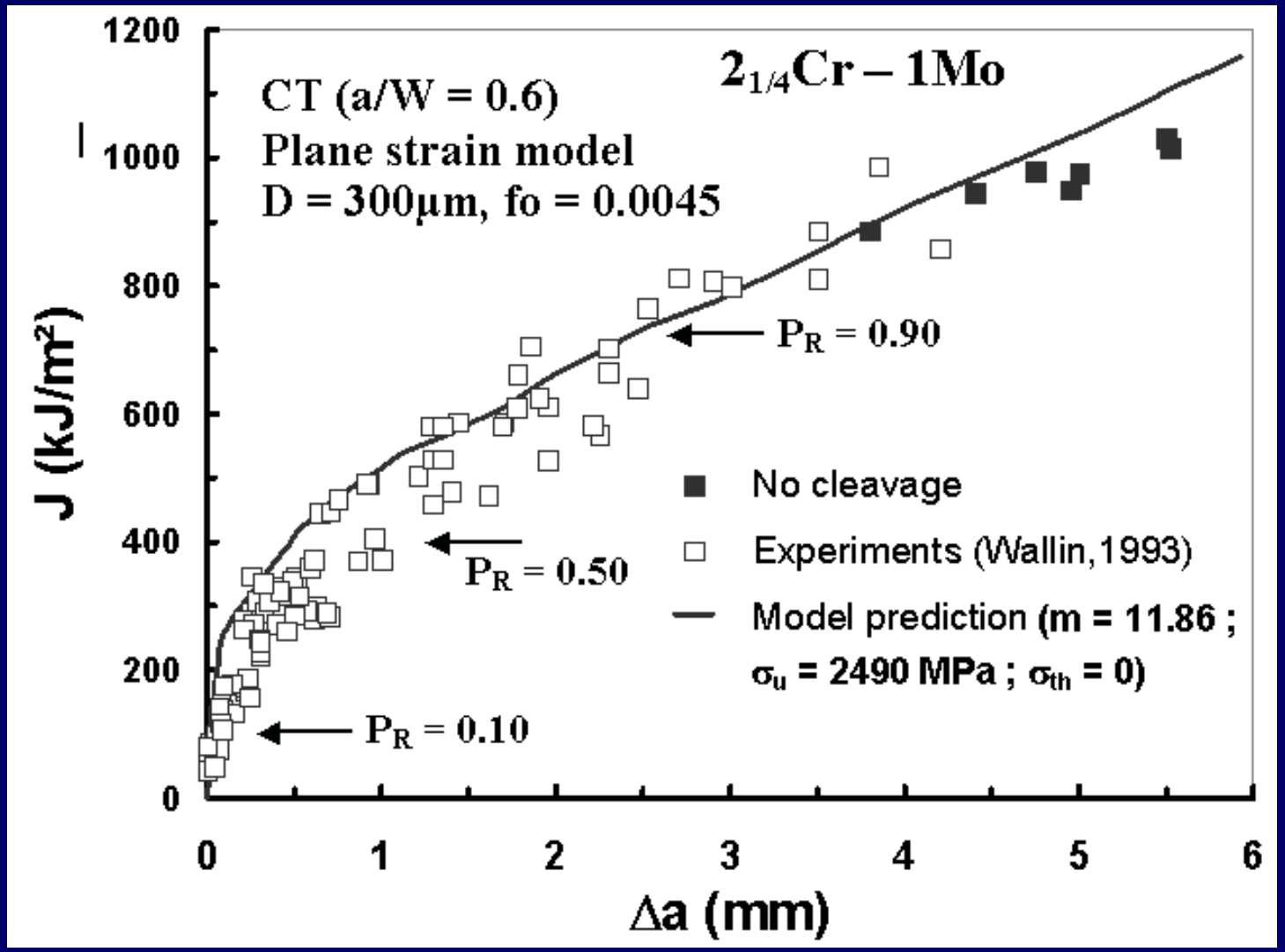
HSLA Steel

Ruggieri & Dodds, 1996



GTN Model $f_0 = 0.0045$, $f_c = 0.20$, $D = 0.30$ mm, $m = 11.86$, $\sigma_u = 2490$ MPa

Gao et al., 1999



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APPLICATION OF THE LOCAL APPROACH TO DUCTILE-BRITTLE TRANSITION IN FERRITIC STEELS

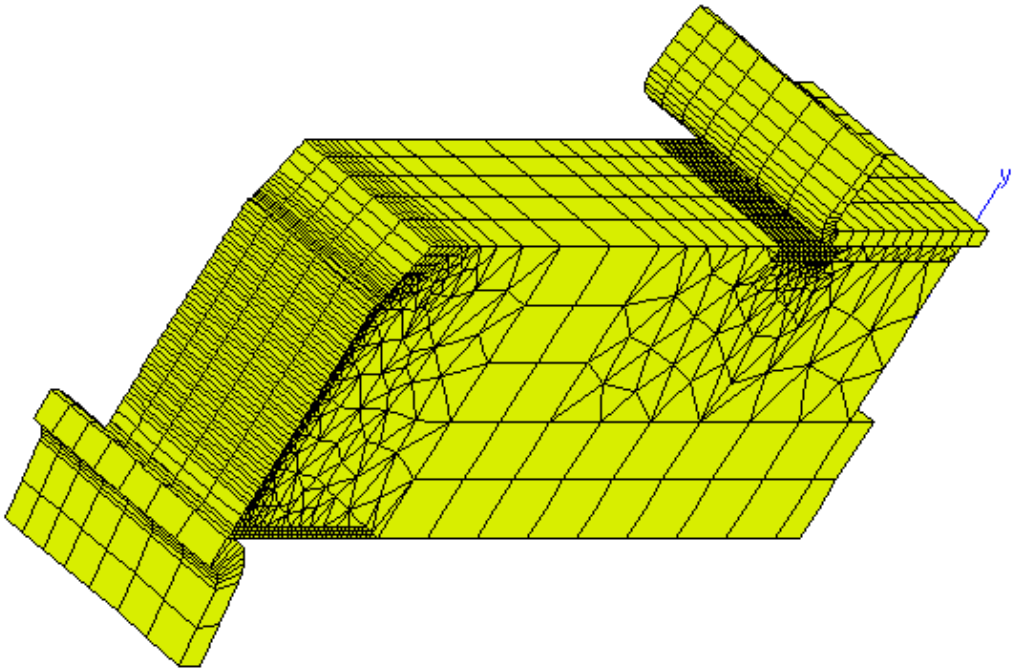
MODELING OF CHARPY IMPACT TEST

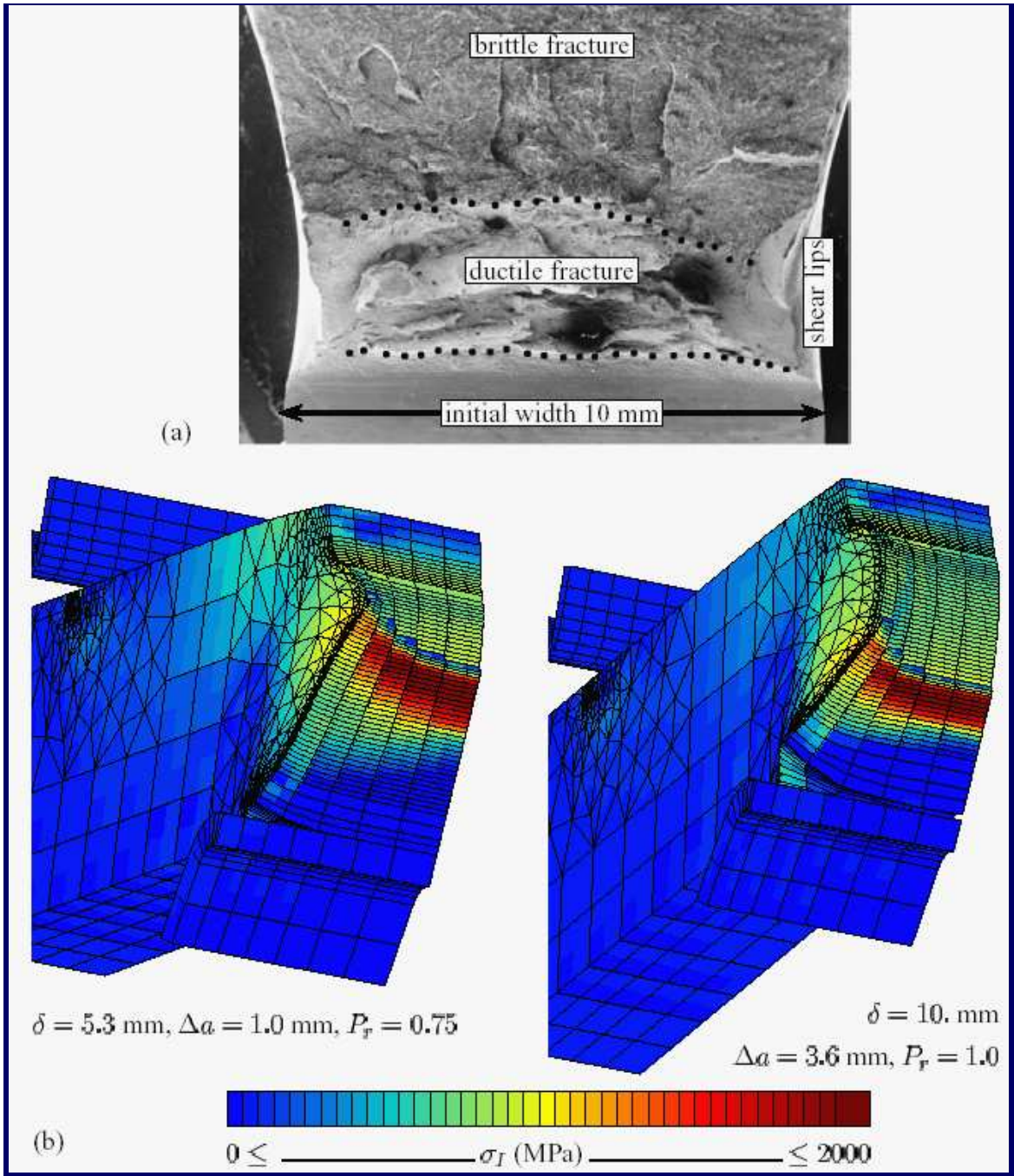
- **MATERIAL : PWR A 508 Steel**
- **NUMERICAL MODELING**
  - **3D**
  - **Viscoplastic Constitutive Laws**
  - **GTN & ROUSSELIER Models for Ductile Fracture**
  - **BEREMIN Model for Cleavage Fracture**
- **COMPARISON EXPERIMENTS & NUMERICAL SIMULATIONS**
  - **Interrupted tests to measure ductile crack growth**

See : B. Tanguy et al., Eng. Fracture Mechanics (2005), Vol. 72. Part I : pp. 49-72. Part II : pp. 413-434.

CHARPY TEST SIMULATION

B. Tanguy





Fracture at –60°C under dynamic conditions :

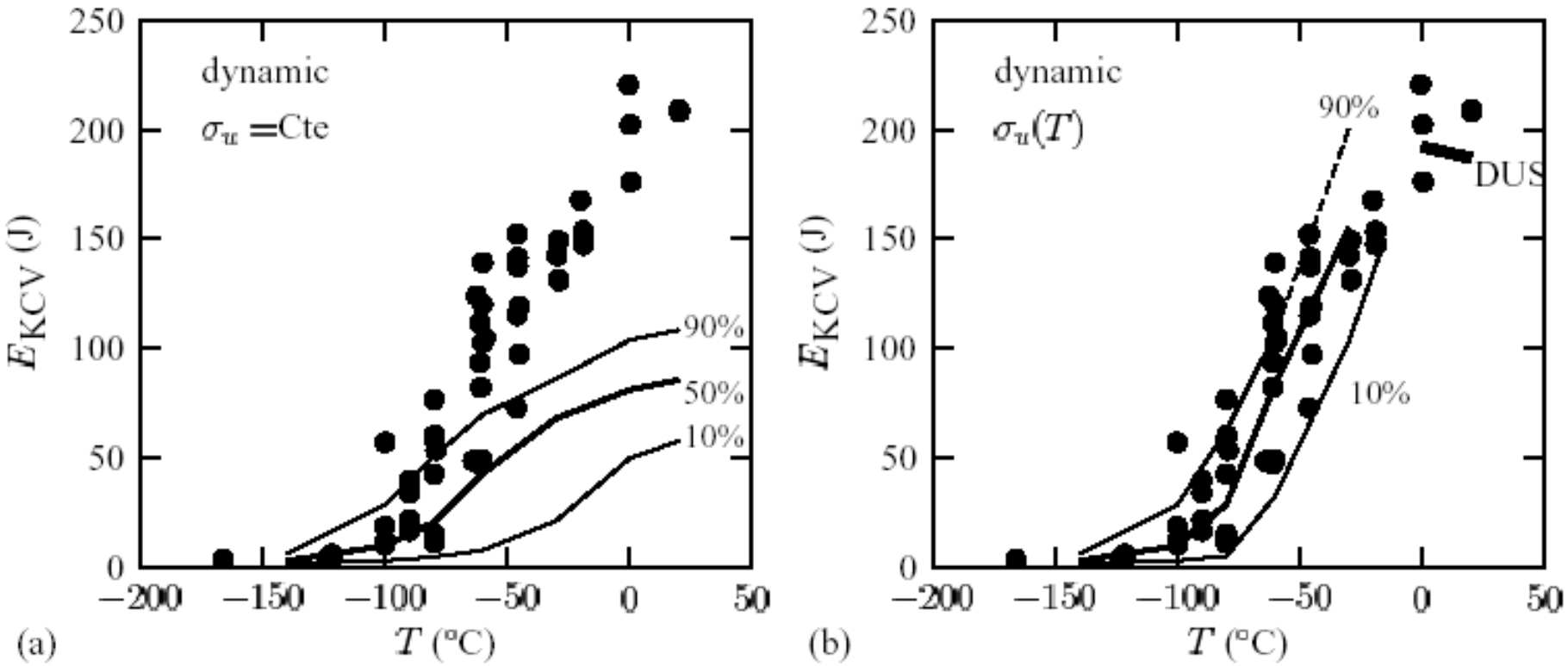
a) Experimental fracture surface,

b) Simulation of ductile crack propagation (contour plots indicate σ_I)

A 508 Steel

- **No Inertial Effect**
- **Strain Rate Effect (Viscoplasticity)**
- **Ductile Damage (Rousselier & Gurson)**
- **Adiabatic Heating**

A 508 STEEL


dynamic
σ_u =Cte
90%
50%
10%
E_{KCV} (J)
T (°C)
(a)
dynamic
$\sigma_u(T)$
90%
10%
DUS
E_{KCV} (J)
T (°C)
(b)

MODELING CHARPY-V TEST - CONCLUSIONS

1 - Accurate Description of Load-Displacement Curves and Ductile Crack Growth Provided that 3D Modeling is Used

2 - Good Description of Tunnelling Effect for Ductile Crack Growth

3 - Necessity of Using a Viscoplastic Constitutive Equation and to account for Adiabatic Heating

4 - Temperature Increase as Large as 150°C

5 - Easy Prediction of Index Temperatures TK_{28} and TK_{68}

6 - Above $\approx$ 100 Joules, σ_u appears to be an Increasing Function of Temperature

CHARPY TESTS ⟶ TUNING DAMAGE MODEL PARAMETERS
⟶ FRACTURE TOUGHNESS PREDICTION

CONCLUSIONS and ADDITIONAL COMMENTS

- Illustration of the benefit of the micromechanical modeling of fracture
- More complex but rewarding : size effect; non-isothermal loading; mixed mode etc…
- Many research areas to be explored :

(1) Cleavage Stress or $\sigma_u = f(\varepsilon, T)$? *See Kotrechko et al.*

(2) Ductile Fracture Models (too) sophisticated ?

(3) New experimental techniques (X-ray 3D Tomography) : Nucleation of cavities

(4) Existing models based on CSM. How far ? Crystallographic aspects

(5) Development of simulation tools : more complex situations (Welds etc…)

(6) Extension of ductile cracks over long distances remains a real challenge

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CONCLUSIONS

- Illustration of the benefit of micromechanical modelling of fracture
- LAF more complex but rewarding : size effect , non-isothermal loading , etc…
- Many research areas remain to be explored :

  - Cleavage stress σ_u (temperature)
  - Ductile fracture models (too) sophisticated
  - Shear dominated ductile fracture
  - New experimental techniques (Tomography)- Cavity nucleation
  - Existing models based on C.M.- How far ? Crystallographic aspects?
  - Development of simulation tools
  - Extension of ductile cracks over long distances remains a real challenge

THANK YOU FOR YOUR ATTENTION

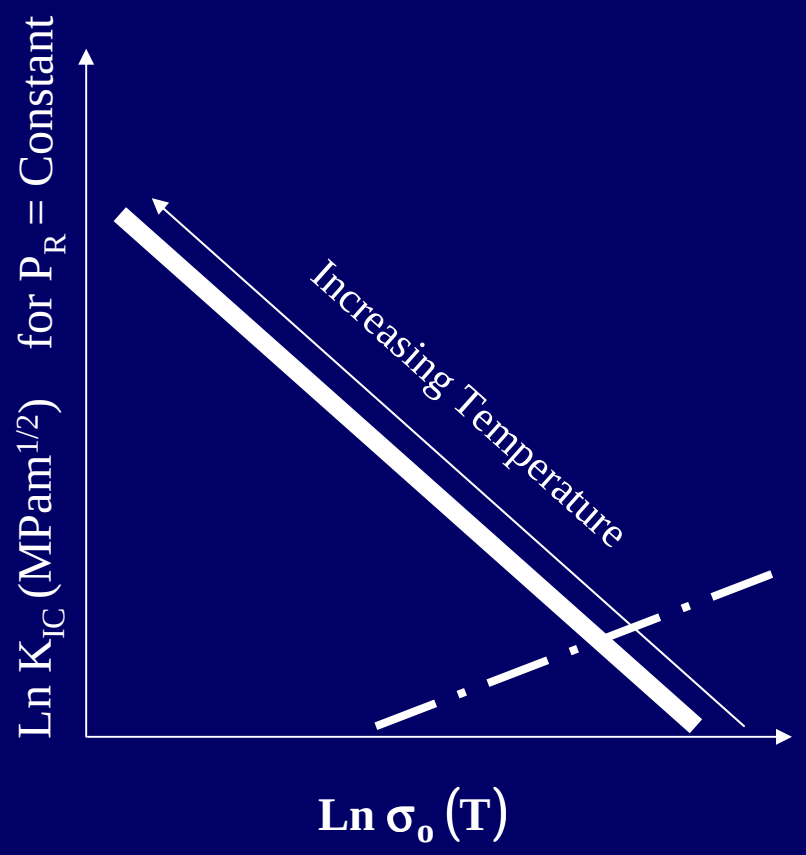
For further information

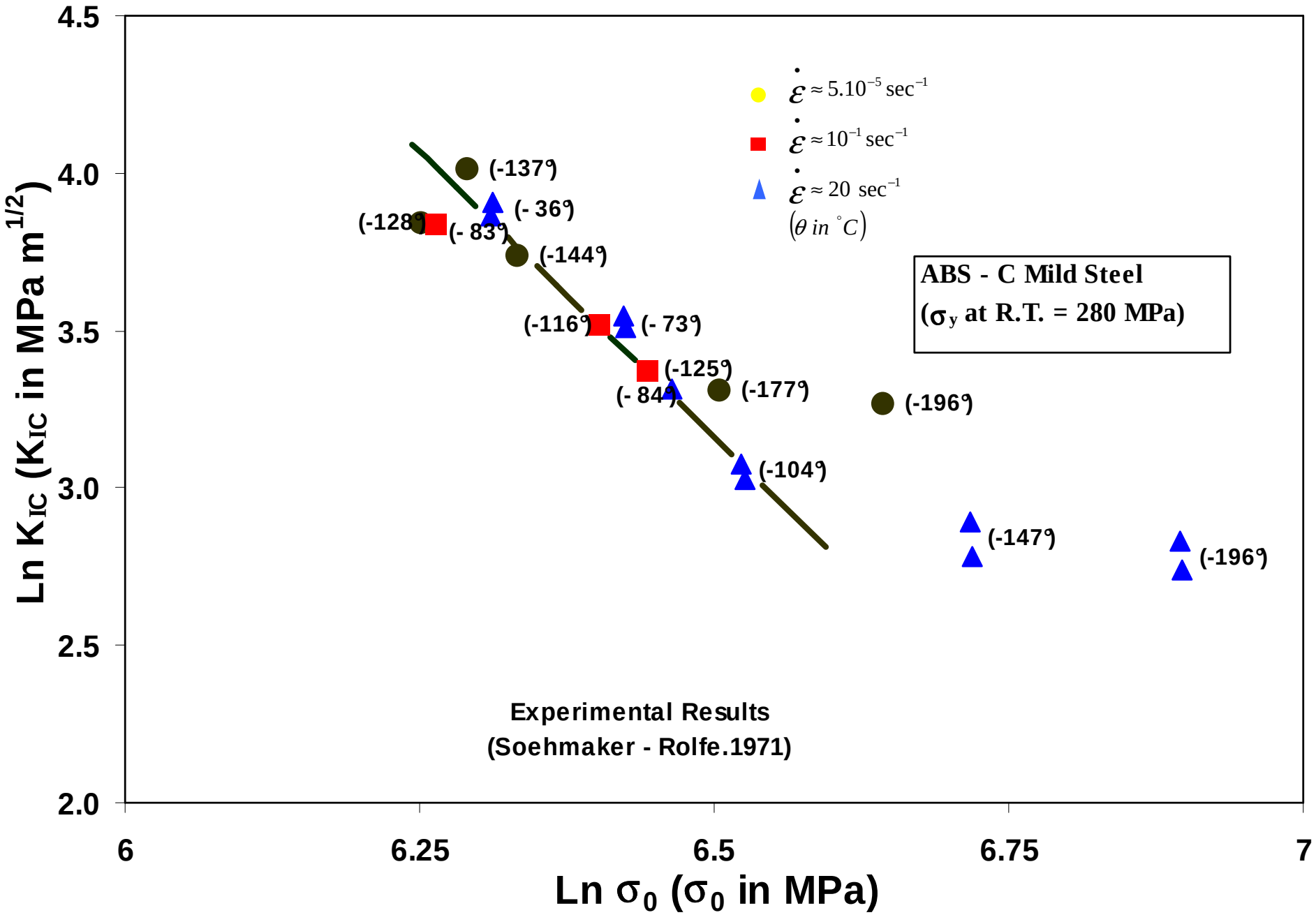
andre.pineau@ensmp.fr

LIMITATION (1) : THRESHOLD WEIBULL STRESS

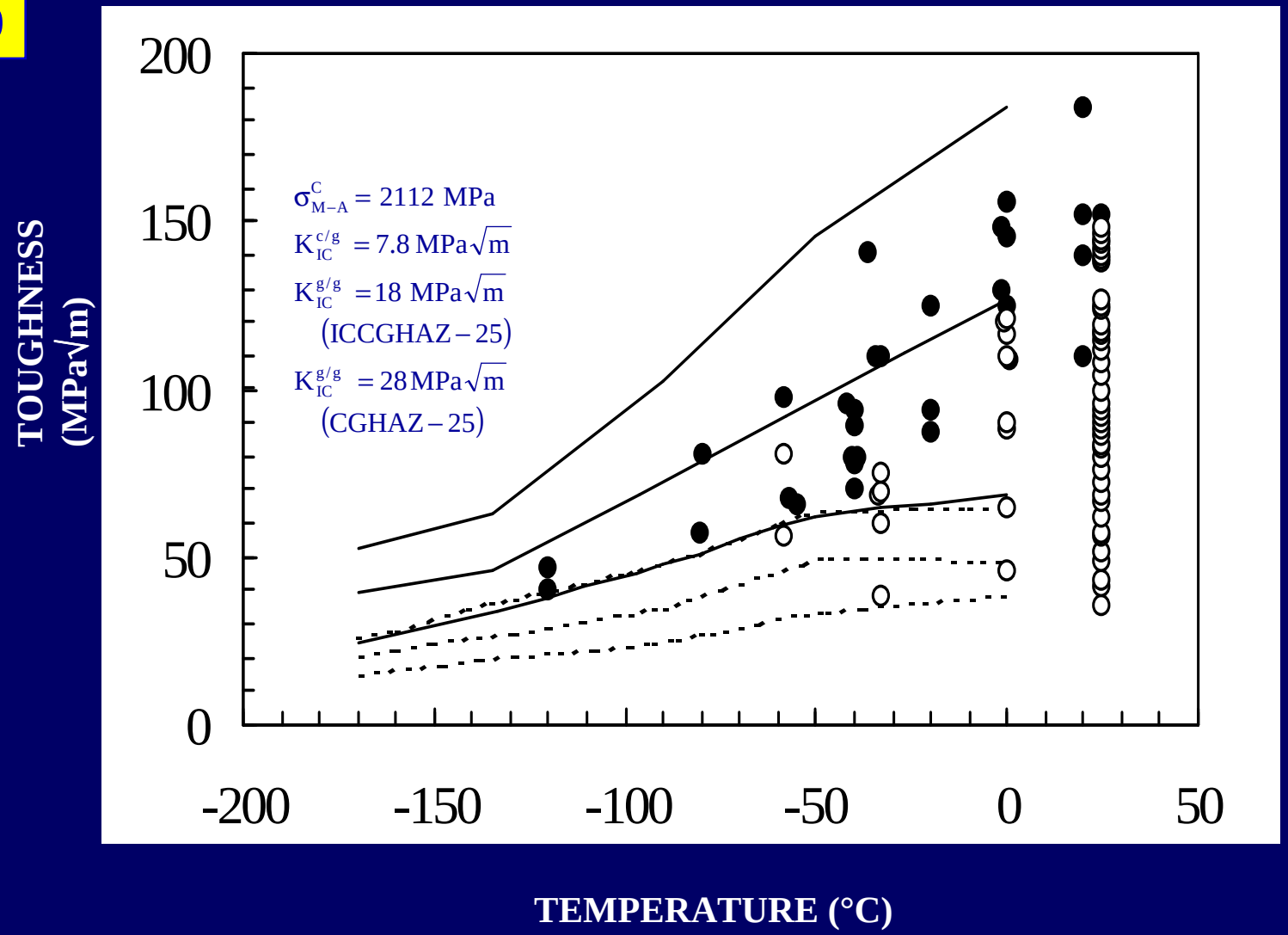
Actually, existence of a threshold stress in Beremin model since plastic deformation over a critical distance (X_c) is a prerequisite to initiate cleavage fracture

$$K_{I\,min} \simeq \sigma_o \sqrt{3\pi X_c}$$

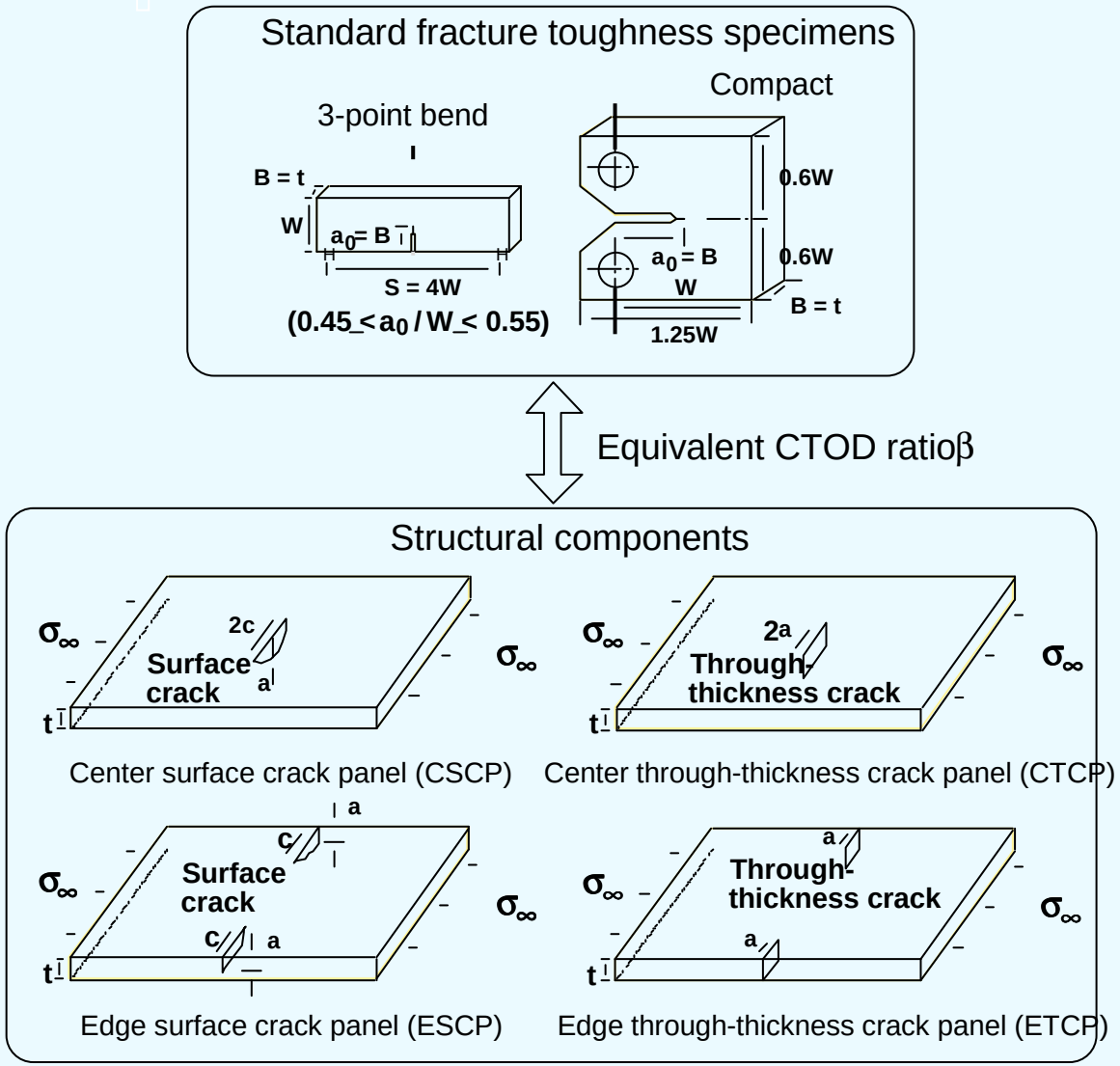



4.5
4.0
3.5
3.0
2.5
2.0
6
6.25
6.5
6.75
7
Ln K_IC (K_IC in MPa m^1/2)
Ln σ_0 (σ_0 in MPa)
ε̇ ≈ 5.10^-5 sec^-1
ε̇ ≈ 10^-1 sec^-1
ε̇ ≈ 20 sec^-1
(θ in °C)
ABS - C Mild Steel
(σ_y at R.T. = 280 MPa)
(-137°)
(- 36°)
(-128°)
(- 83°)
(-144°)
(-116°)
(- 73°)
(-125°)
(- 84°)
(-177°)
(-196°)
(-104°)
(-147°)
(-196°)
Experimental Results
(Soehmaker - Rolfe.1971)

E 450



Results of the “double barrier” model with TPB specimens.
Open circles denote microcrack events, solid circles are for final fracture of the specimens.
Solid (resp. dotted) lines represent 10%, 50% and 90% probabilities for the specimen to fracture (resp. for a cleavage microcrack to propagate across a particle/matrix boundary) as given by the DB model.



Standard Fracture Toughness specimens and wide plate components linked with the equivalent CTOD ratio β