

Local Approach to Fracture (LAF) as a Metallurgical and Mechanical Tool to Model Brittle Fracture and Ductile-to-Brittle Transition (DBT) in Structural Steels

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- I. INTRODUCTION
- II. BRITTLE CLEAVAGE FRACTURE : Main Characteristics
- III. THEORY OF BRITTLE FRACTURE
 - III – 1. Weakest Link Theory
 - III – 2. Effect of Inhomogeneities
 - III – 3. Further Developments
- IV. DUCTILE FRACTURE : Micromechanisms & Modeling Ductile Crack Growth
- V. DUCTILE TO BRITTLE TRANSITION
- VI. CONCLUSIONS

SCOPE

- MATERIALS
 - (Essentially) Ferritic Steels
 - Pressure Vessel Steels : 16MND5 (B), 22NiMoCr37 (B), 21/4Cr 1Mo (M)
 - Offshore Structural Steels : E 450, E 36
- LENGTH SCALE EFFECT
- SIZE EFFECT ON FRACTURE TOUGHNESS
- SCATTER IN RELATION WITH METALLURGICAL INHOMOGENEITIES
- FRACTURE MECHANICS SPECIMENS & CHARPY TESTS
- 2D / 3D ASPECTS
- ISOTHERMAL & NON ISOTHERMAL TESTS

See T. Yuritzinn et al. « Warm pre-stressing tests on specimens with semi-elliptical cracks and analysis of the results » EFM,(2010), vol.77,pp.71-83
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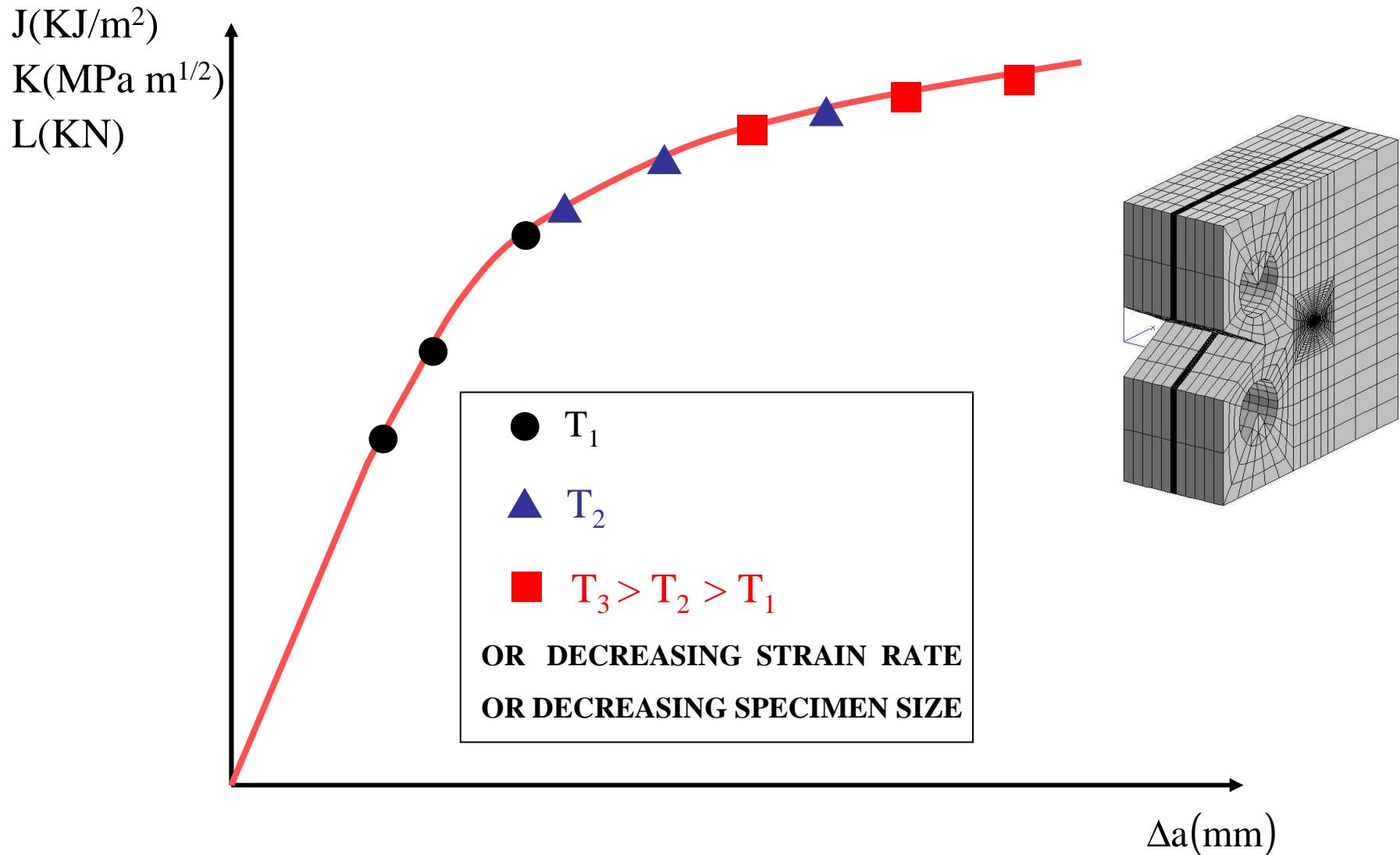
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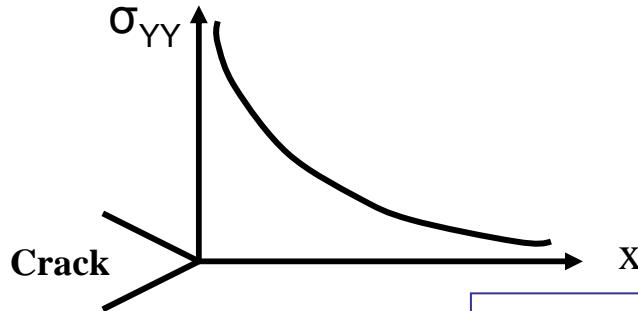
IV. DUCTILE FRACTURE : Micromechanisms & Modeling Ductile Crack Growth

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DUCTILE – TO - BRITTLE TRANSITION - DEFINITION





GLOBAL APPROACH

$\sigma - \epsilon$ Field

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

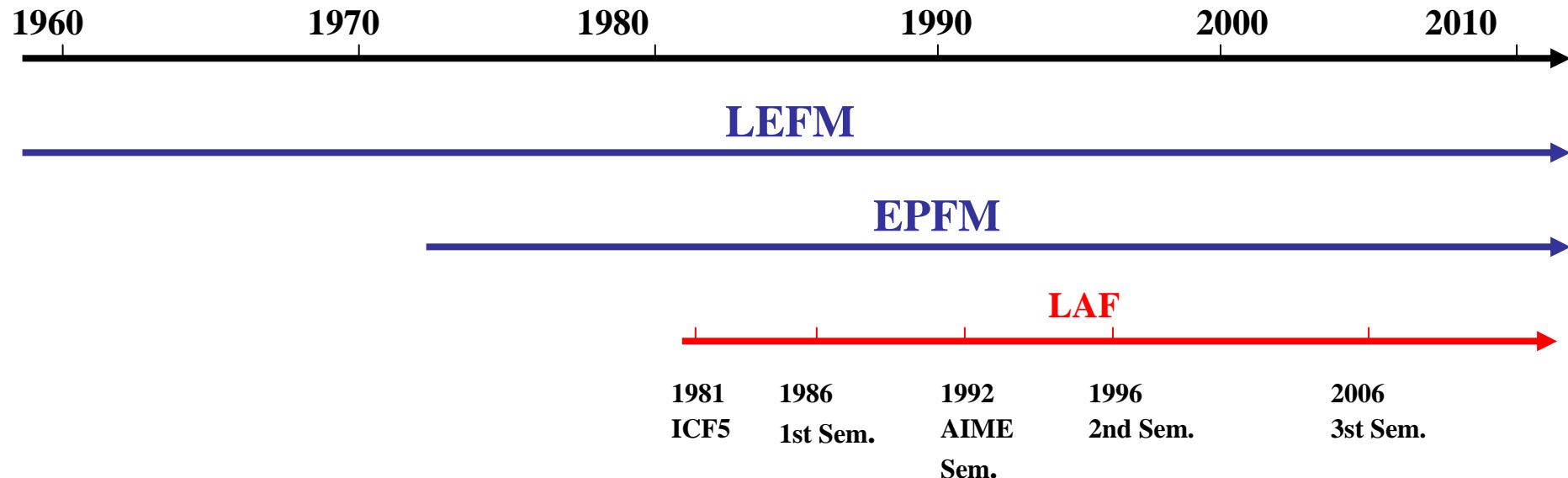
LOCAL APPROACH

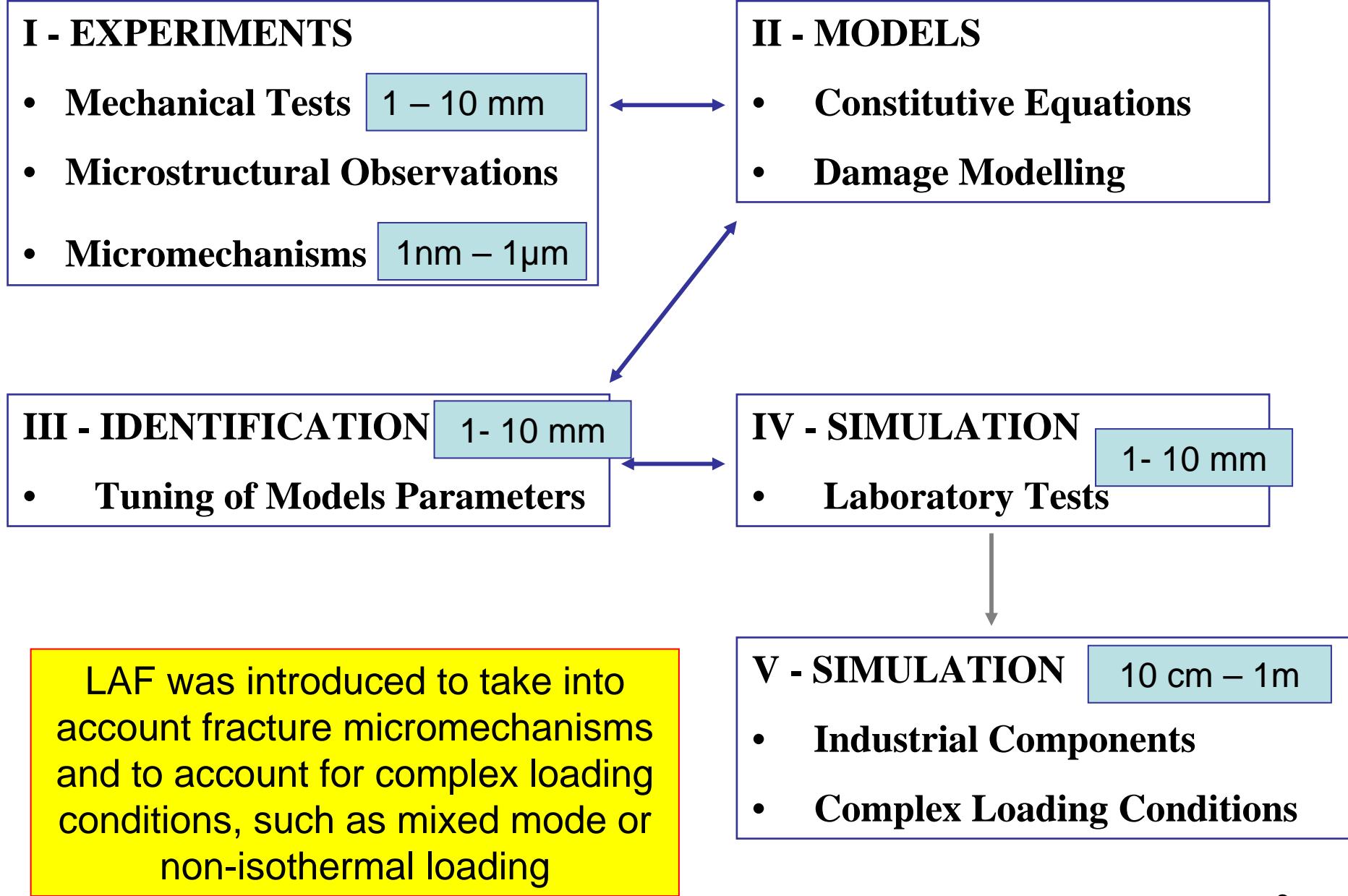
Crack Tip

+

Physically-based
Fracture Criteria

→ COMPUTATIONAL FRACTURE MECHANICS





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BRITTLE CLEAVAGE FRACTURE - MAIN CHARACTERISTICS

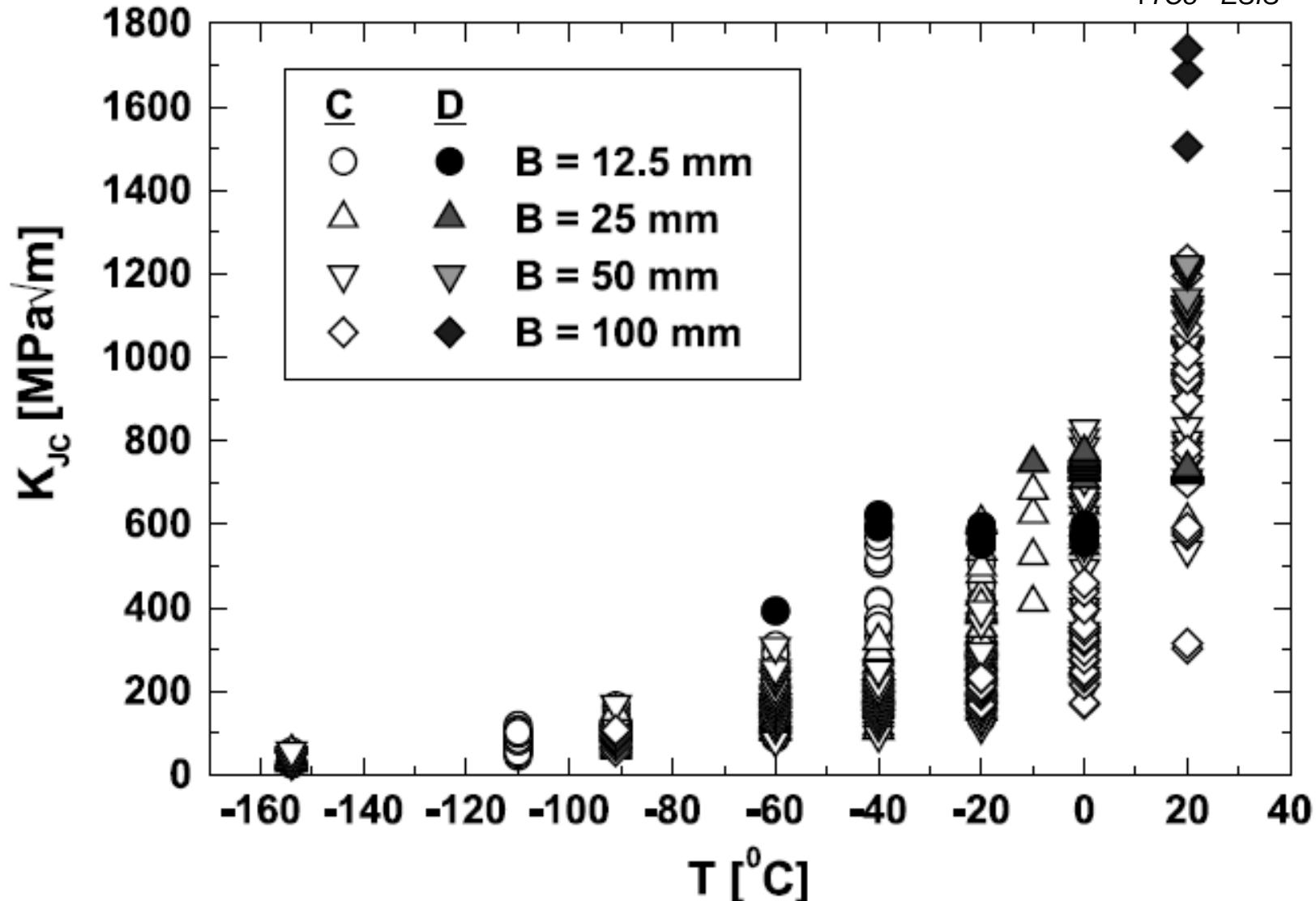
- TEMPERATURE DEPENDENCE
- SCATTER
- SPECIMEN SIZE EFFECT
- GEOMETRICAL DEPENDENCE
- LOADING RATE EFFECT
- EFFECT OF METALLURGICAL VARIABLES & INHOMOGENEITIES

EURO FRACTURE TOUGHNESS DATA SET

TEMP. & SIZE EFFECT

22NiMoCr37 N = 757

K. Wallin, EFM, 2002,
Vol. 69, pp. 451-481,
+ TC8 - ESIS



9

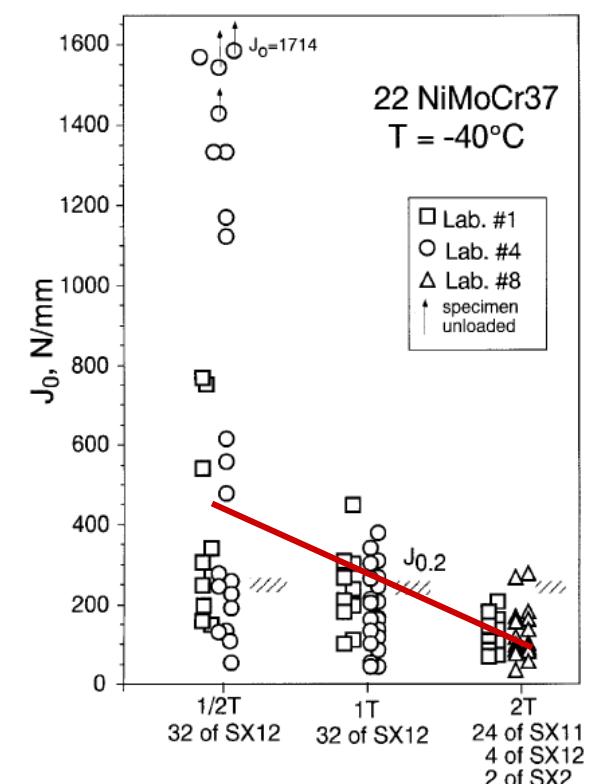
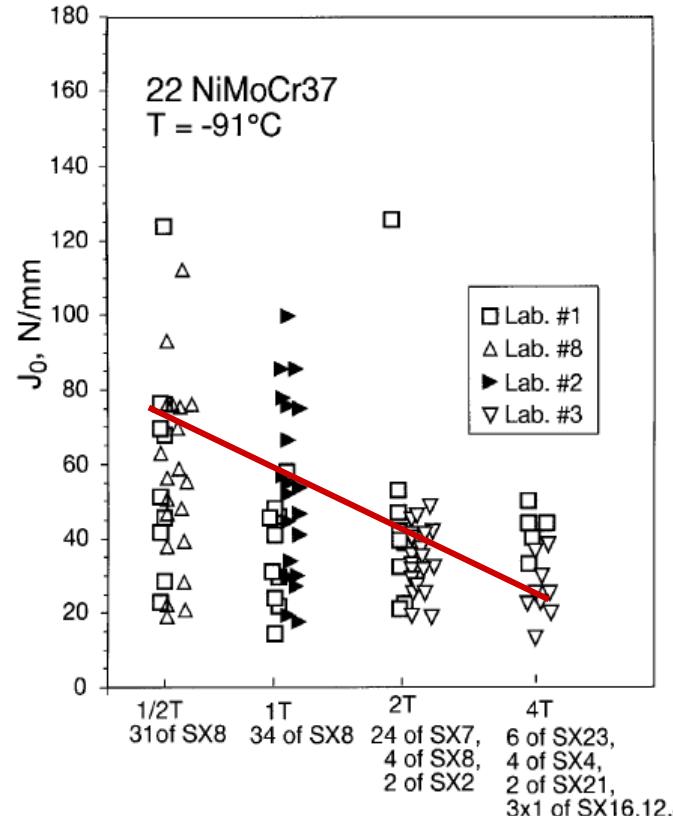
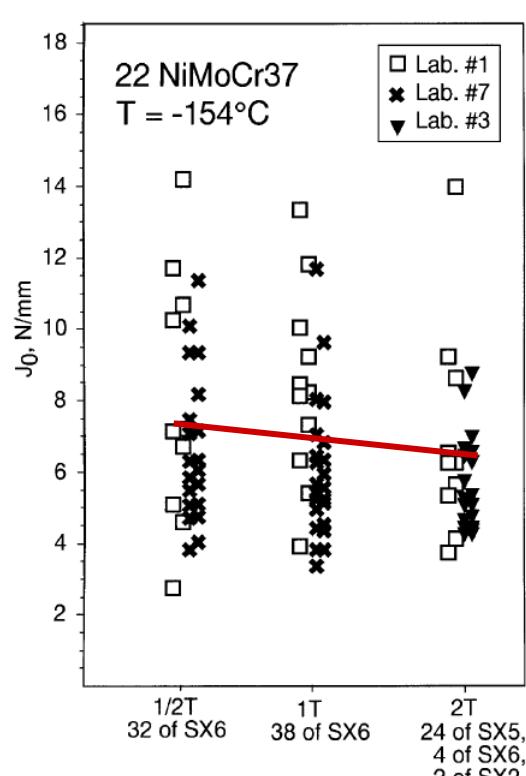
EURO FRACTURE TOUGHNESS DATA SET

J.Heerens, D.Hellmann, EFM, 2002, Vol.69, pp.441-449

See also R.Moskovic, EFM, 2002, Vol.69, pp.511-530

B.K. Neale, EFM, 2002, Vol.69, pp.497-509

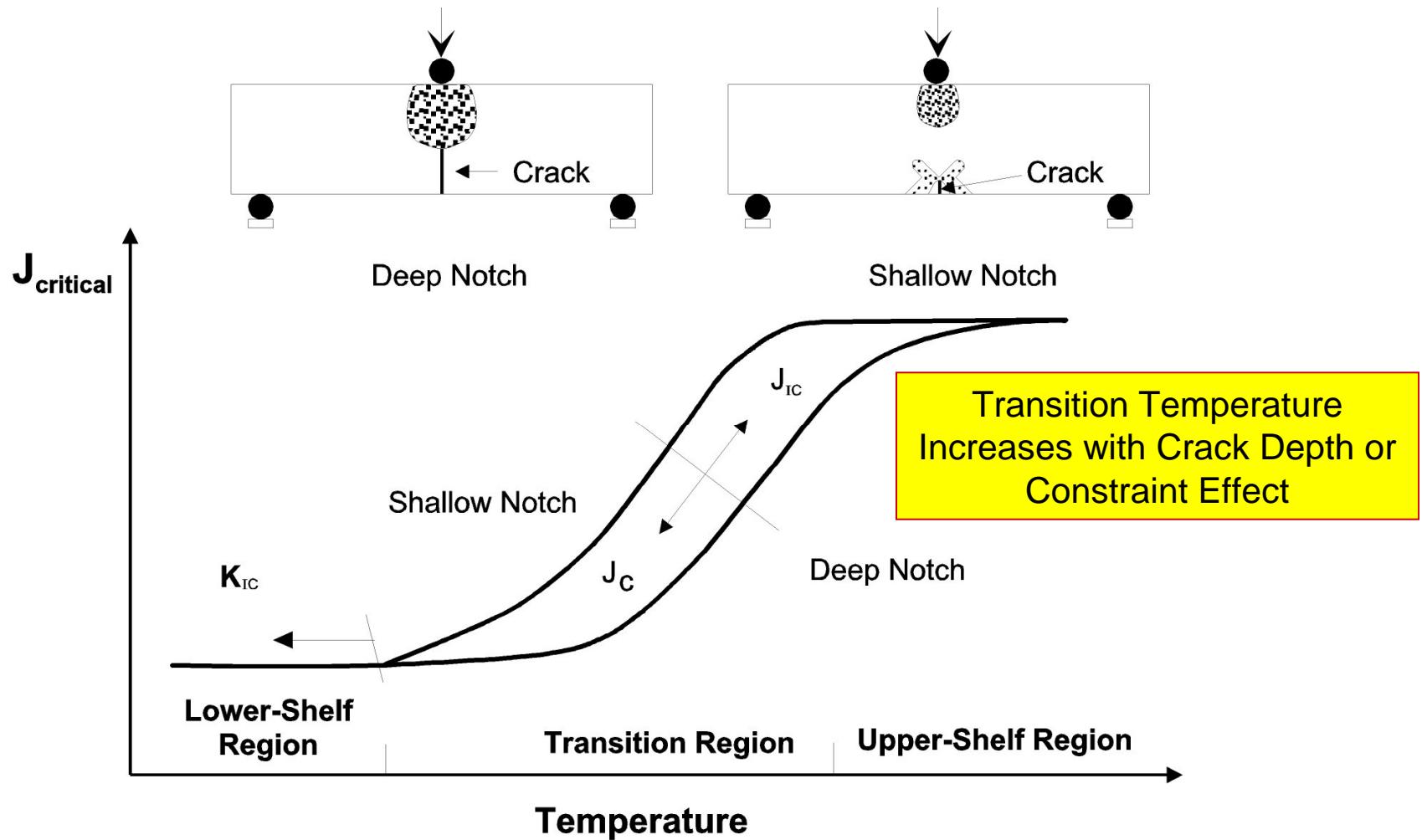
SCATTER & SPECIMEN SIZE EFFECT



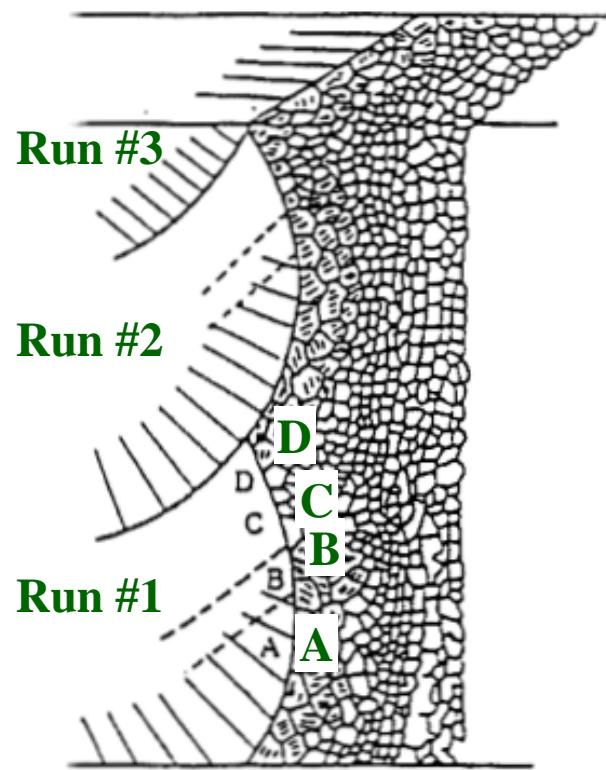
CONSTRAINT EFFECT

- W.A. Sorem et al. *Int. J. Fracture*, (1991), **47**, 105-126
- D. Tigges et al. *ECF 10*, (1994), **1**, 637-64
- J. Sumpter, *ASTM STP 1171*, (1993), 492-502

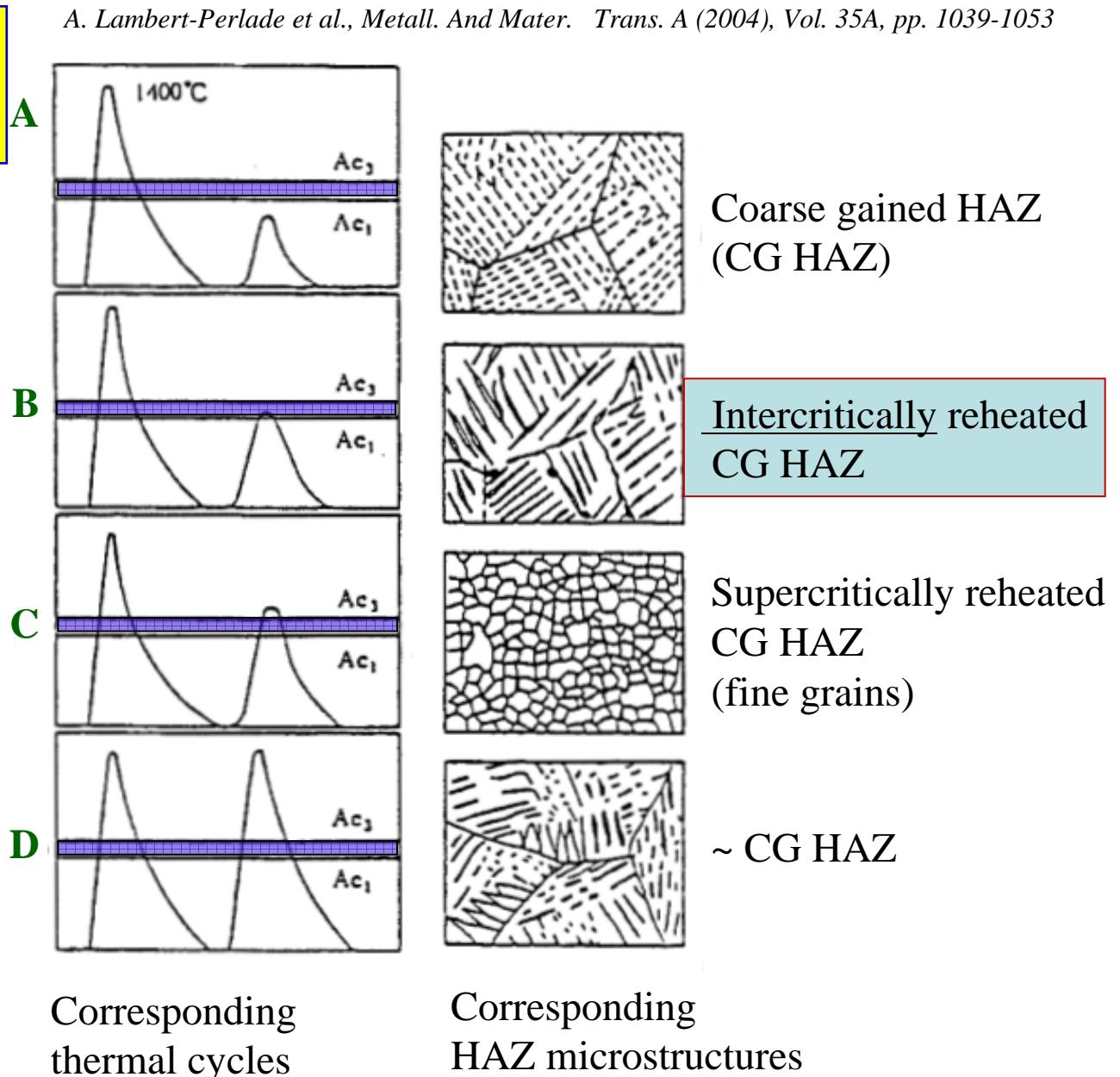
Short Crack Effect



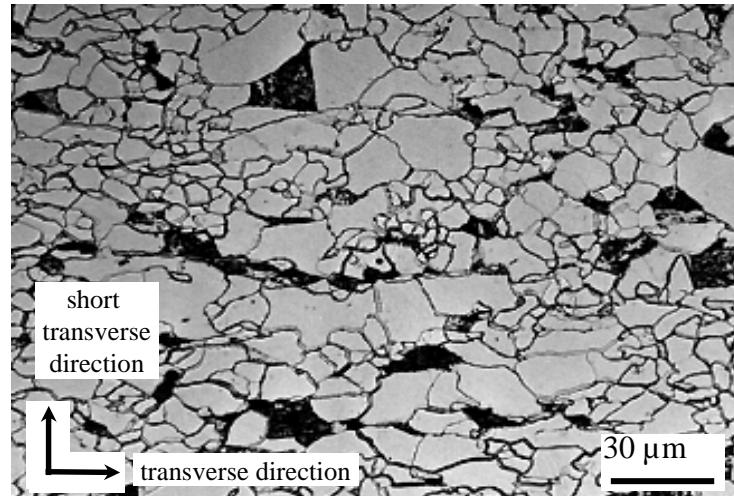
METALLURGICAL INHOMOGENEITIES



Welded Structures

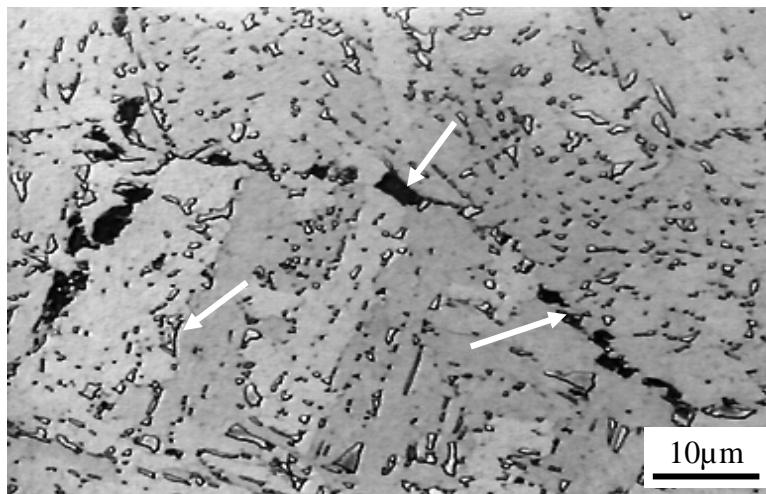


BASE METAL (ferrite-Pearlite)



E 450

ICCGHAZ-25 (Bainite)

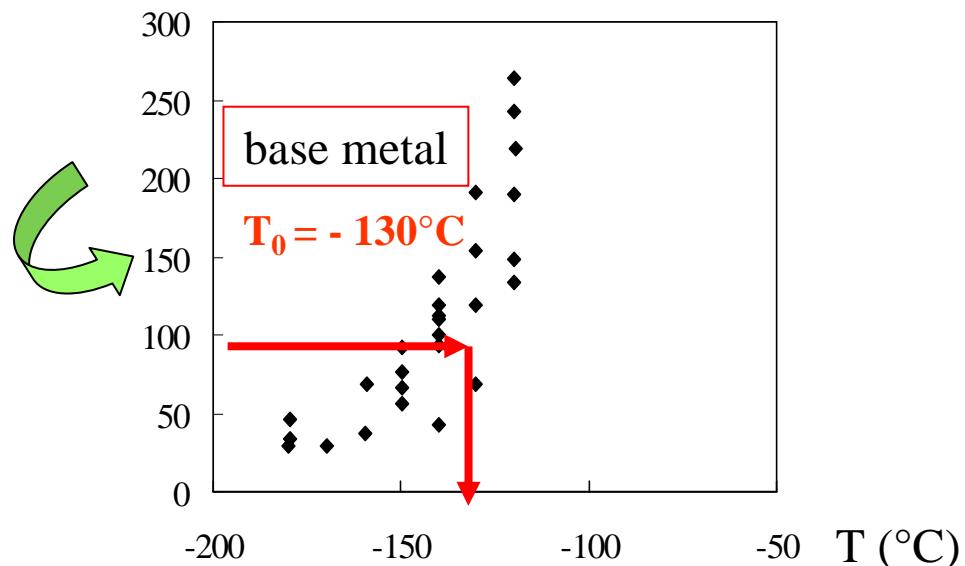


Arrows indicate the presence of martensite- austenite (MA) constituents

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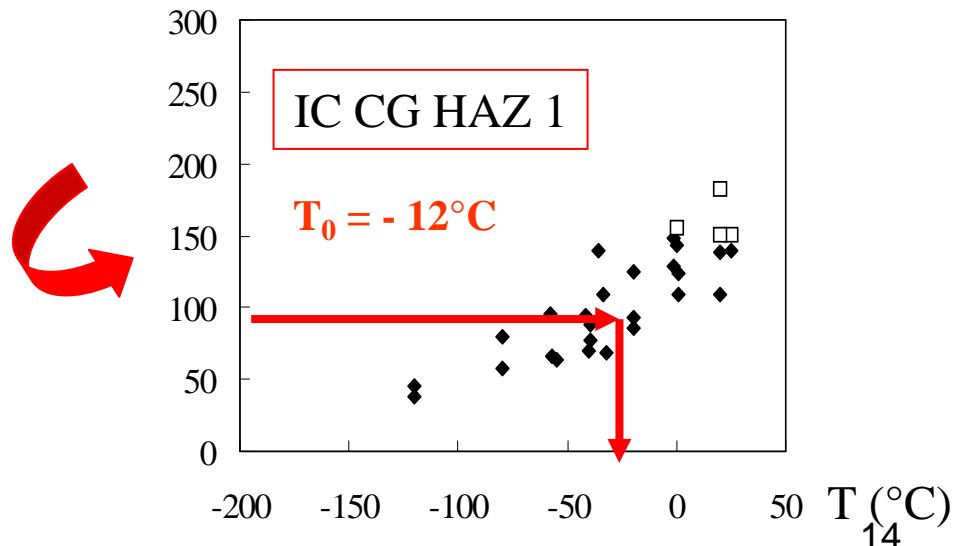
- ductile stable crack propagation over > 0.2 mm

K_{Jc} (MPa.m^{1/2})



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

K_{Jc} (MPa.m^{1/2})



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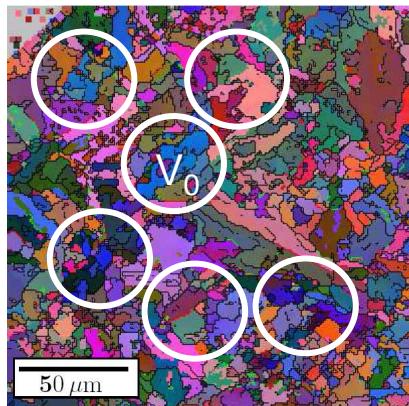
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WEAKEST LINK THEORY - BEREMIN MODEL



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

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

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

Power Law

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

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

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

$$m = 2\beta - 2$$

WEIBULL

Exponential Law

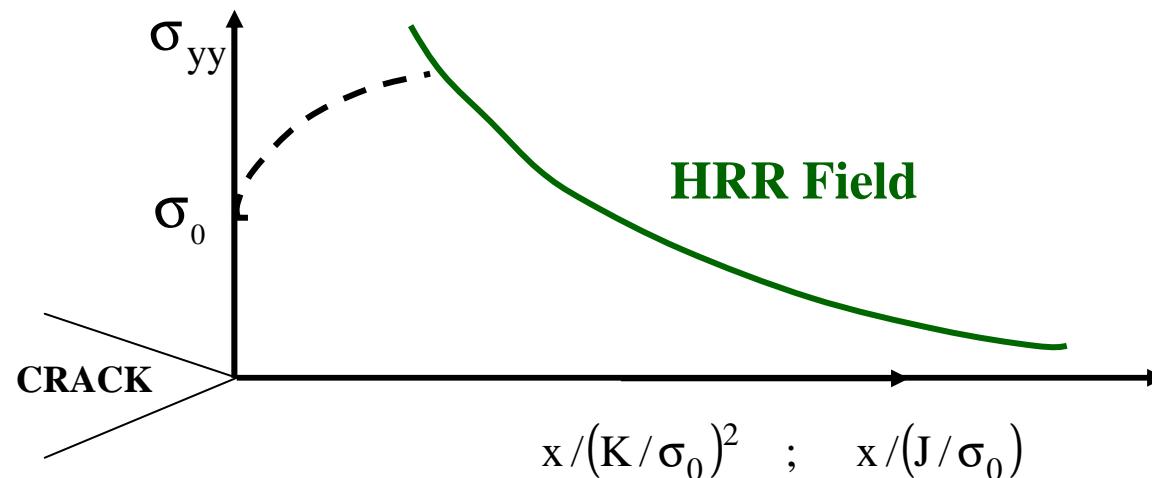
$$p(\text{Size} > l) = \exp \left[- \left(\frac{l - l_u}{l_0} \right)^n \right]$$

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

GUMBLE

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 (1983) (S.S.Y.)



HRR

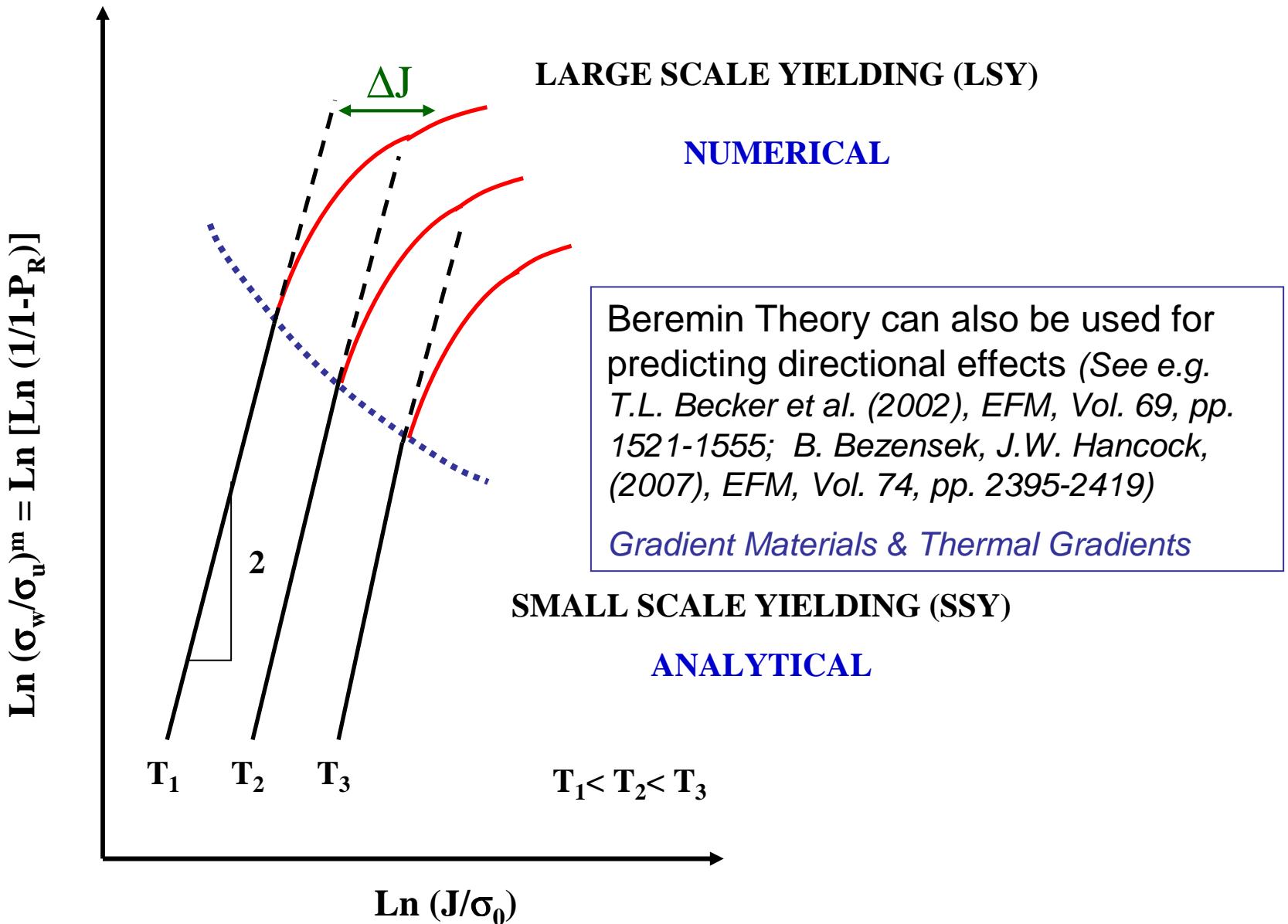
$$\sigma_{YY} = \sigma_0 f\left(\frac{x}{(K/\sigma_0)^2}\right) = \sigma_0 g\left(\frac{x}{J/\sigma_0}\right)$$

B : Specimen Thickness
C_m (n) : constant

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

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

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



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 $K_{IC}, K_{JC} \gg K_I \min$
- when $K_{JC}(\text{medium}) / (\sigma_o(T))^{1-m/4} = \text{Cst}$

- $K_I \min \approx 20 \text{ MPa}\sqrt{\text{m}}$
- $K_o \Rightarrow P_R = 0.63$
- $K_{JC}(\text{medium}) = 30 + 70 \exp[0.019(T - T_o)]$
 $(K \text{ in } \text{MPa}\sqrt{\text{m}}; T \text{ in } {}^\circ\text{C})$
- $T_o \rightarrow K_{JC}(\text{median}) = 100 \text{ MPa}\sqrt{\text{m}}$
for $B = 25 \text{ mm}$

A. Lambert-Perlade, PhD Thesis, 2001

$$\Delta a \leq 0.2 \text{ mm}$$

$$m = 22$$

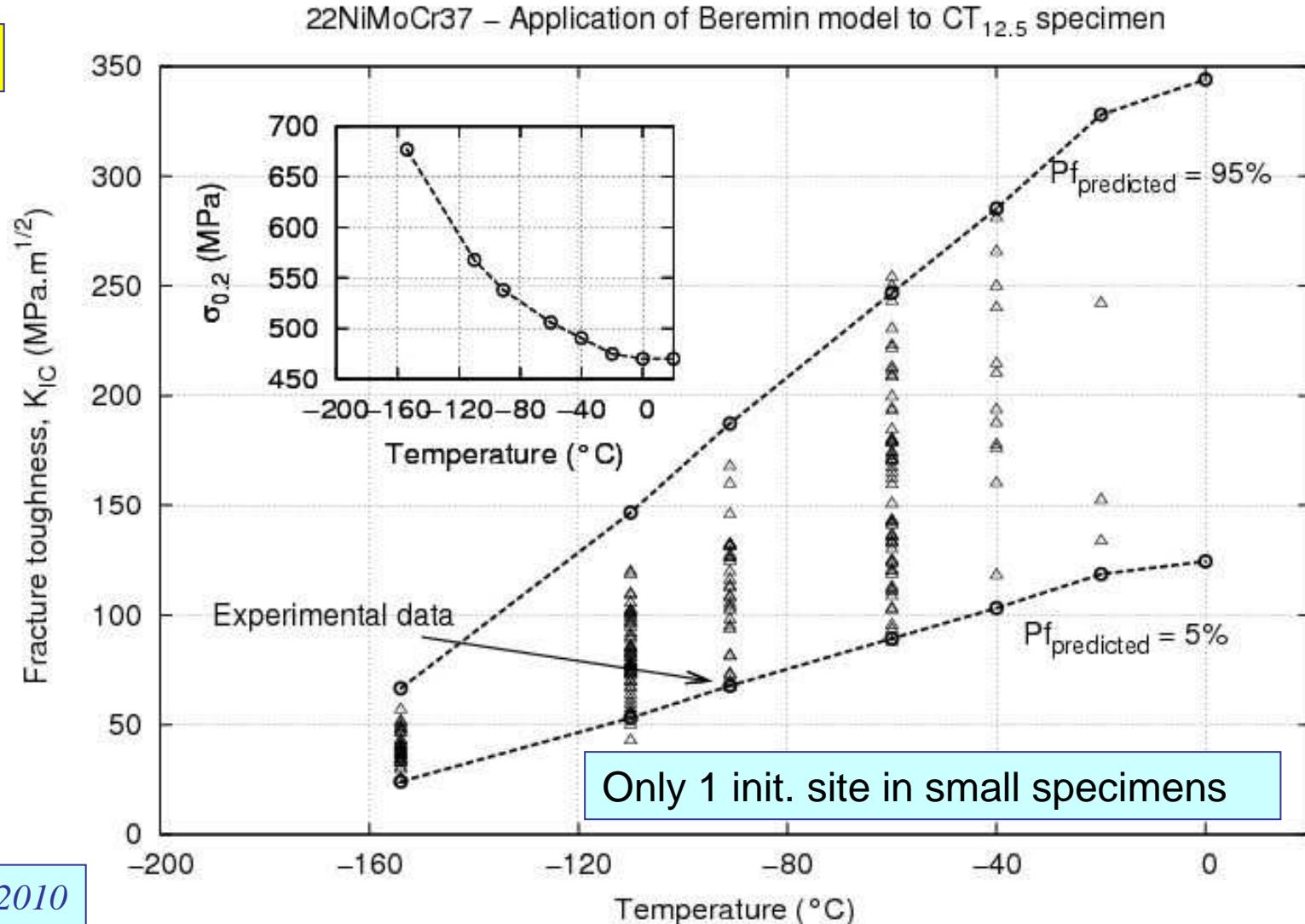
$$\sigma_u = 2550 \text{ MPa}$$

$$C_m = 1.5 \cdot 10^6$$

CT12.5 N = 190



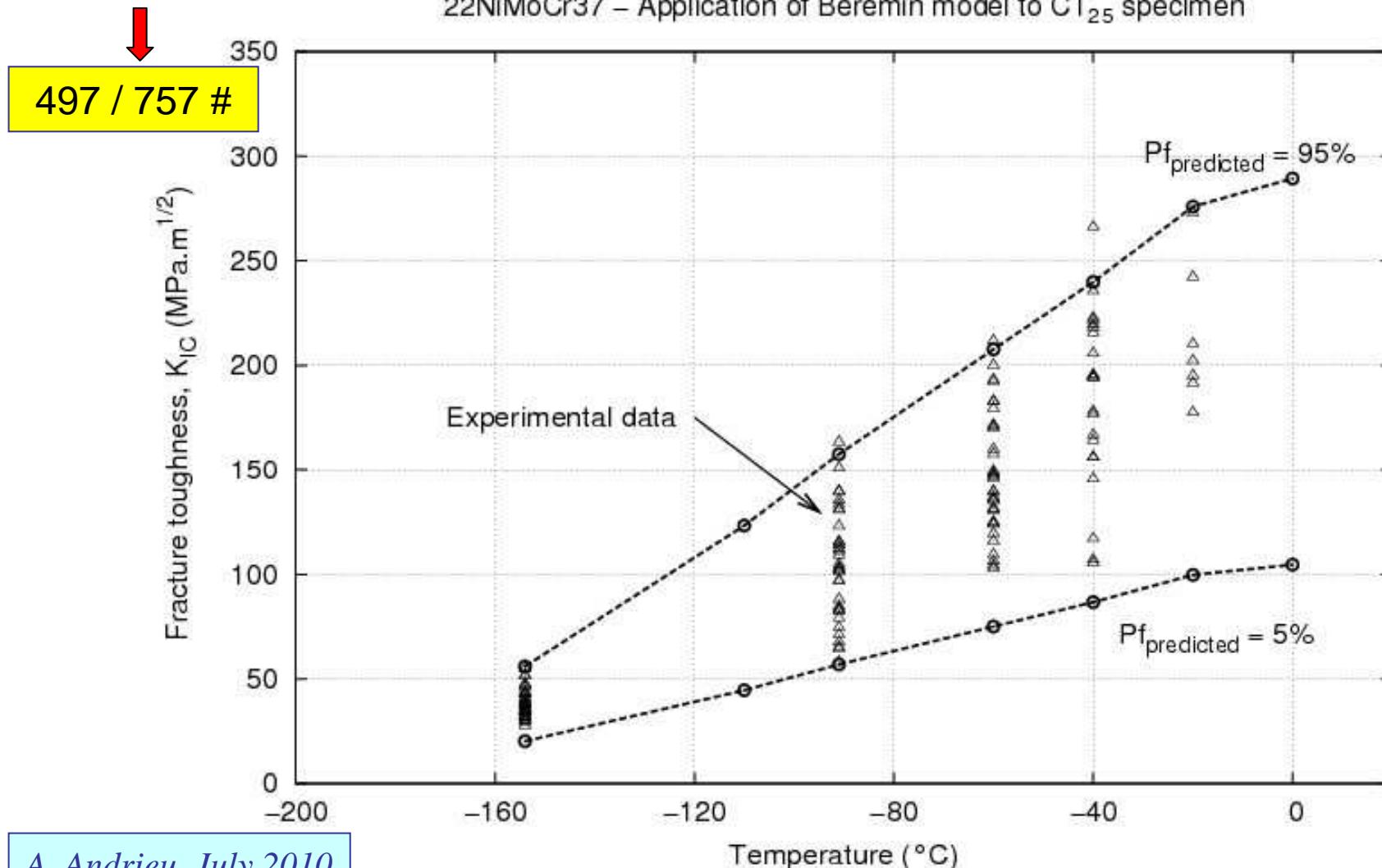
497 / 757 #



A. Andrieu, July 2010

$\Delta a \leq 0.2 \text{ mm}$ $m = 22$ $\sigma_u = 2550 \text{ MPa}$ $C_m = 1.5 \cdot 10^6$

CT25 N = 136

22NiMoCr37 – Application of Beremin model to CT₂₅ specimen

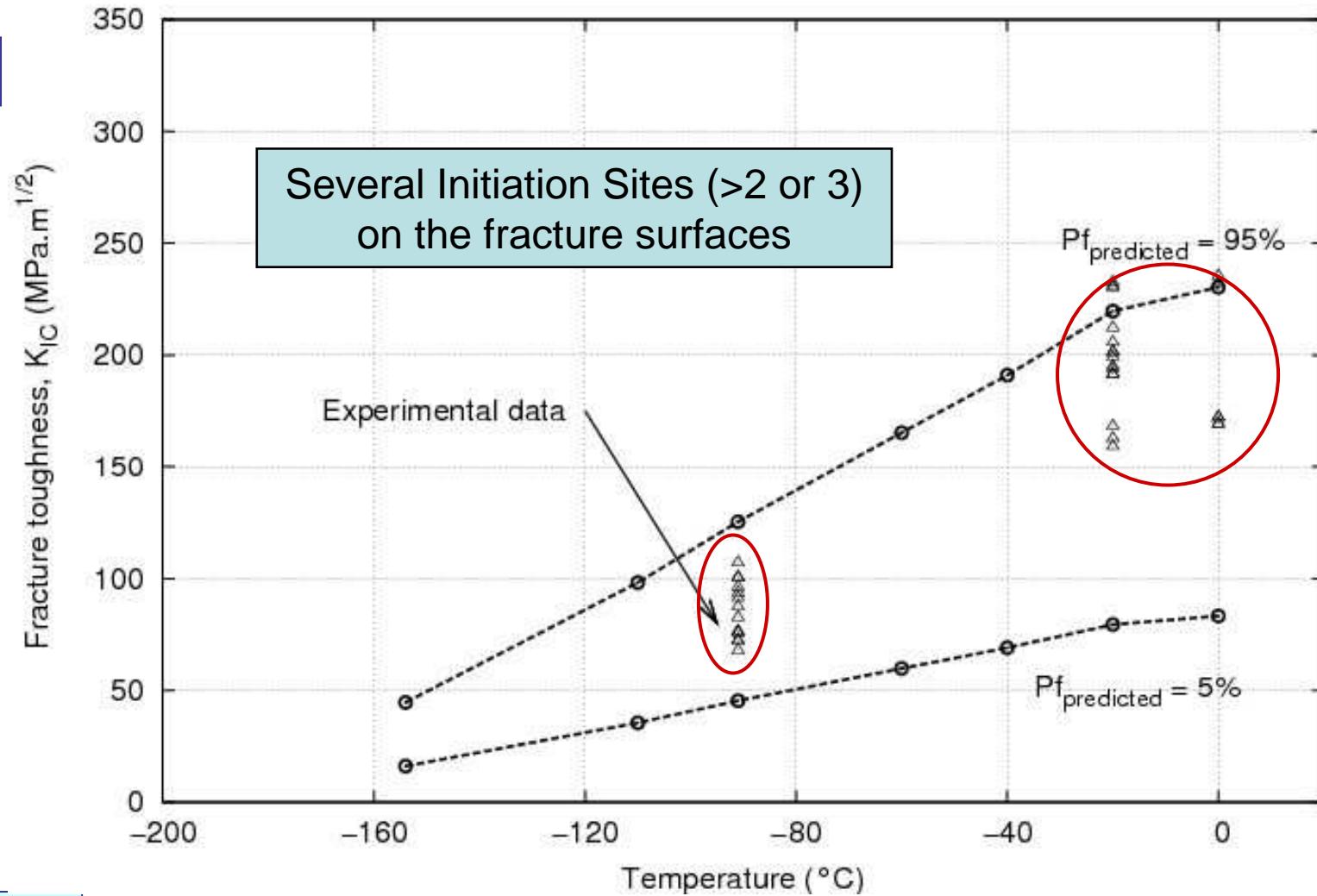
A. Andrieu, July 2010

$\Delta a \leq 0.2 \text{ mm}$ $m = 22 \quad \sigma_u = 2550 \text{ MPa}$ $C_m = 1.5 \cdot 10^6$

CT100 N = 34



497 / 757 #

22NiMoCr37 – Application of Beremin model to CT₁₀₀ specimen

EURO FRACTURE TOUGHNESS DATA SET

J.Heerens, D.Hellmann, EFM,
2002, Vol.69, pp.421-449

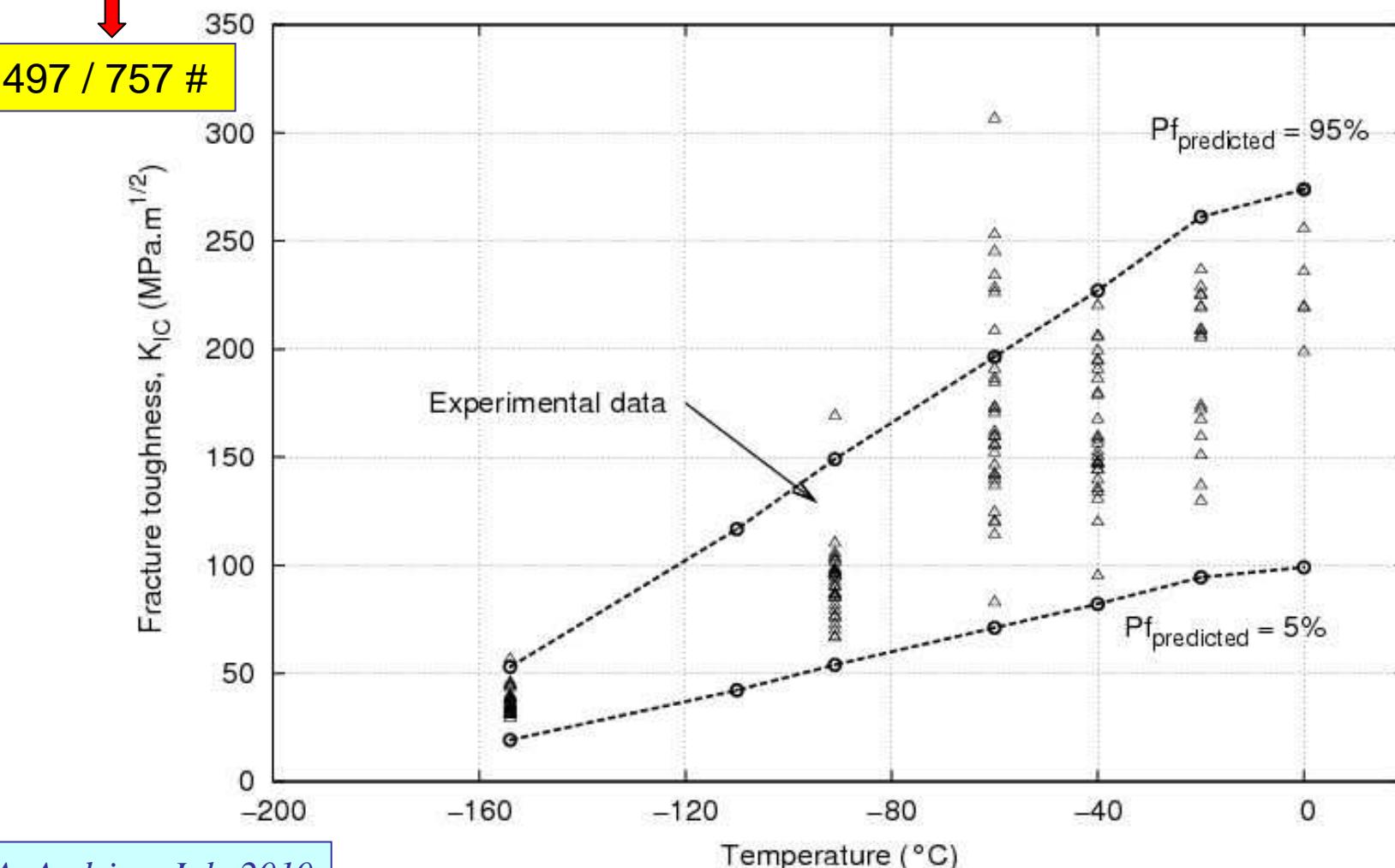
$\Delta a \leq 0.2 \text{ mm}$

$m = 22$ $\sigma_u = 2550 \text{ MPa}$

$C_m = 1.5 \cdot 10^6$

CT50 N = 137

22NiMoCr37 – Application of Beremin model to CT₅₀ specimen



A. Andrieu, July 2010

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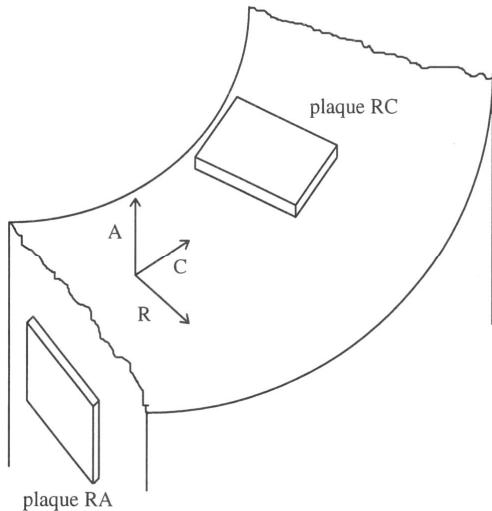
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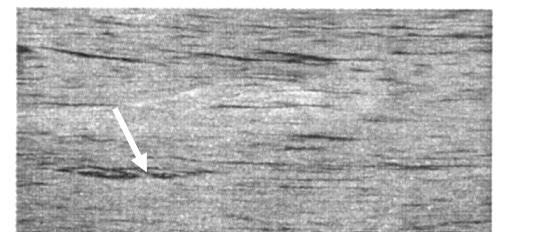
VI. CONCLUSIONS

16MND5 PWR STEEL - SEGREGATED ZONES

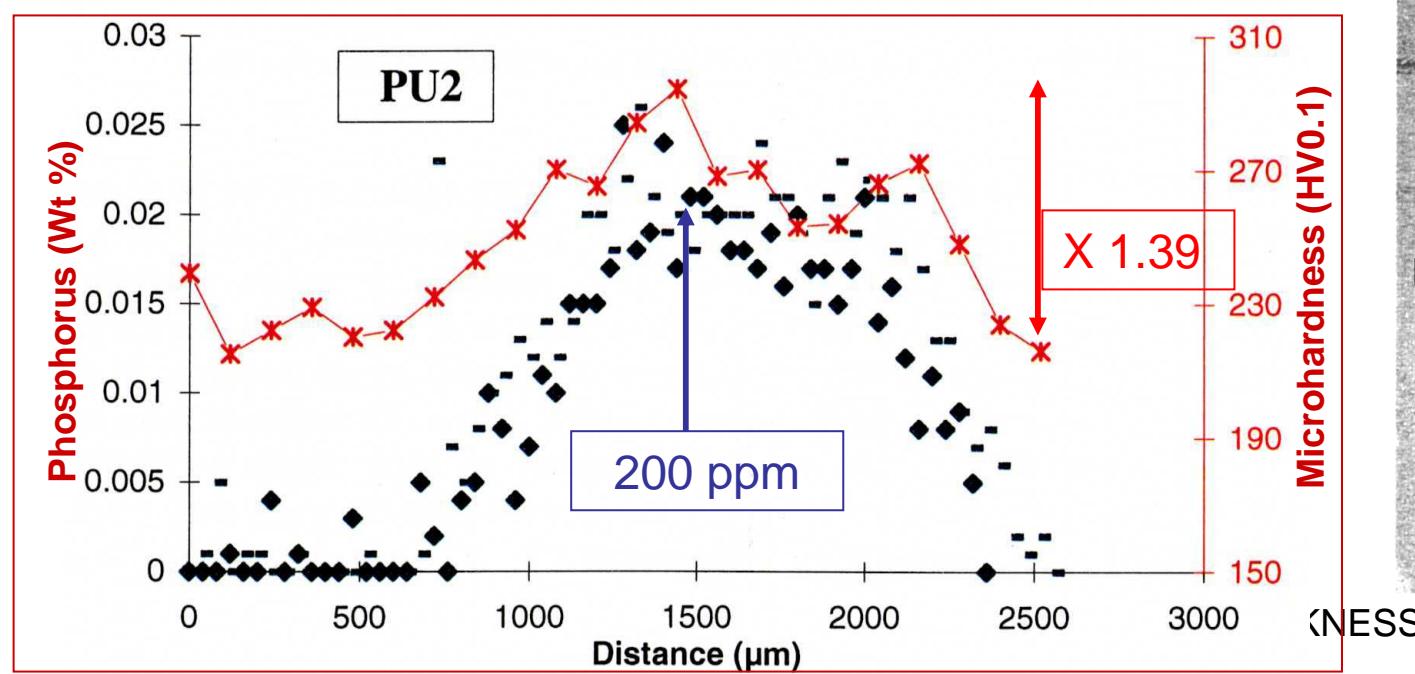
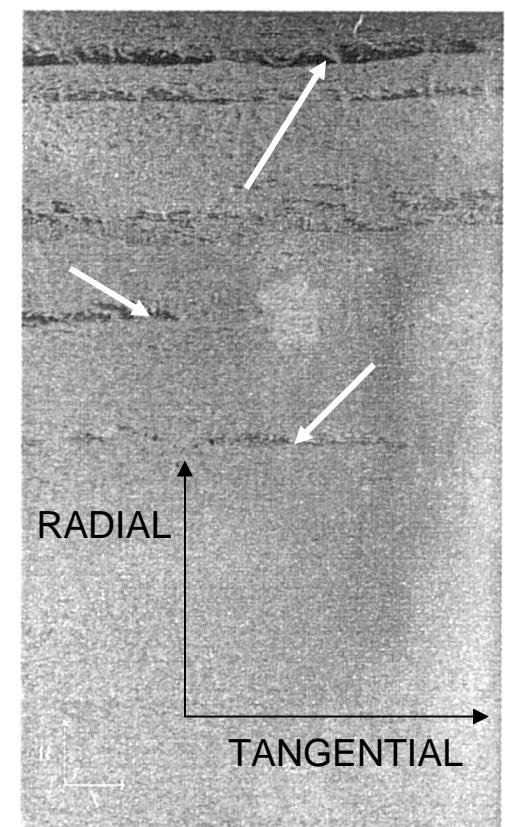


C. Naudin, PhD Thesis, 1999

↓ peau interne ↓ INTERNAL



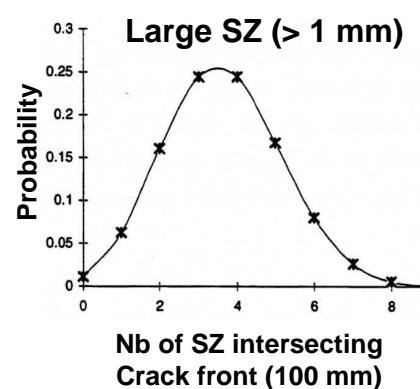
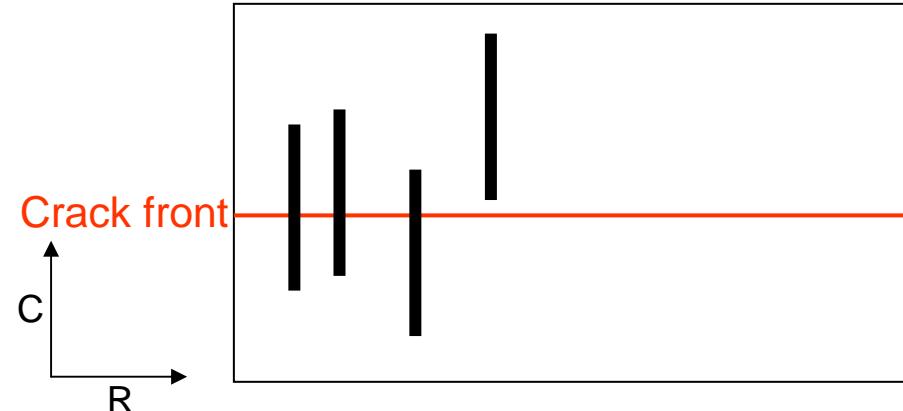
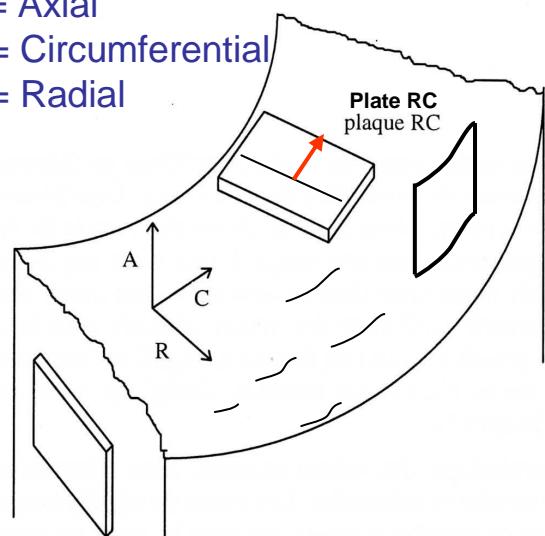
INTERNAL ↓ peau interne ↓



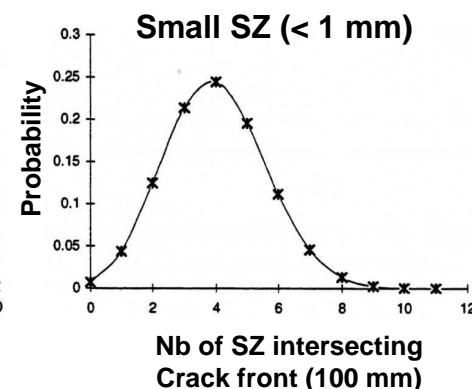
16MND5 PWR STEEL - SEGREGATED ZONES

C. Naudin, PhD Thesis, 1999

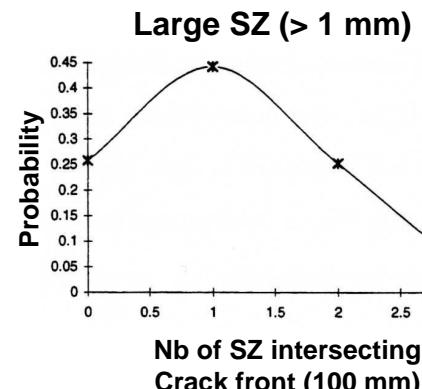
A = Axial
C = Circumferential
R = Radial



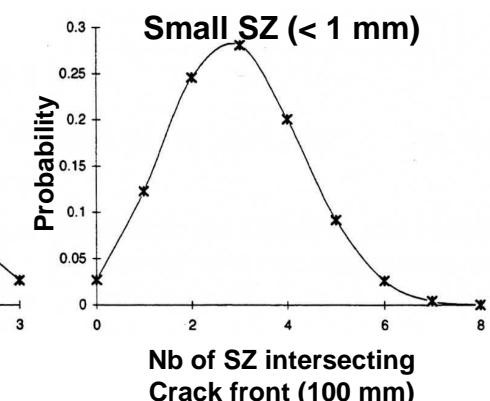
$$\bar{N} = 3.64 \pm 2.31$$



$$\bar{N} = 4 \pm 2.55$$



$$\bar{N} = 1.10 \pm 0.69$$

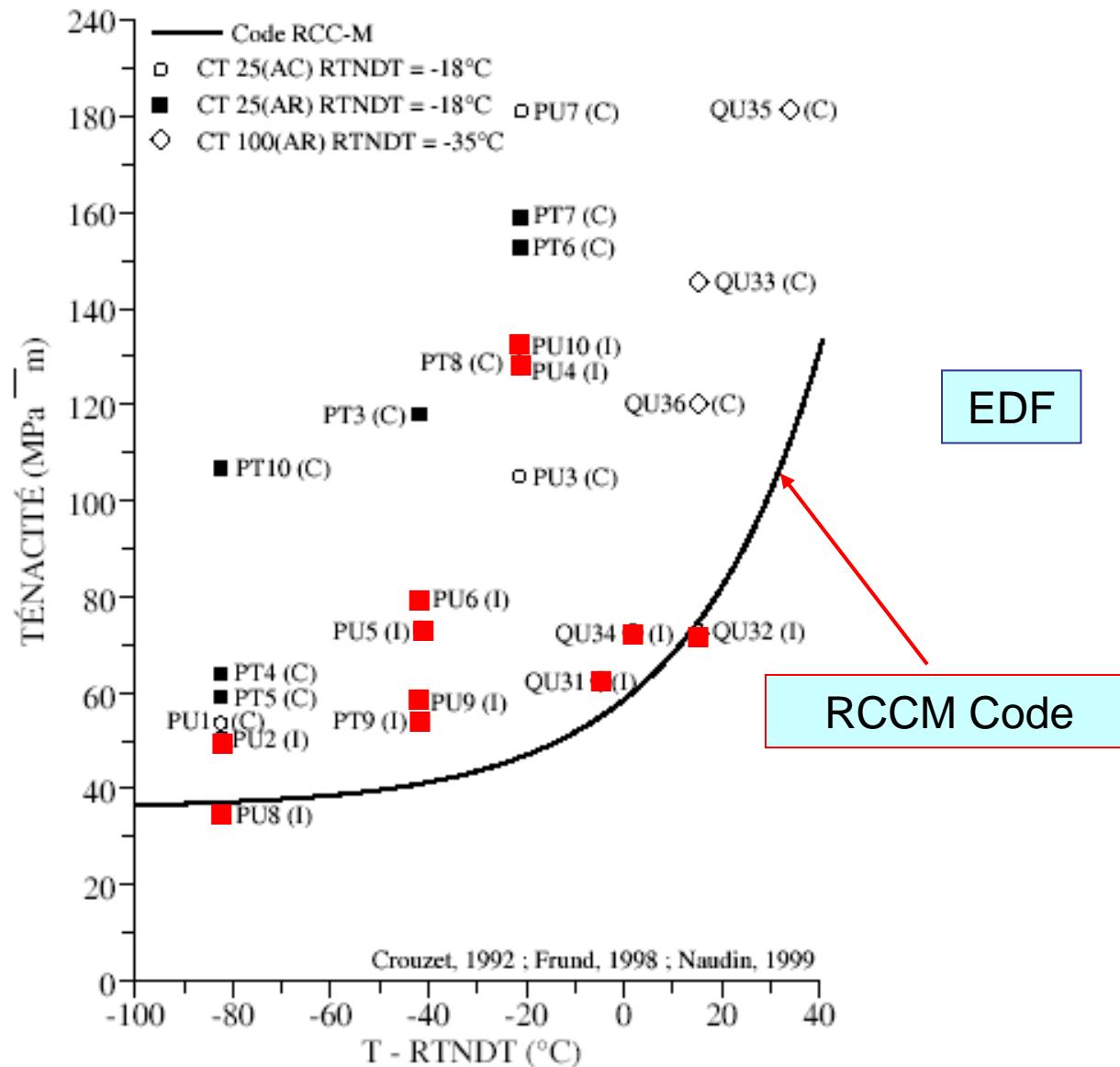


$$\bar{N} = 2.91 \pm 1.85$$

16MND5 PWR STEEL - SEGREGATED ZONES

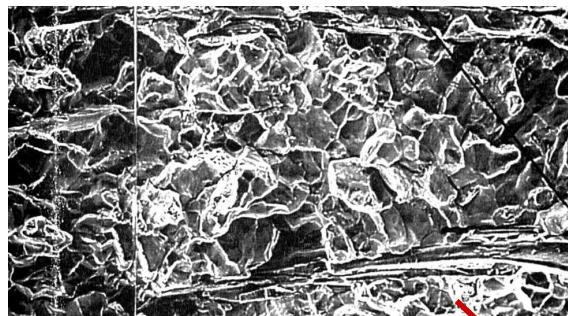
C.Naudin ,PhD, 1999

C = Cleavage
I = Intergranular



16MND5 PWR STEEL - SEGREGATED ZONES

C. Naudin, PhD, 1999

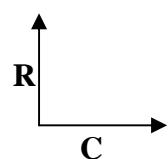
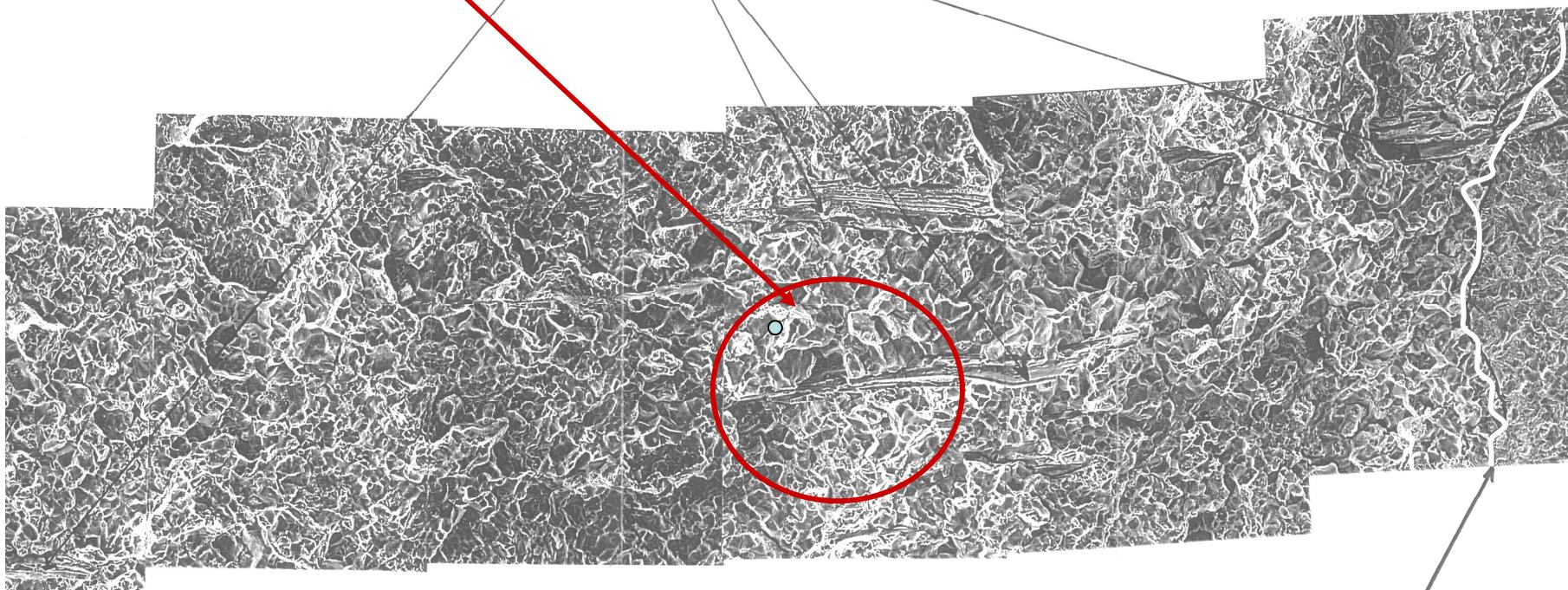


MnS inclusions

Intergranular Fracture

CT Specimen - Number PU5
Intergranular initiation sites
Temperature = - 60°C

$$K_{IC} = 74 \text{ MPa}\sqrt{\text{m}}$$



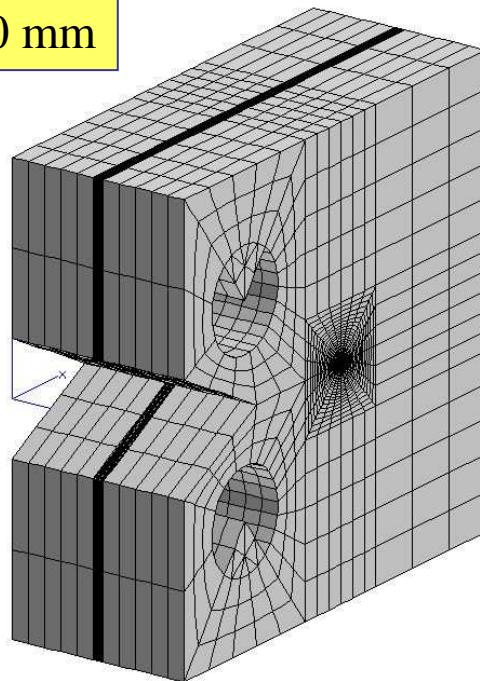
Crack propagation direction

200 μm

Fatigue crack front

28

CT Specimen W = 20 mm



FE Calculations

Double Isotropic Hardening For Both Materials

$$\sigma_Y^{SZ} / \sigma_Y^{BM} = 1.39$$

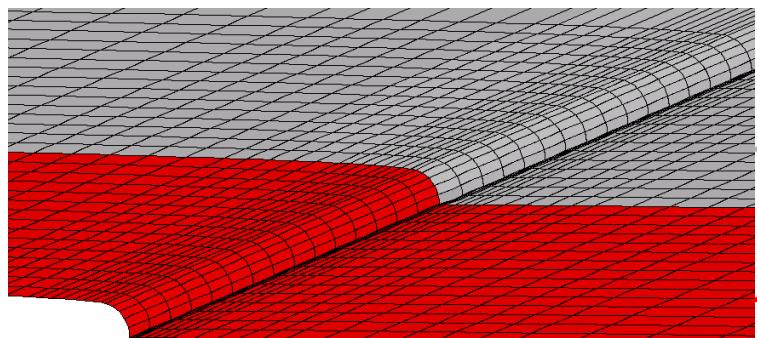
A T=-100°C	E (GPa)	$R_{0.2}$ (MPa)	B1	Q1	B2	Q2
MB	200	539.6	12.16	324.3	0.422	296
MI	240	750	12.16	434	0.422	450

Constitutive Equations

T = -100°C	σ_u (MPa)	m	V_0 en μm^3
MI	3700	15	50
MB	2710	22	50

Fracture Properties

$$K = 45 \text{ MPa.m}^{0.5}$$

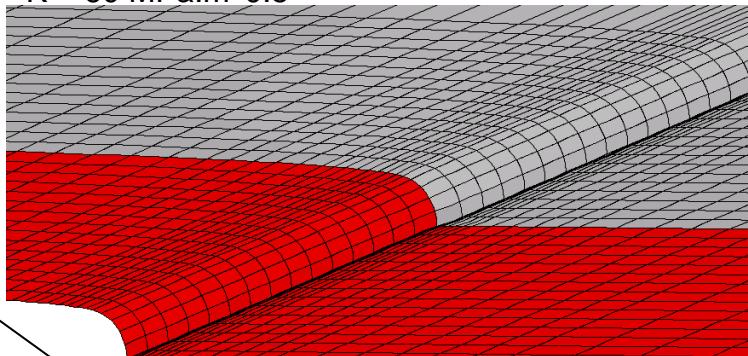


CRACK TIP

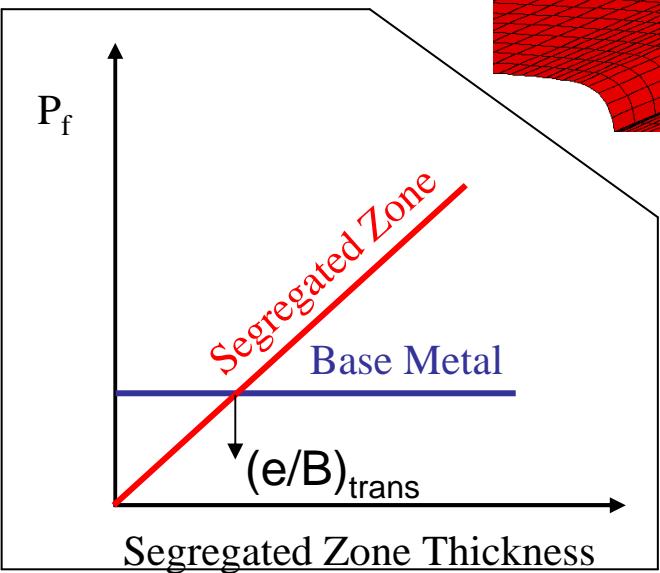
MATRIX – Soft & Tough Material

SEGREGATED Material
Strong & Brittle

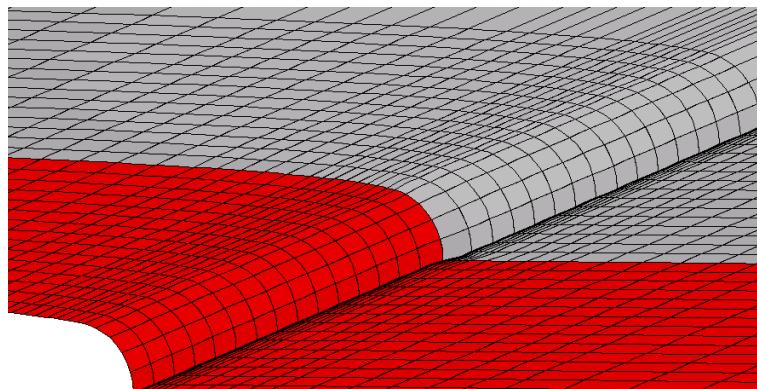
$$K = 60 \text{ MPa.m}^{0.5}$$



CTOD



$$K = 75 \text{ MPa.m}^{0.5}$$



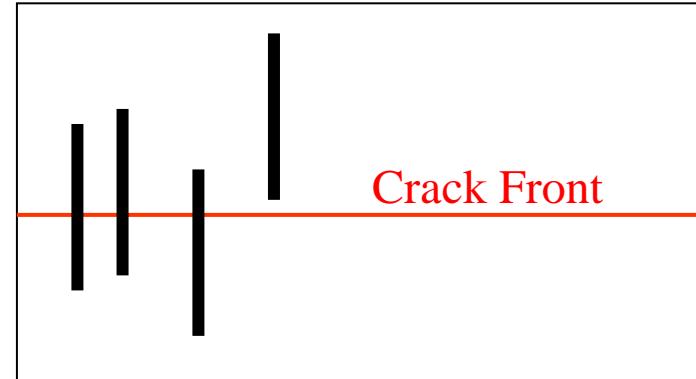
$$(e / B)_{trans} = \sigma_{Y1}^{m_1-2} / \sigma_{Y2}^{m_2-2} \cdot V_{02} / V_{01} \cdot \sigma_{u2}^{m_2} / \sigma_{u1}^{m_1} \cdot C_{m1} / C_{m2}$$

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16MND5 PWR STEEL - SEGREGATED ZONES

$$(CTOD)_b = (CTOD)_l \quad l = \text{segregated zone}$$

$$K_l = K_b \left(\frac{\sigma_l}{\sigma_b} \right)^{1/2}$$



$P_{\text{int}}(n) = \text{Probability that } n \text{ SZ intersect the crack front}$

$$\text{Poisson's Law: } P_{\text{int}}(n) = \exp(-\theta Bl) \frac{(\theta Bl)^n}{n!}$$

$$\theta = \text{Area fraction of SZ} (2.66 \cdot 10^{-2} \text{ mm}^{-2})$$

$$(1 - P_f) = (1 - P_{f1})(1 - P_{f2})$$

Base
SZ

$l = \text{platelets mean length}(15 \text{ mm})$

$$= \exp - \left\{ \frac{K_{IC}^4 B_{eff} \sigma_b^{m_b-4} C_m^b}{V_0 \sigma_u^{m_b}} \right\}$$

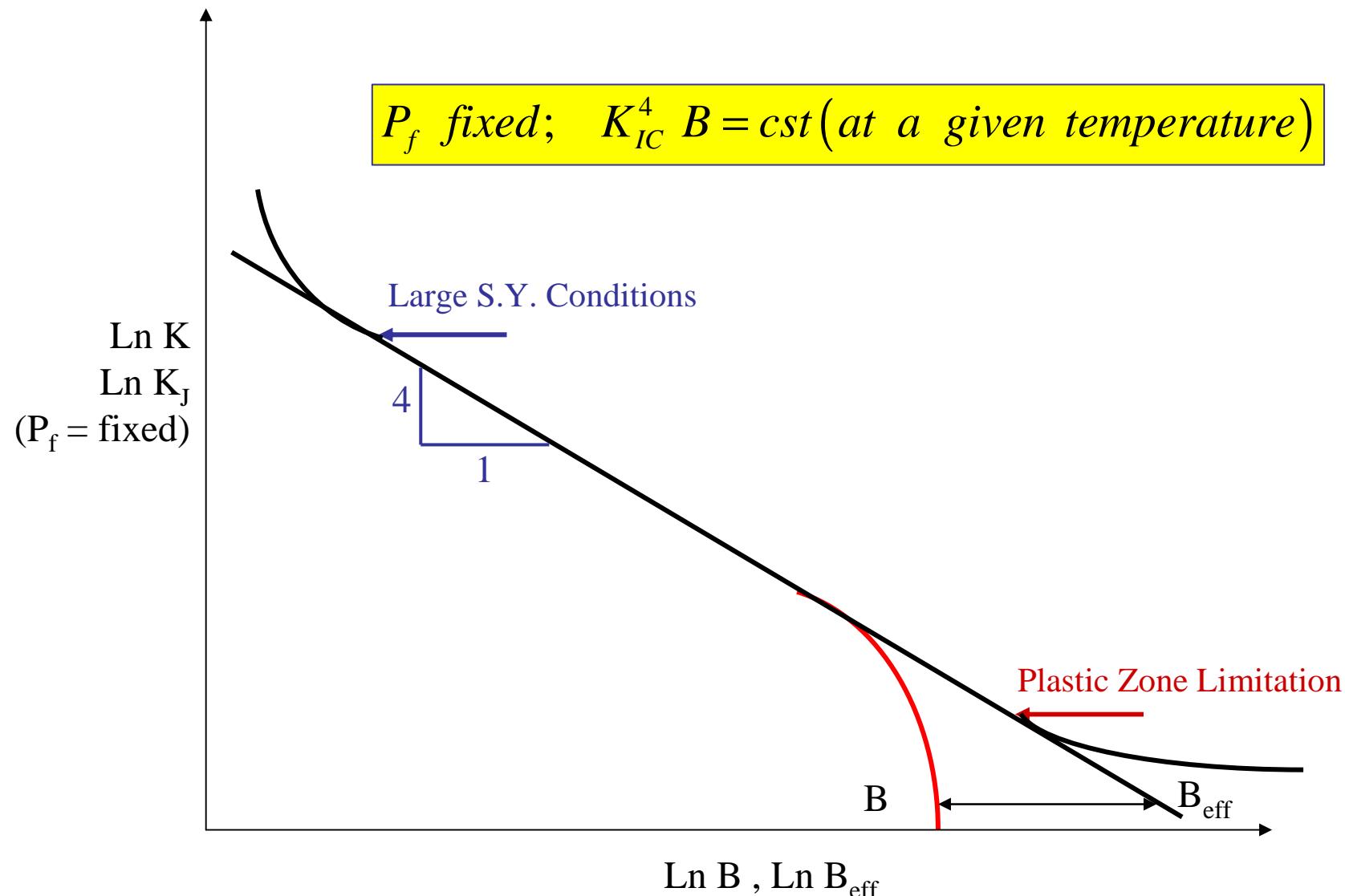
$$B_{eff} = B \left[\left(1 - \frac{e_{eff}}{B} \right) + \frac{e_{eff}}{B} \left(\frac{\sigma_l^{m_l-2}}{\sigma_b^{m_b-2}} \right) \left(\frac{\sigma_{ub}^{m_b}}{\sigma_{ul}^{m_l}} \right) \left(\frac{C_m^l}{C_m^b} \right) \right]$$

$$e_{eff} = P_{\text{int}} n \bar{e}$$

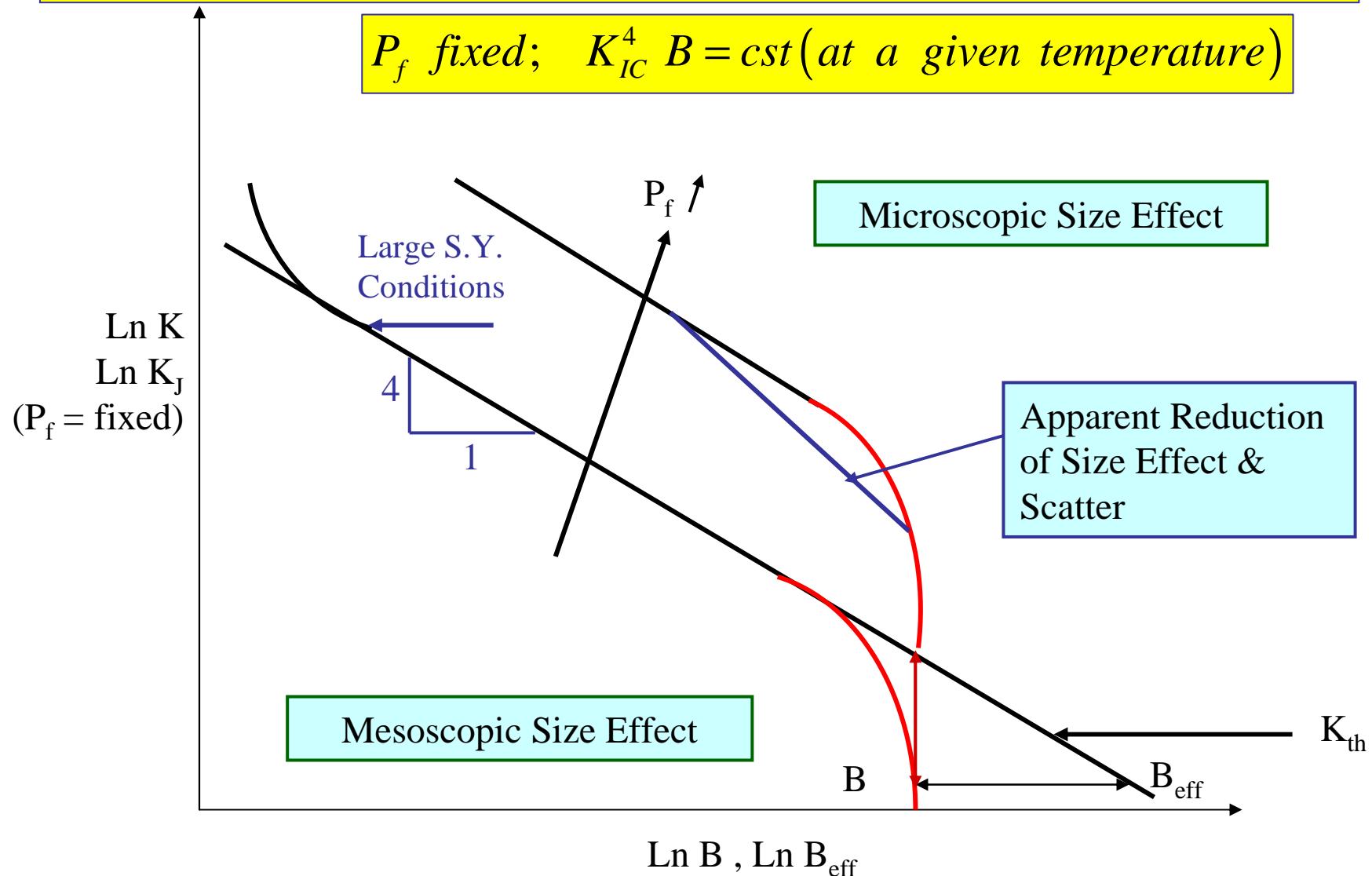
$$\bar{e} = \text{mean platelet thickness}(2 \text{ mm})$$

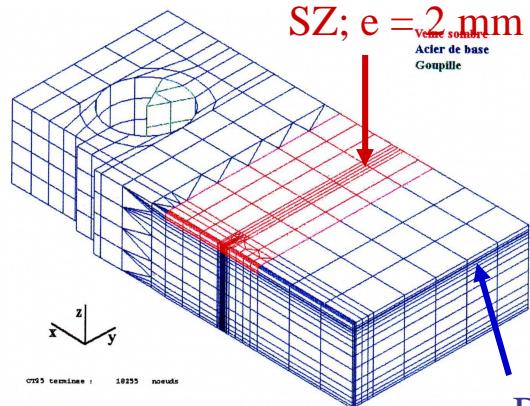
31

Material Size Requirements for Applying SSY Solution to Macroscopically Inhomogeneous Materials



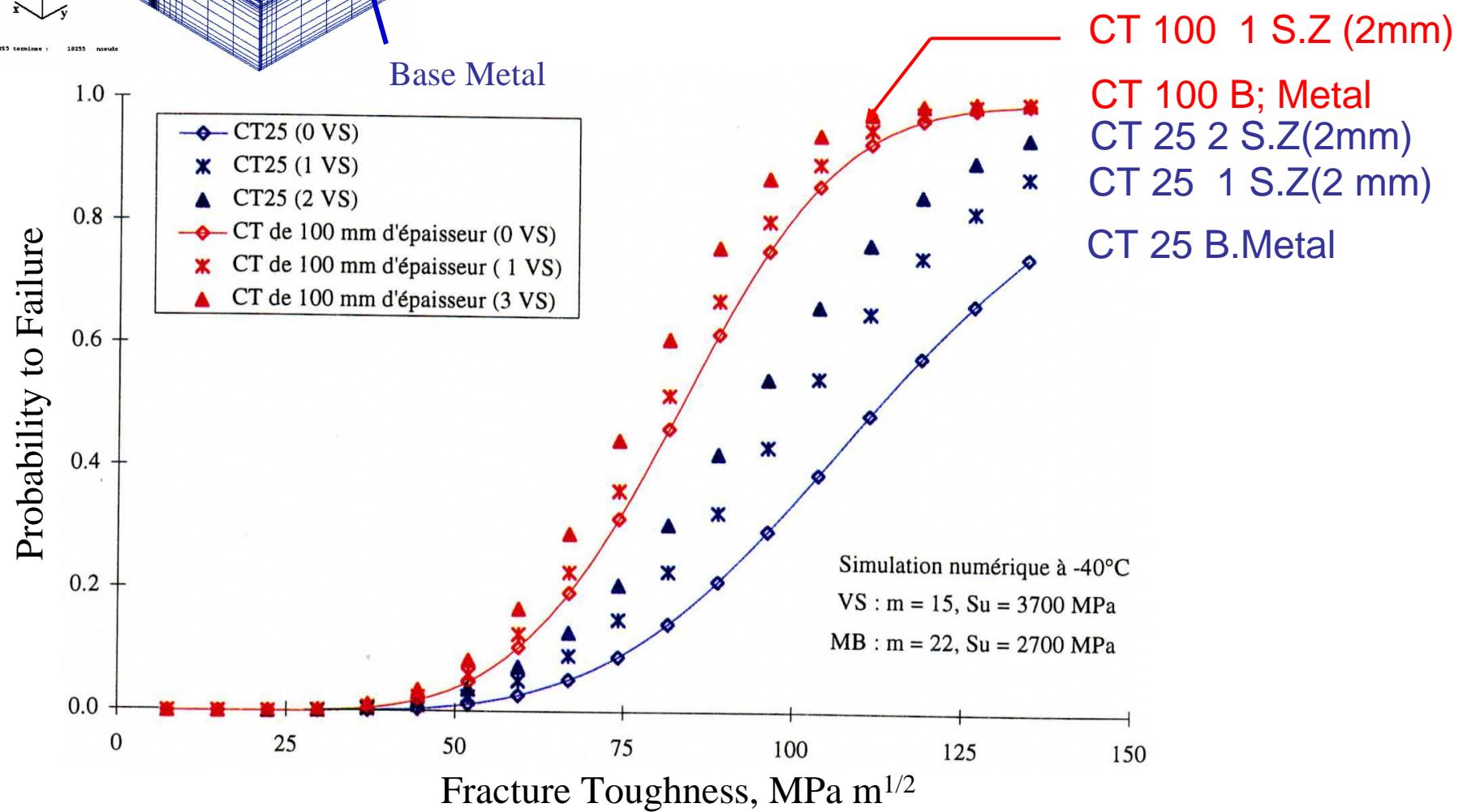
Material Size Requirements for Applying SSY Solution to Macroscopically Inhomogeneous Materials

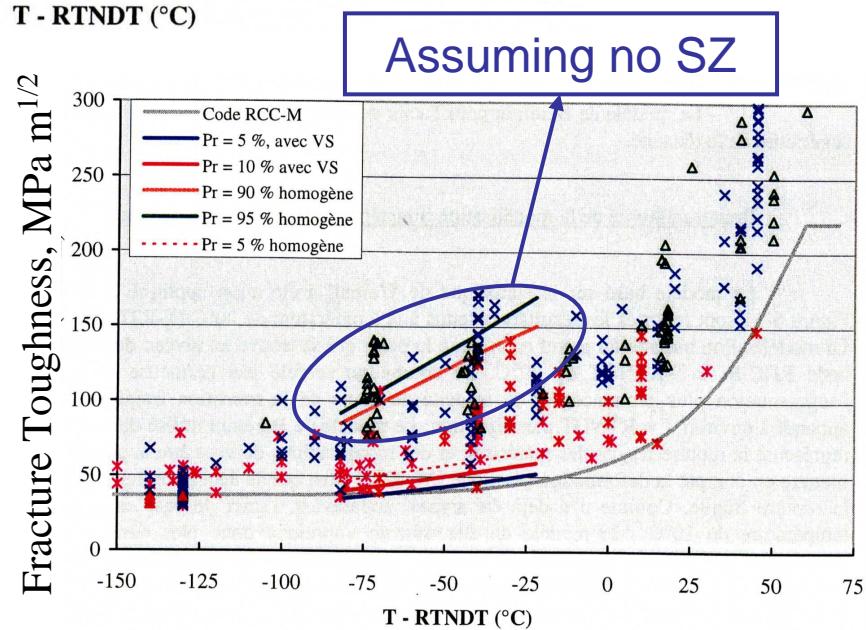
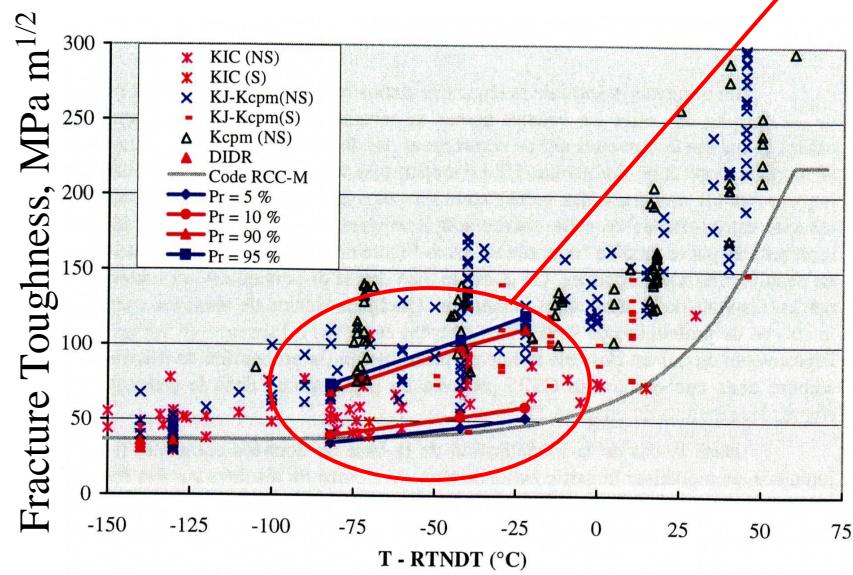
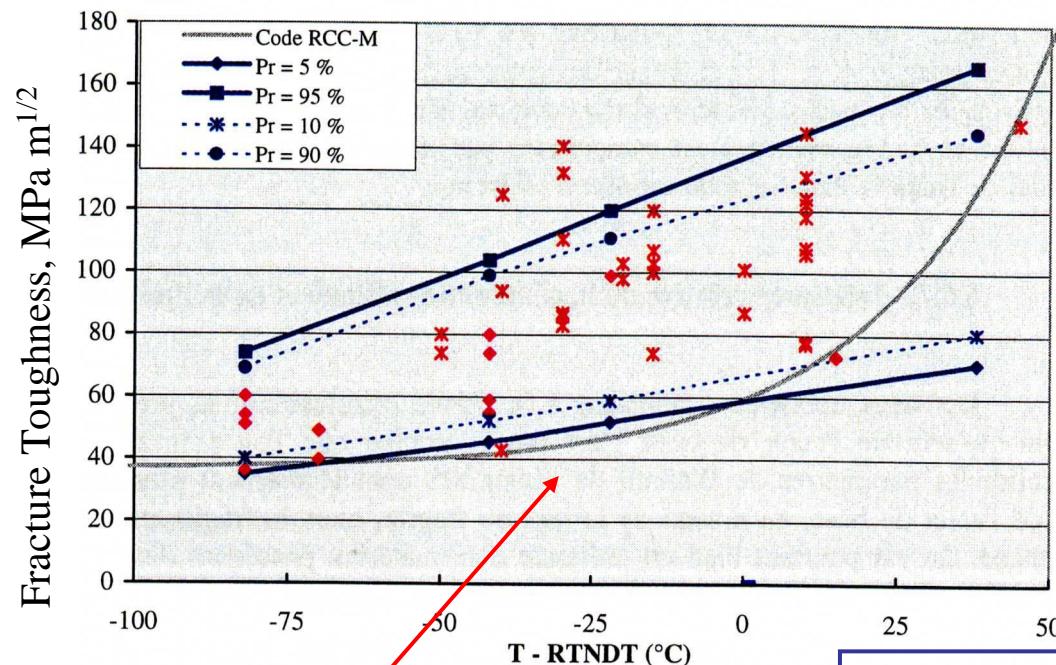




$$BM \quad \sigma_Y = 539.6 \text{ MPa}, \sigma_u = 2710 \text{ MPa}, m = 22, V_0 = (50\mu\text{m})^3$$

$$SZ \quad \sigma_Y = 750 \text{ MPa}, \quad \sigma_u = 3700 \text{ MPa}, m = 15, V_0 = (50\mu\text{m})^3$$





BEREMIN MODEL – LIMITATIONS - FURTHER DEVELOPMENTS

- (1) • THRESHOLD WEIBULL STRESS ?**

- (2) • STRAIN and/or TEMPERATURE DEPENDENCE OF MODEL PARAMETERS (m and σ_u)?**

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

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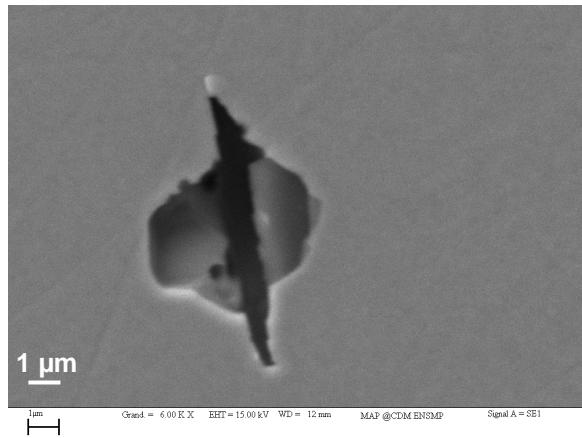
IV. DUCTILE FRACTURE : Micromechanisms & Modeling Ductile Crack Growth

V. DUCTILE TO BRITTLE TRANSITION

VI. CONCLUSIONS

FURTHER DEVELOPMENTS

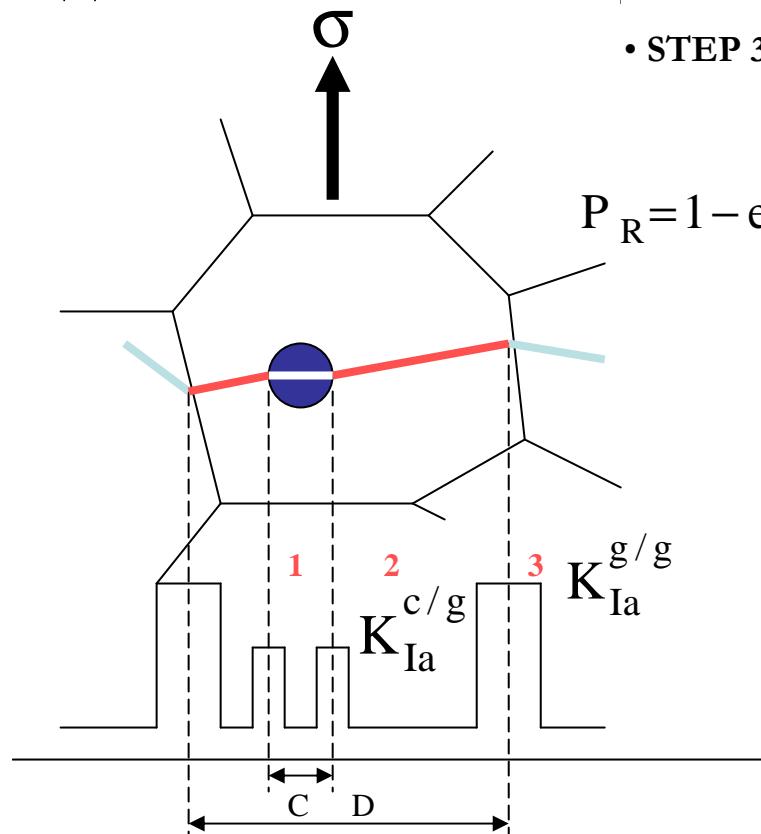
- Tables for C_m Coefficient in Beremin Expression
- $\gamma_{\text{eff}} \gg \gamma_s$ ($\times 1000 - 10\,000$)
 - *Grain boundary crossing in particular twist grain boundaries*
 - *Cleavage microcrack percolation in a damaged zone at crack tip*
 - *Multiple barrier models : Sequential micromechanisms and conditionnal statistics*
- Another source of scatter : Stress distribution in polycrystals
 - *Polycrystalline Plasticity*



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

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

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

+ Conditionnal Probability

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CRACKS AT GRAIN BOUNDARIES (1)

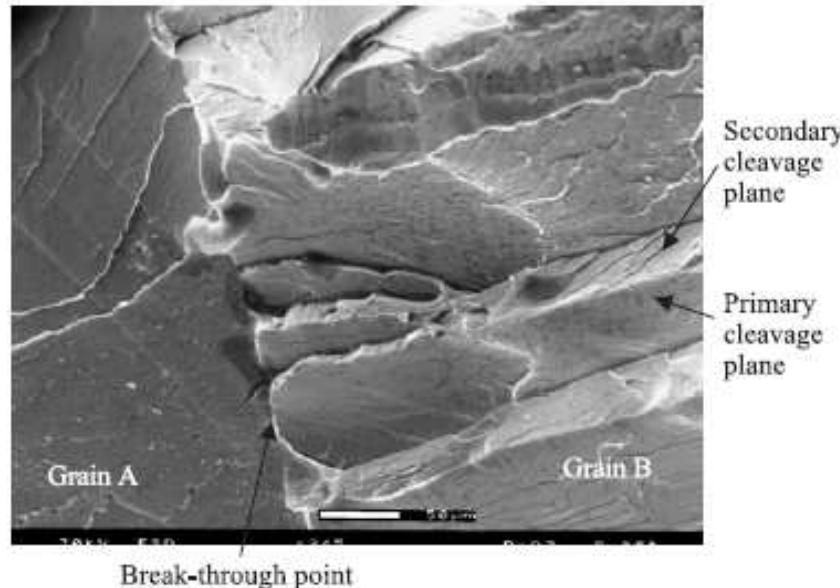
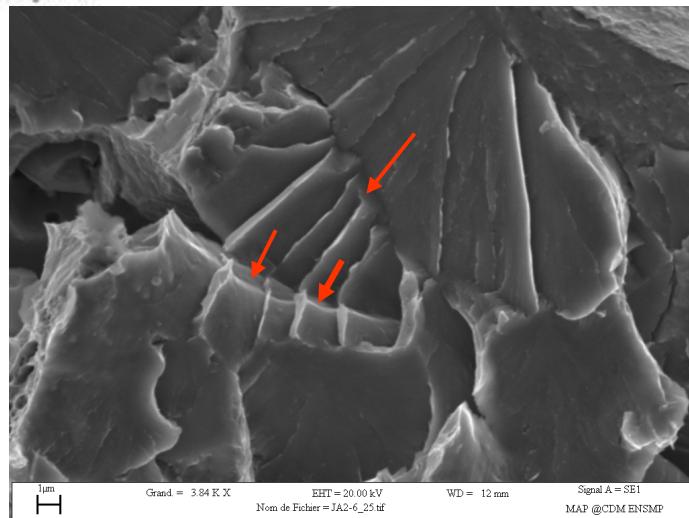


Fig. 1. SEM fractography of a high-angle grain boundary in a Fe-3%S bicrystal.



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

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

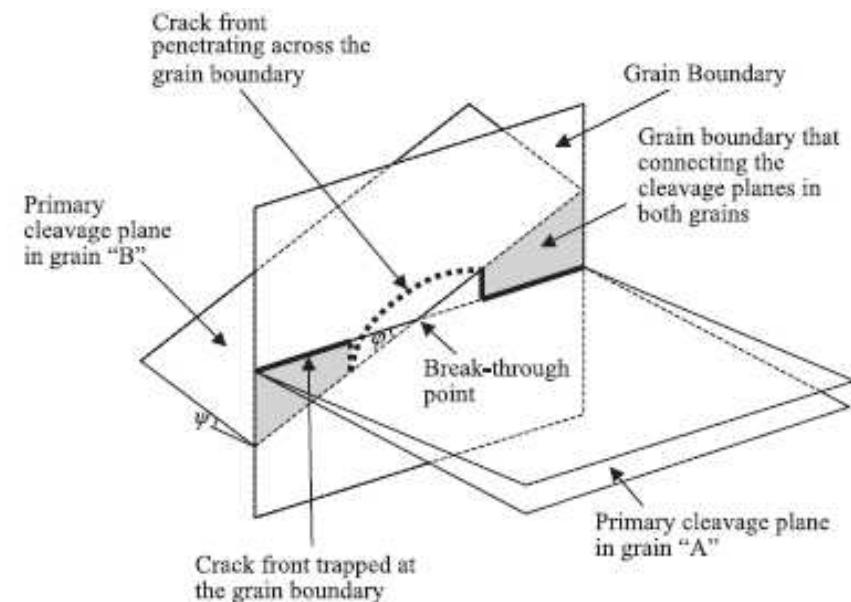
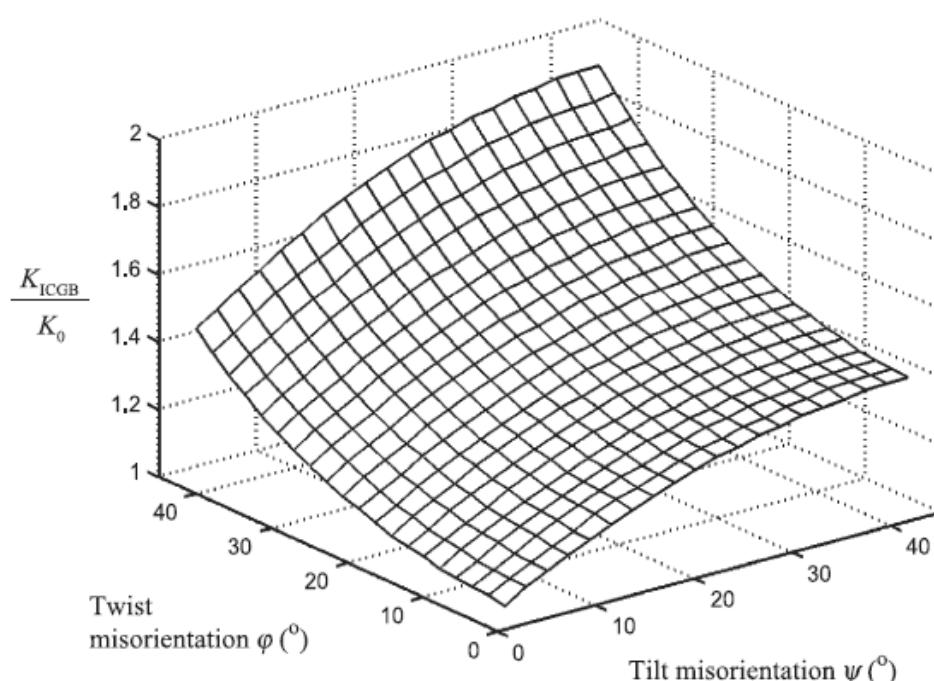


Fig. 2. A schematic diagram of the cleavage cracking across a high-angle grain boundary around a breakthrough point.

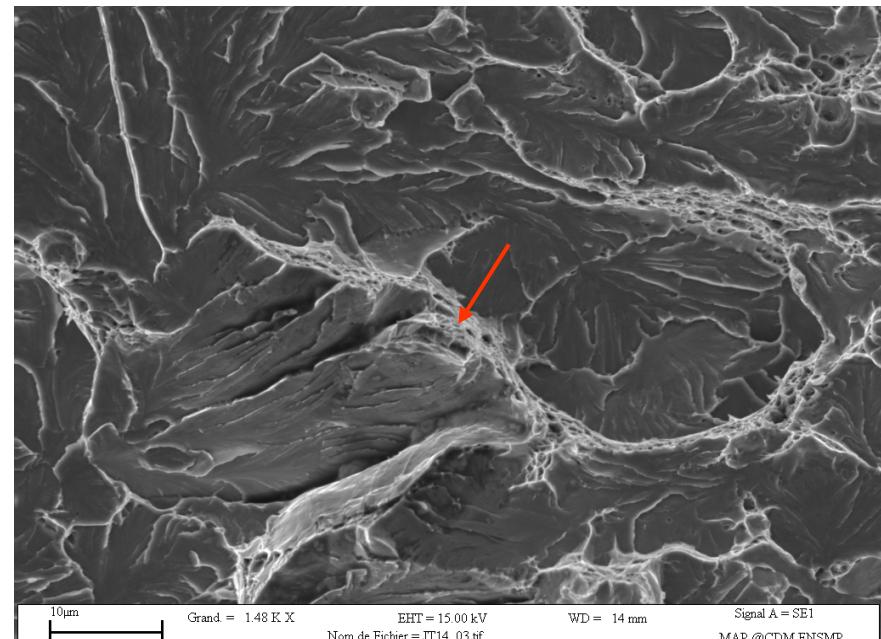
CRACKS AT GRAIN BOUNDARIES (2) & MIXED FRACTURE MODES

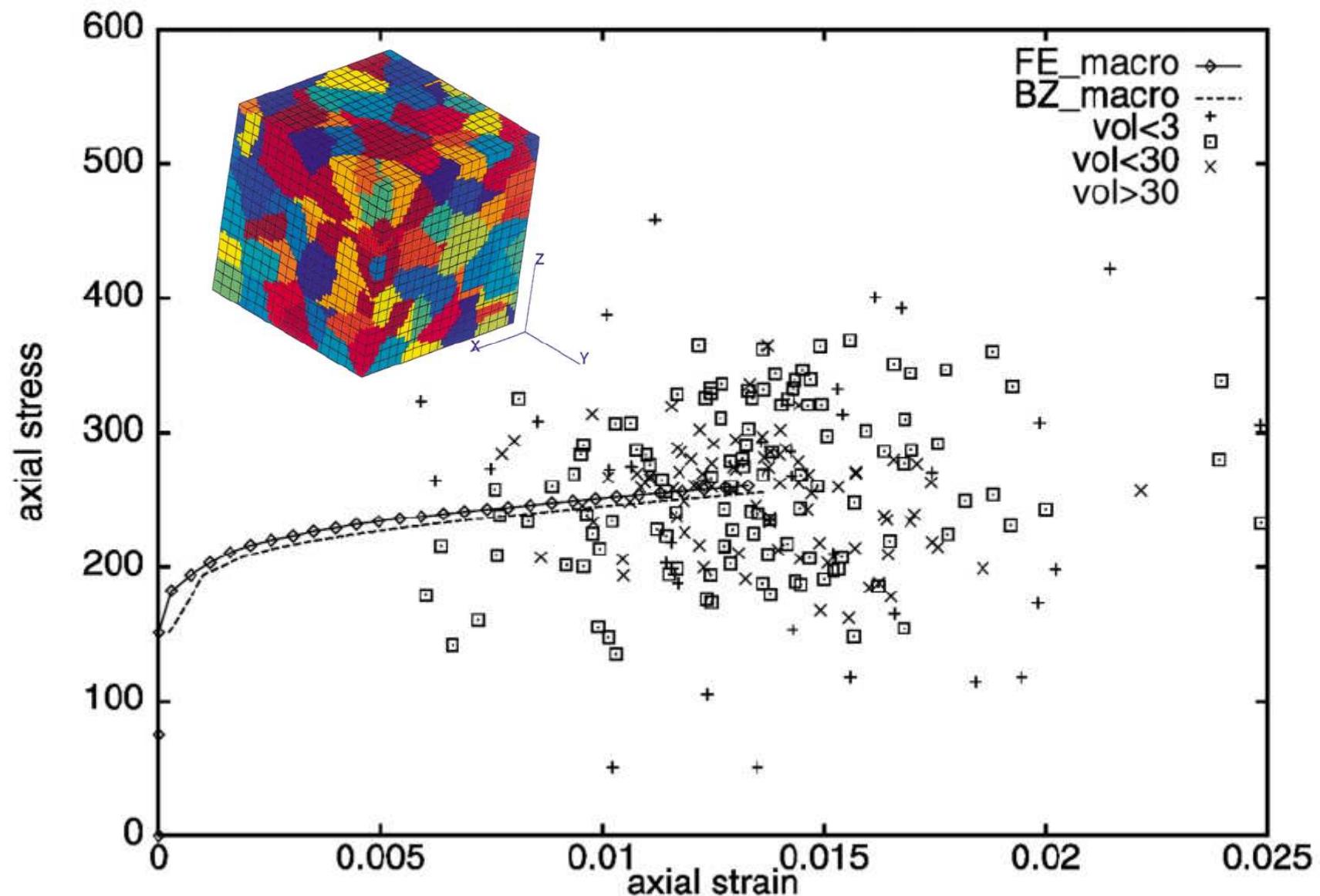


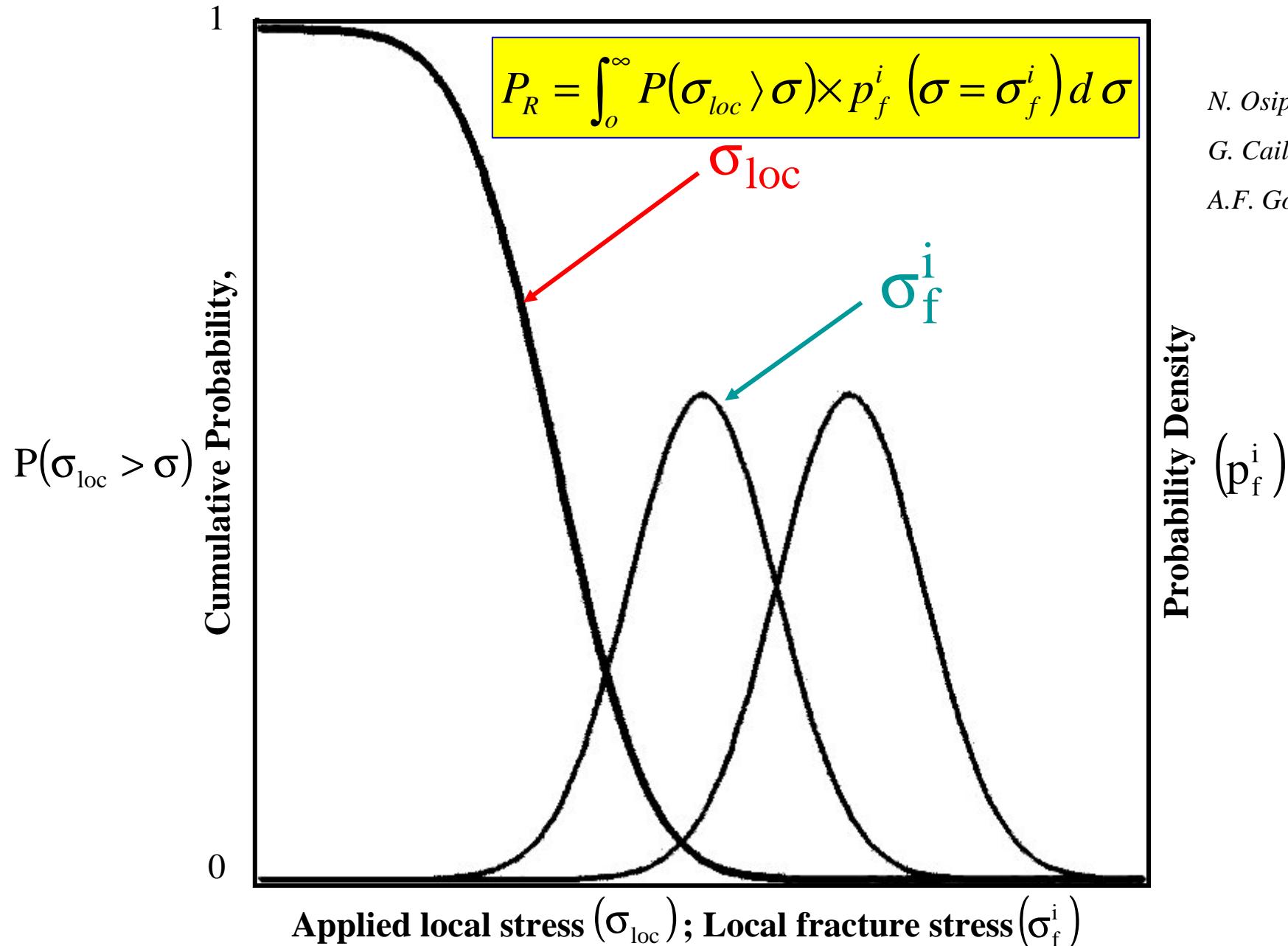
*Qiao, Argon, Mat. Letters,
Vol.54, 2008, pp. 3156-3160*

CLEAVAGE CRACK PERCOLATION
BY DUCTILE FRACTURE

BOTH EFFECTS CONTRIBUTE
TO THE INCREASE OF
EFFECTIVE SURFACE ENERGY







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N. Osipov

G. Cailletaud

A.F. Gourgues

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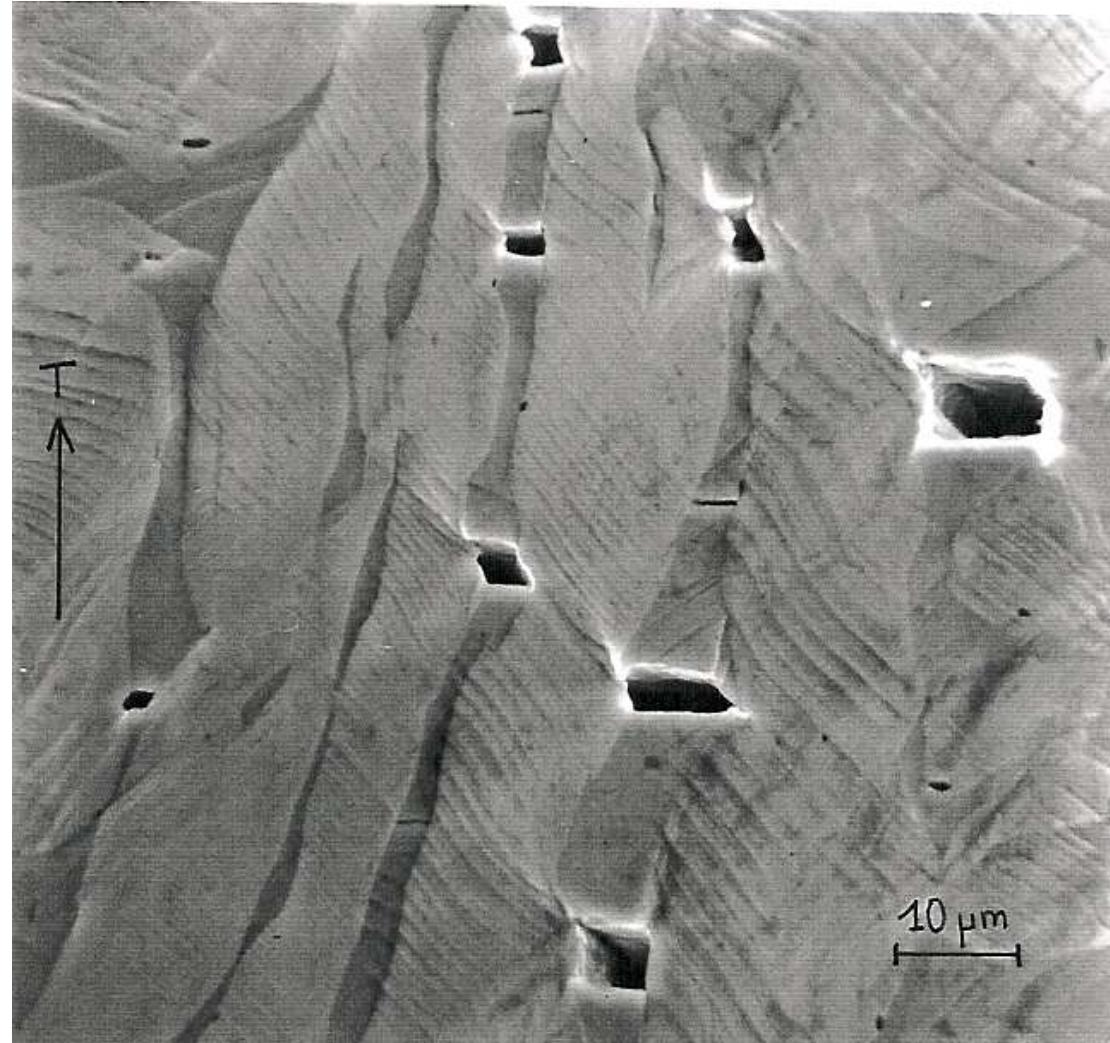
VI. CONCLUSIONS

DUCTILE FRACTURE MICROMECHANISMS

DUPLEX STAINLESS STEEL

L. Devillers-Guerville, 1998

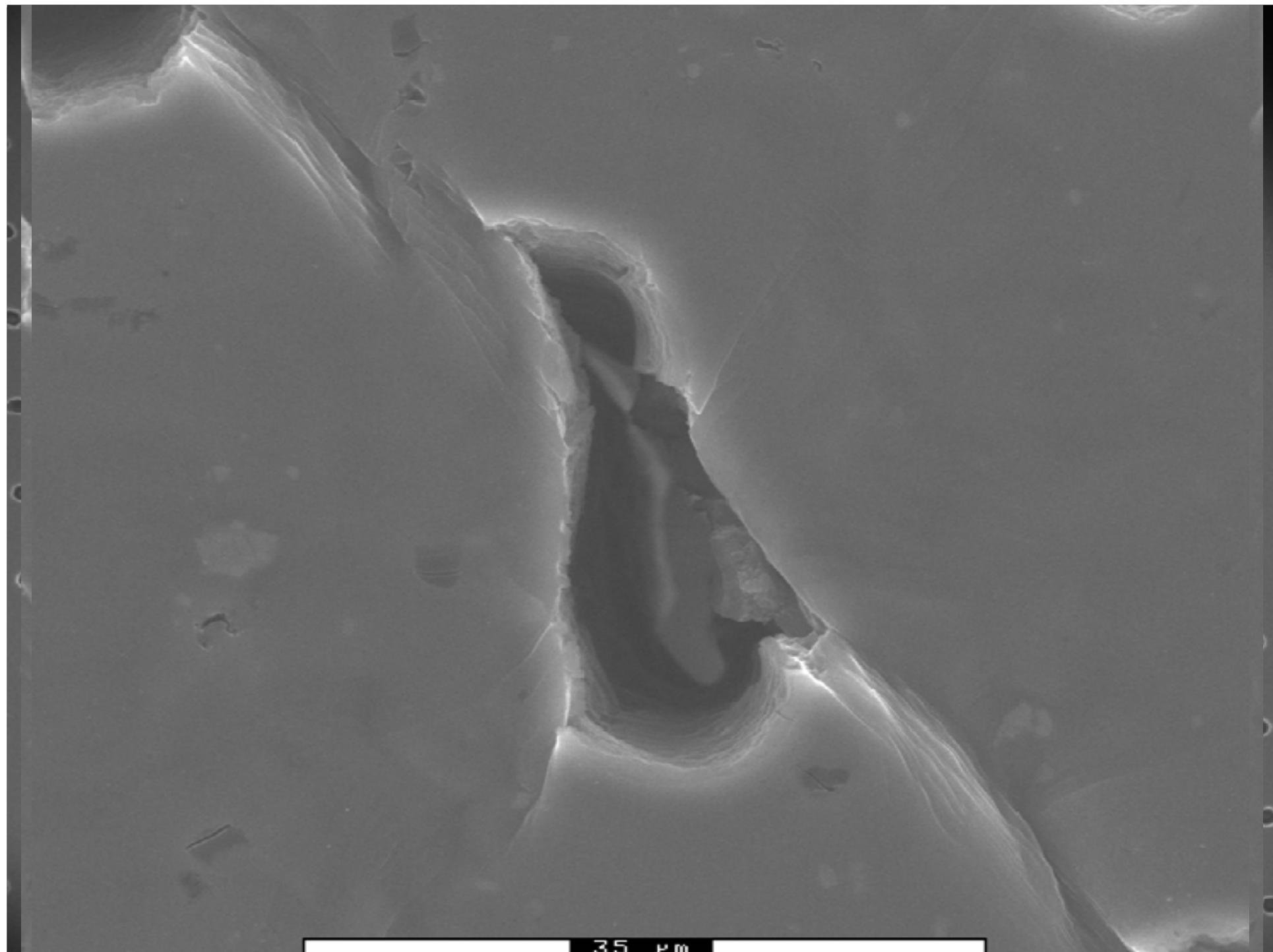
Cavity nucleation
& growth from
embrittled ferrite



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DUCTILE FRACTURE (MICROMECHANISMS)

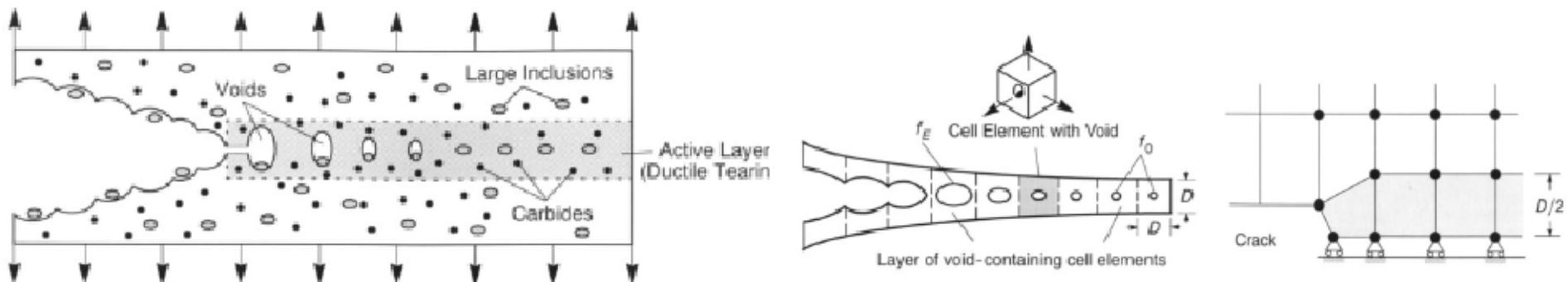
- NUCLEATION:
 - Still poorly understood
 - Very much material dependent
 - Link with Gurson model
- CAVITY GROWTH:
 - Large Research Effort since Gurson (1977) Model
 - See e.g. G.T.N. (1972, 1984); G.L.D (1997, 1994, 2001); Benzerga, Besson (2004); Pardoen Hutchinson (2000); Pardoen (2006)
 - Single crystals (J.Kyzar, 2005, 2008)
- CAVITY COALESCENCE: Partly understood
 - Thomason Model (1985, 1990)
 - Very much remains to be done
 - Strongly Material dependent



35 μ m

DUCTILE FRACTURE (MODELING)

- STRATEGY 1: Neglect coupling effects between mechanical fields & damage
(See e.g. D'Escatha & Devaux, (1979))
- STRATEGY 2: Explicit modeling of cavities ahead of crack tip using refined finite element meshes
(See e.g. Aravas, Mc Meeking (1985); Tvergaard, Hutchinson (2002))
- STRATEGY 3: Introduction of cohesive zone model
(See e.g. Tvergaard, Hutchinson (1992); Brocks et al.,(2003))
- STRATEGY 4: Computational cells
Pursued mainly by groups in France, Germany, U.K., U.S.



SUMMARY ABOUT MECHANISMS

- Void coalescence is a second stage of void growth but with plastic flow localized in the intervoid ligament
- Void coalescence can take place
 - (1) \pm normal to the main loading direction « internal necking »
 - (2) \pm in the direction of maximum shear « coalescence in shear»
 - (3) in columns (precursor of transverse delamination/splitting)

depending on the void arrangement, loading mode and strain hardening capacity

- Void coalescence can be accelerated by the presence of a second population of voids (in shear : « void sheeting »)
- Void coalescence should not be confused with plastic localization mechanisms resulting from the damage induced softening, involving effects of the structure and boundary conditions

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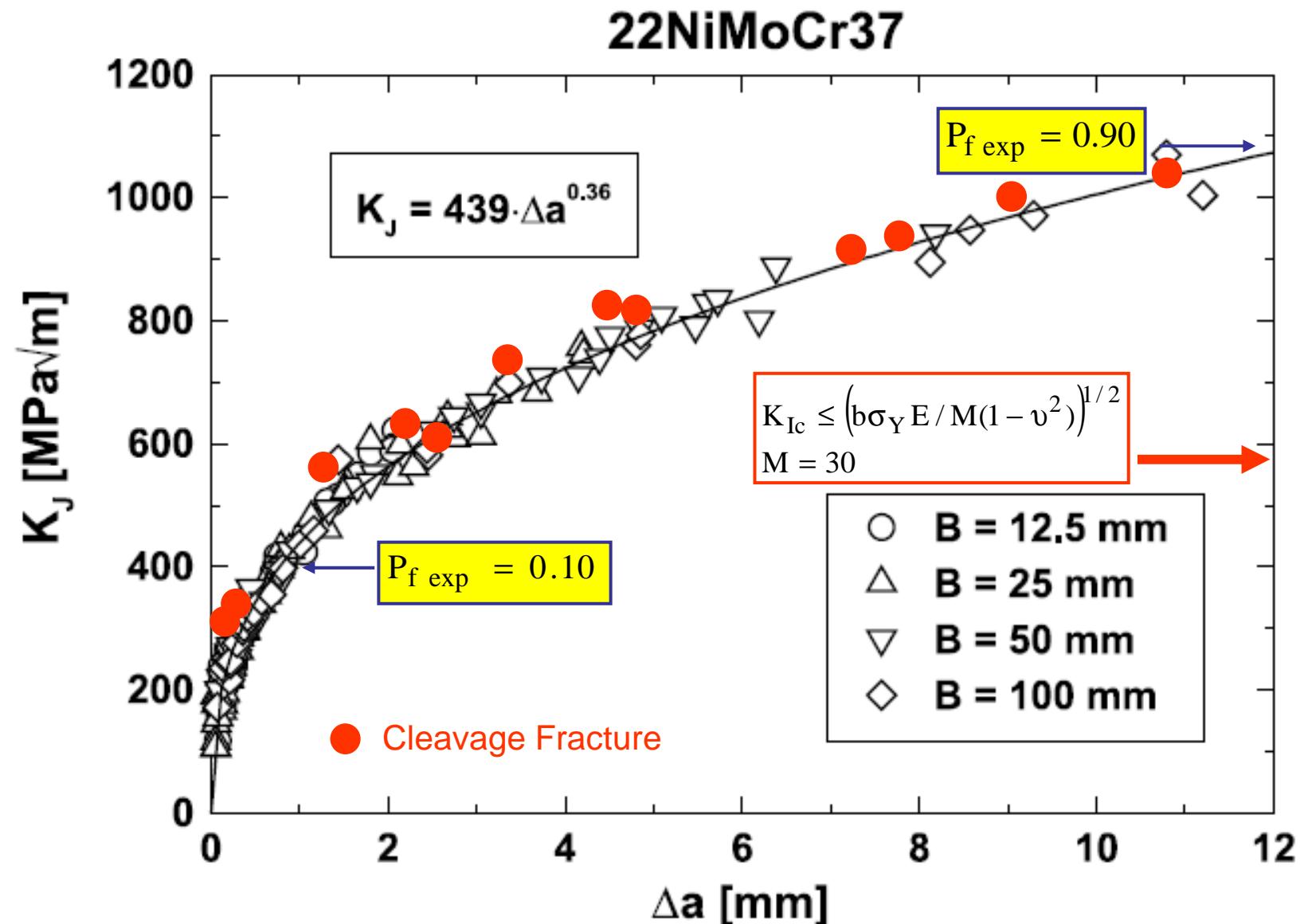
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WHY DOES A TRANSITION EXIST ?

1 - PROBABILISTIC ASPECT

Volume of sampled material increases with crack growth

(See e.g. Brückner, Munz (1984); Wallin, (1993))



2 - MESO-MECHANICAL ASPECT

Maximum stress increases with crack growth



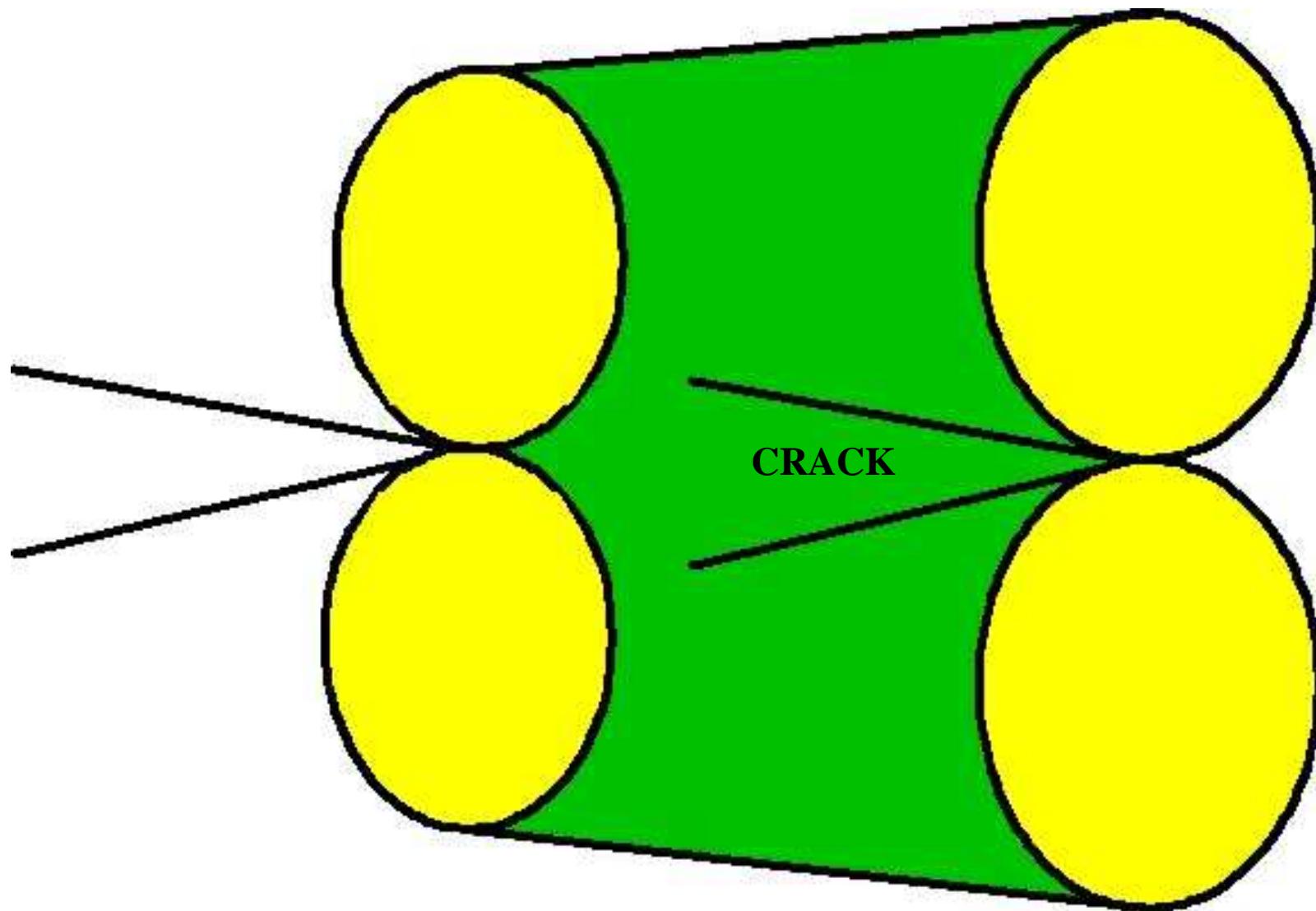
3 - MICRO-MECHANICAL ASPECT

Local stresses amplified by cavity growth

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



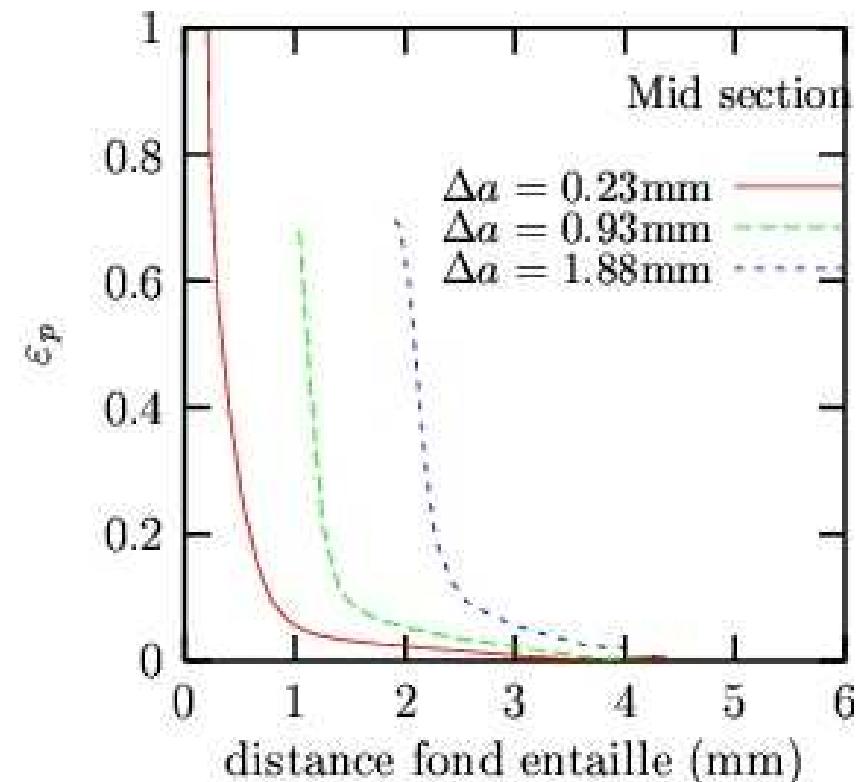
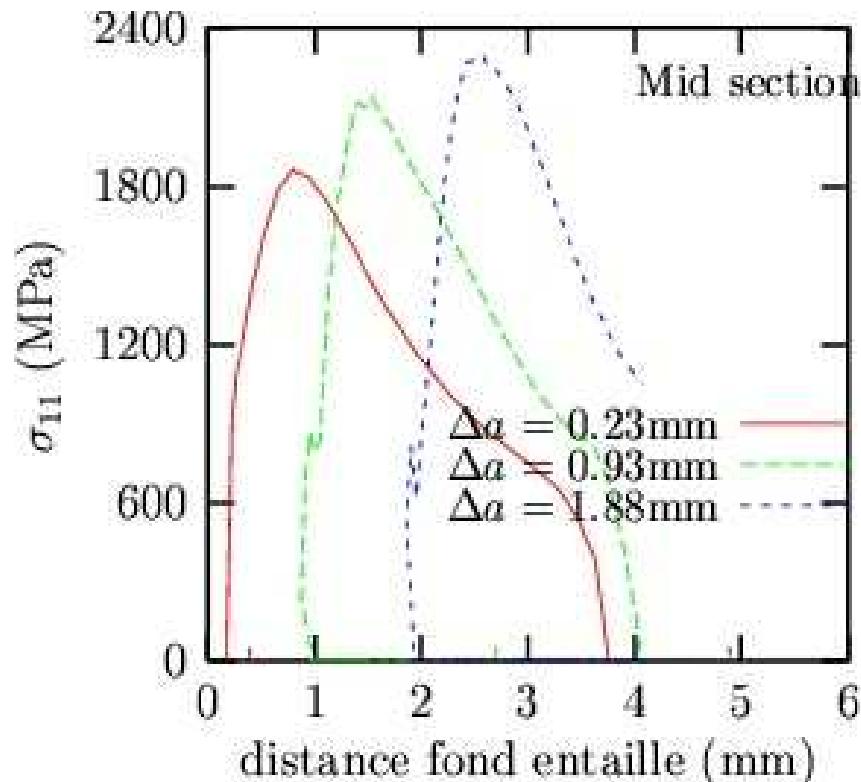
PROPAGATING CRACK



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MAXIMUM STRESS AHEAD OF A PROPAGATING CRACK

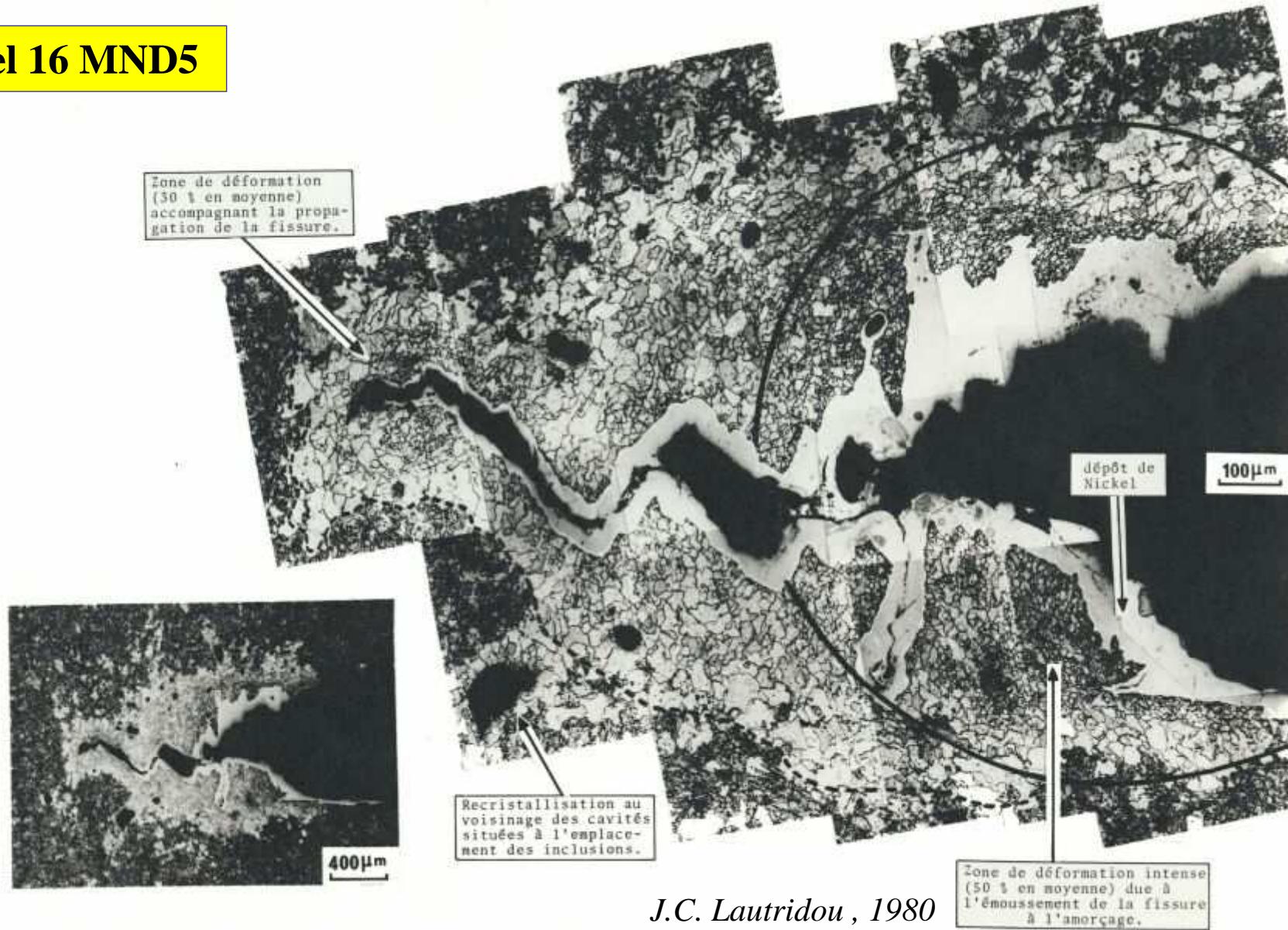
CHARPY V SPECIMEN



B. Tanguy, 2001

Steel 16 MND5

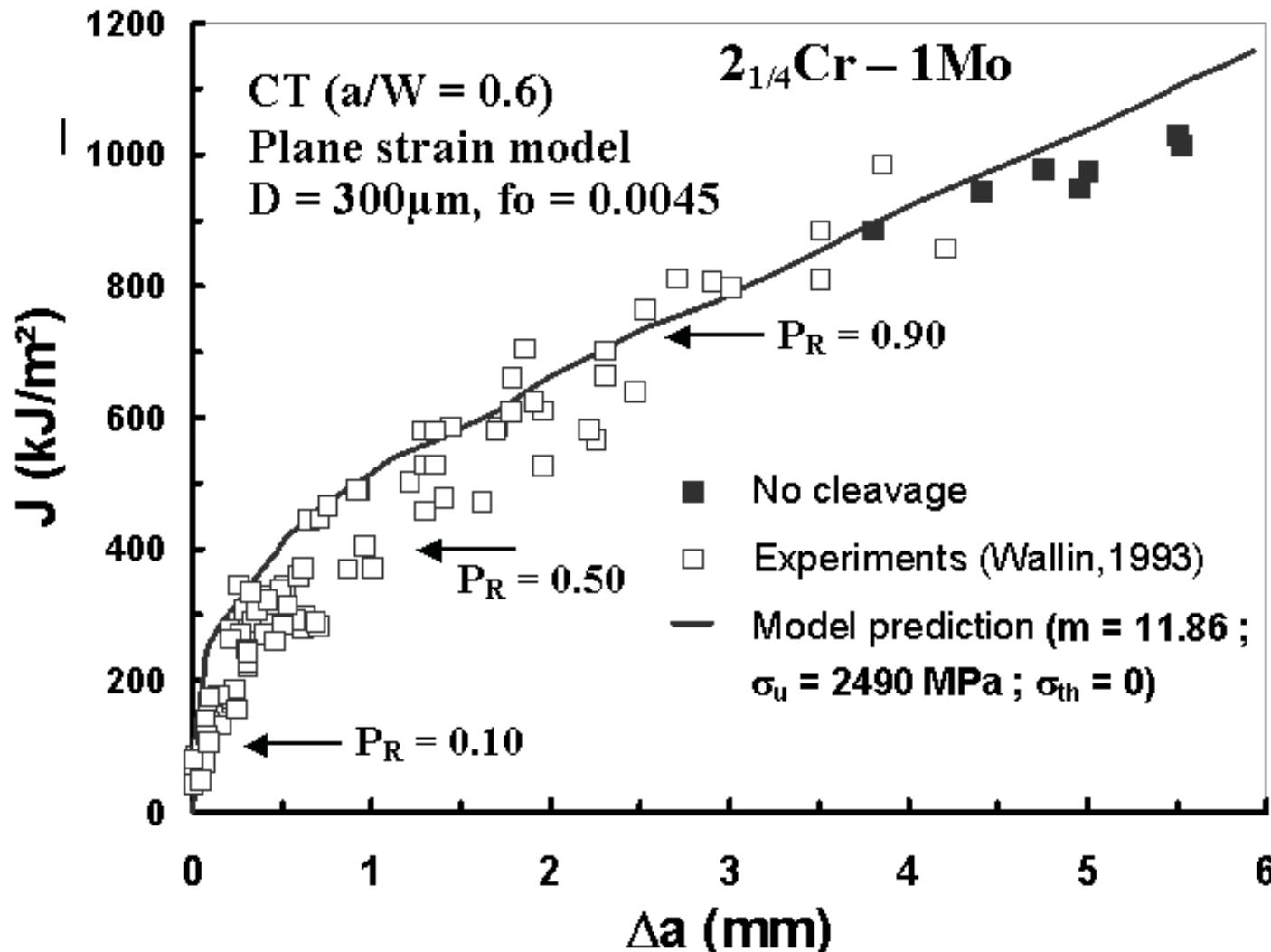
FIGURE IV-24 Recristallisation des régions fortement déformées au voisinage d'une fissure en cours de propagation. Virole sens long.



J.C. Lautridou , 1980

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

Gao et al., 1999



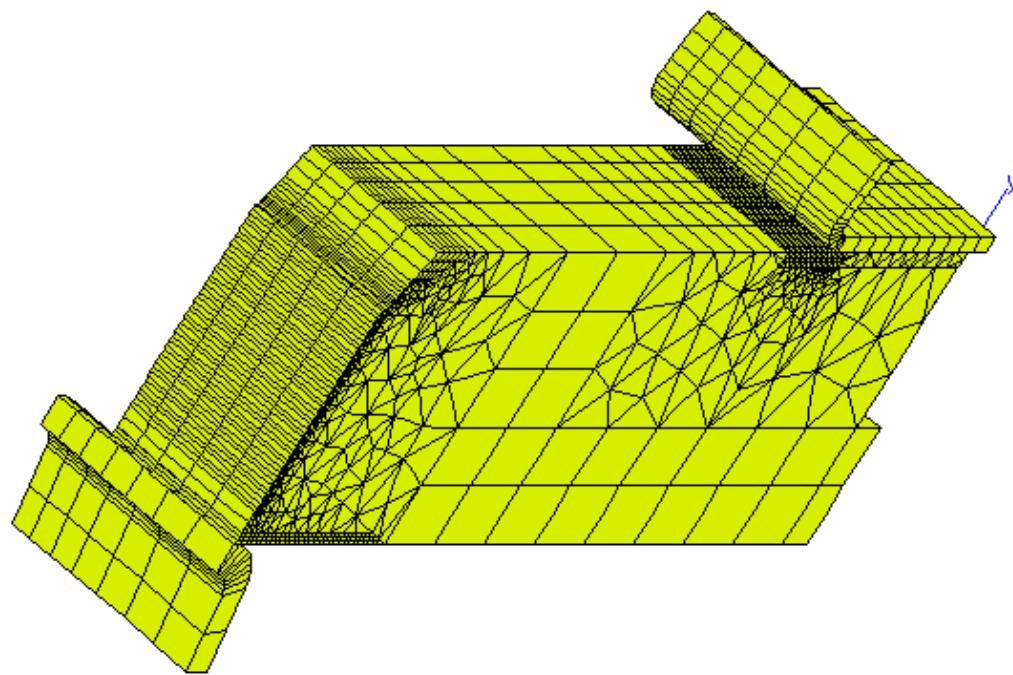
WHAT ABOUT EURO FRACTURE TOUGHNESS DATA SET ?

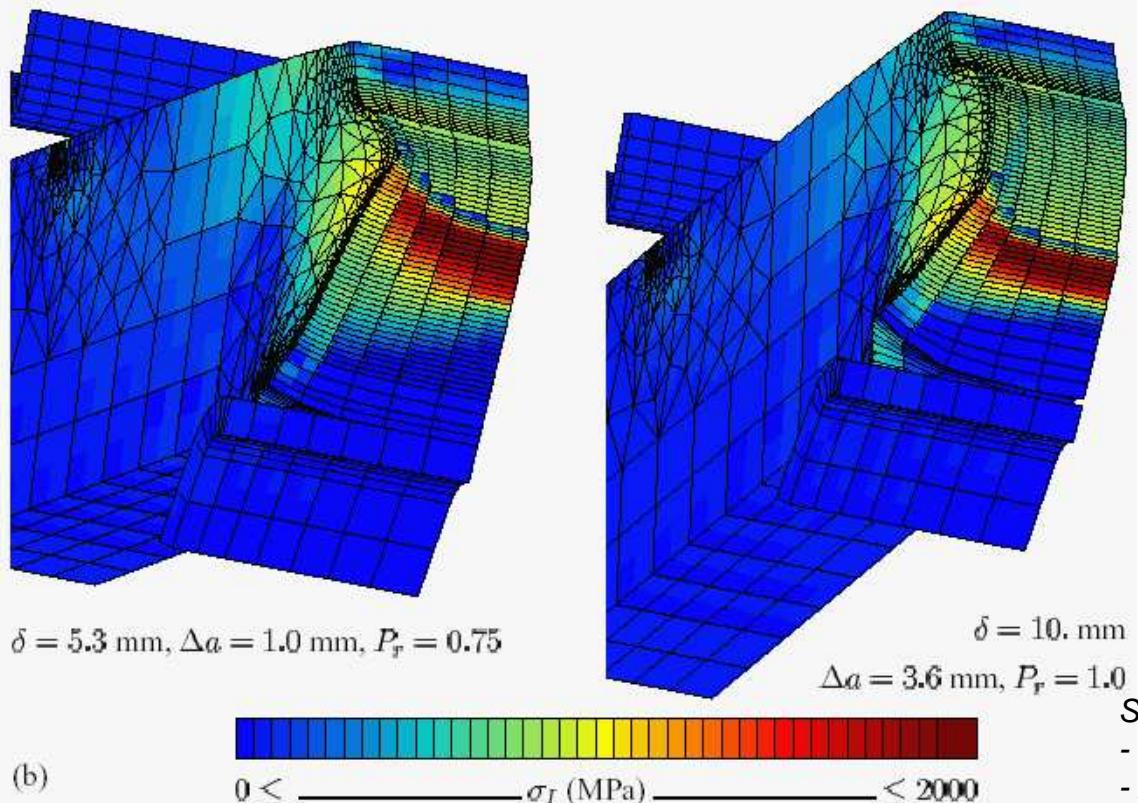
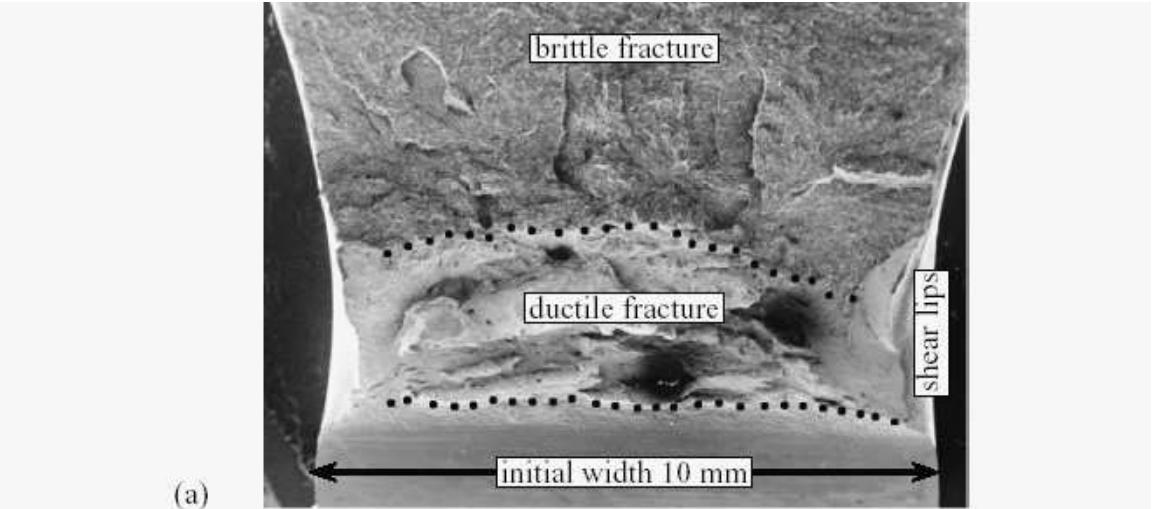
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MODELING OF CHARPY IMPACT TEST IN PWR STEEL

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

- 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





Fracture at -60°C under dynamic conditions :

- Experimental fracture surface,
- Simulation of ductile crack propagation
(contour plots indicate σ_I)

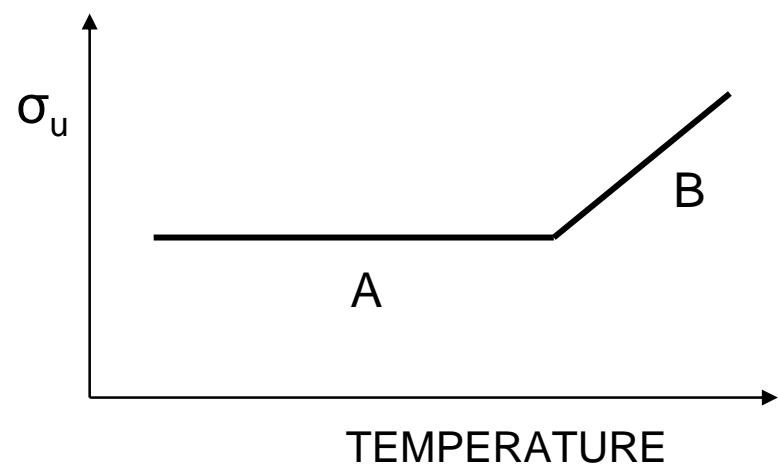
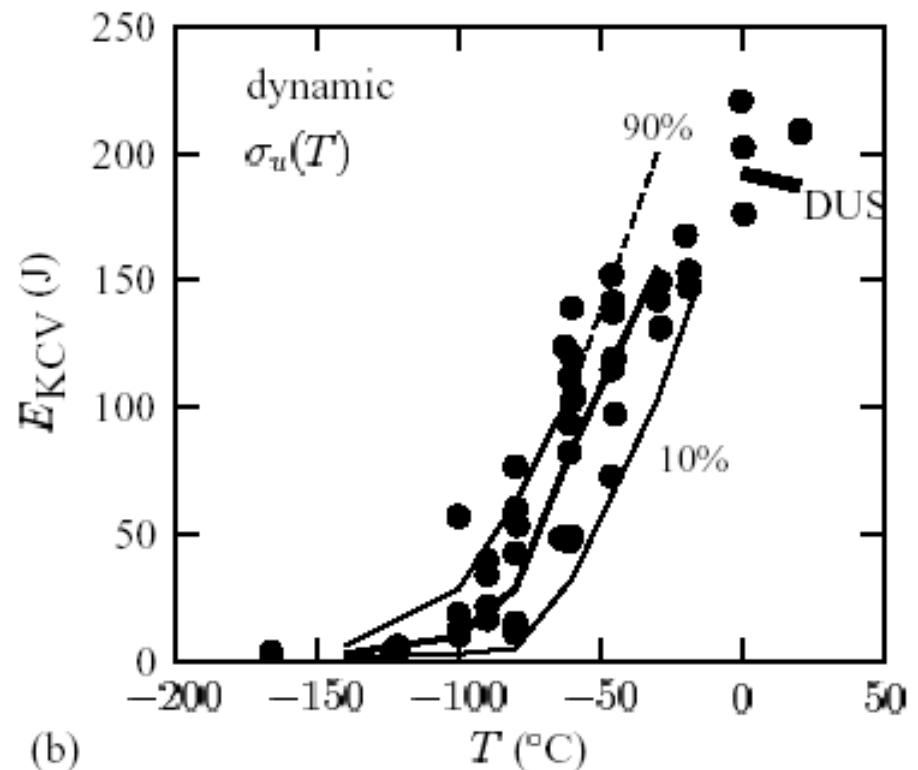
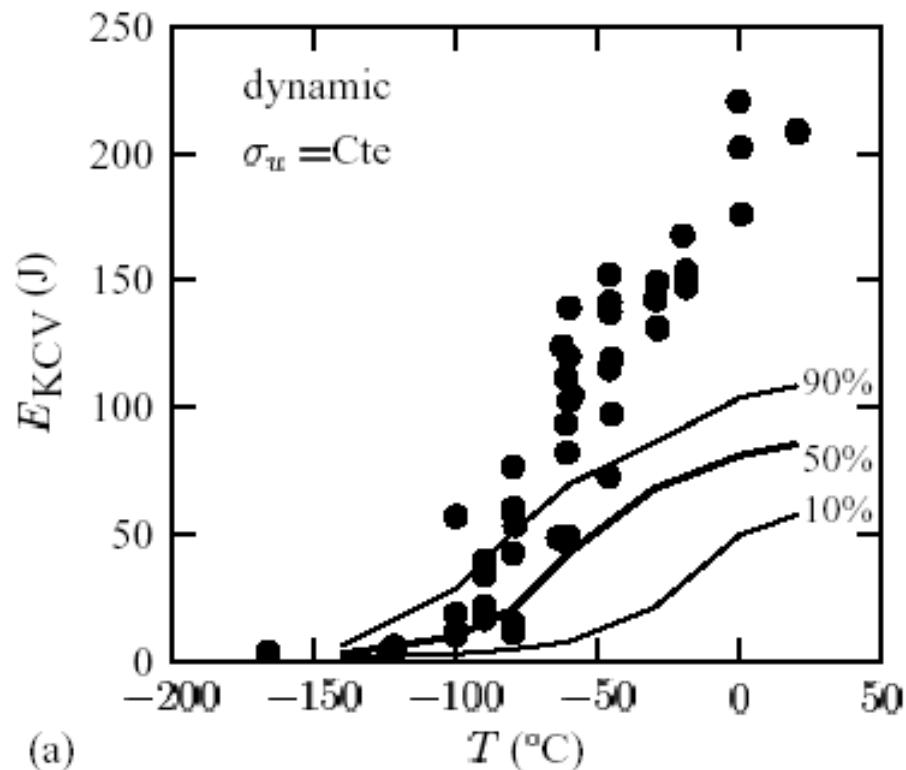
A 508 Steel

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

See also :

- Schmitt et al., IJPVP, 1994, Vol. 59, pp. 21-29
- A.Rossoll, PhD Thesis, 1998

A 508 STEEL



- A regime: Cleavage without significant ductile crack growth
- B regime : Cleavage after large ductile crack growth: Influence of the damaged zone which reduces local stresses by local crack « shielding » effect

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CONCLUSIONS & PROSPECTS

- CLEAVAGE

- $\gamma_{\text{eff}} \gg \gamma_s$ - Temperature dependence – Needs more detailed metallographical observations
- Microstructural barriers – Collective behaviour of cleavage microcracks
- Polycrystalline plasticity

- INTERGRANULAR

- $\gamma_{\text{int}} = f$ (impurity content). Threshold ?
- Intergranular initiation in relation with intragranular inhomogeneities in plastic deformations within grains in a polycrystal
- Competition between Cleavage & Intergranular in macroscopically inhomogeneous materials

- DUCTILE

- Concentrate more on cavity nucleation & cavity coalescence
- Orientation of fracture surfaces (flat vs slant fracture)
- Microtomography,Laminography  (See also : T. Morgeneyer et al. Acta Mater., vol.56, 2008,p.1651)

- CRACK ARREST

- Still poorly understood

- DEVELOPMENT of more sophisticated models but which should remain tractable

THANK YOU FOR YOUR ATTENTION

andre.pineau@ensmp.fr

ISO-27 306 (2009) *Method of loss correction of CTOD
fracture toughness assessment of steel components*

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$$[\ln(1/(1-0.05)) / \ln(1/(1-0.95))]^{1/2} = 6.531$$

J. Heerens, 2002

With the exception of 100 mm specimens more than 50% of the specimens showed single initiation sites

