BSSM Conference, Southampton, Aug. 2018

THE PHYSICS AND MECHANICS OF DYNAMIC SHEAR LOCALIZATION

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ISF
OUTCOME (ITN-Horizon 2020)

Technion (1912-1924)

Haifa (North of Israel)

Technion today…

17 Faculties
1 School of Medicine

About 13000 students

3 Nobel laureates

The Dynamic Fracture Laboratory (DFL)

Develop tools (**experimental** and **numerical)** to:

1. Investigate the **thermomechanical response of materials** subjected to high loading rate (constitutive testing, failure modes and mechanisms)

2. Investigate the response of **cracks** subjected to impact loading (dynamic fracture mechanics)

3. **Structural health monitoring** (end effects, AC electrical tomography)

Research themes

- » Dynamic fracture mechanics
- » Thermomechanics of dynamic flow and fracture
- » Shear localization
- » Dynamic and ballistic behavior of polymers
- » Scaling of structural response to blast
- » New experimental techniques. High triaxiality
- » Dynamic testing of advanced ceramics: relation to microstructure.
- » Wave propagation in gels and soft matter
- » Structural health monitoring
- » Electrical impedance tomography
- » Scaling in dynamic fragmentation
- » Numerical simulation of dynamic structural failure
- » Biomechanics of dental implants (session BSSM)

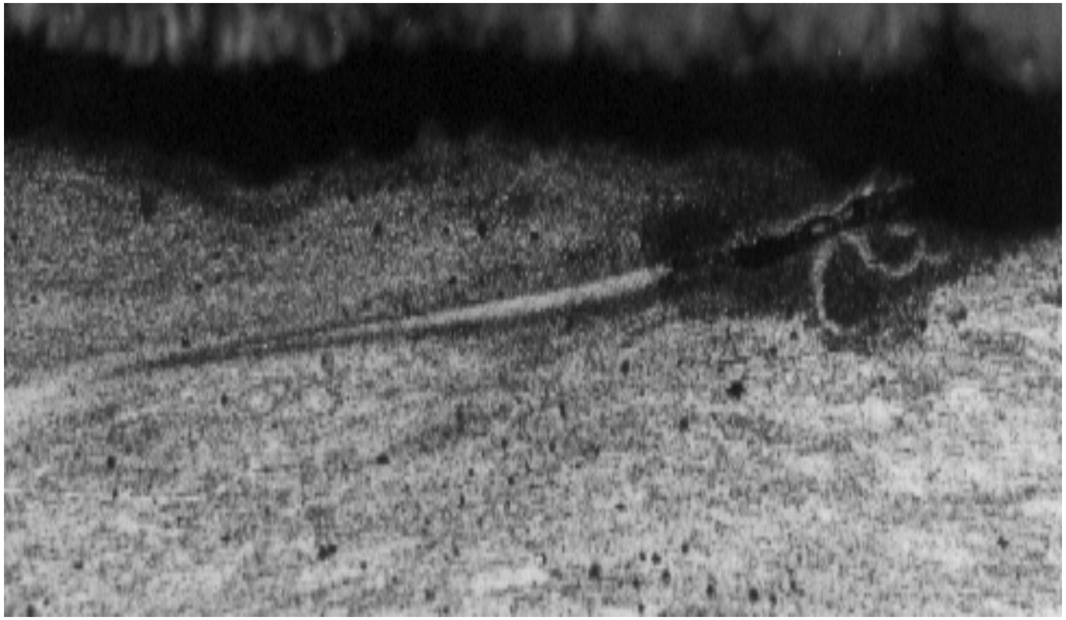
Outline of the talk

- Statement of the problem
- On adiabatic shear: experiments (*macroscale*) and *criterion*
- Experiments (*microscale*) – thermomechanics - microstructure
- Modelling
- Conclusions

ADIABATIC SHEAR FAILURE

- **Material / structural instability** causing localization of the shear deformation into a narrow band when a material is subjected to *dynamic loading* (Tresca, 1879).

- Observed in many ***metals*** and ***polymeric*** *materials (Bai and Dodd)*

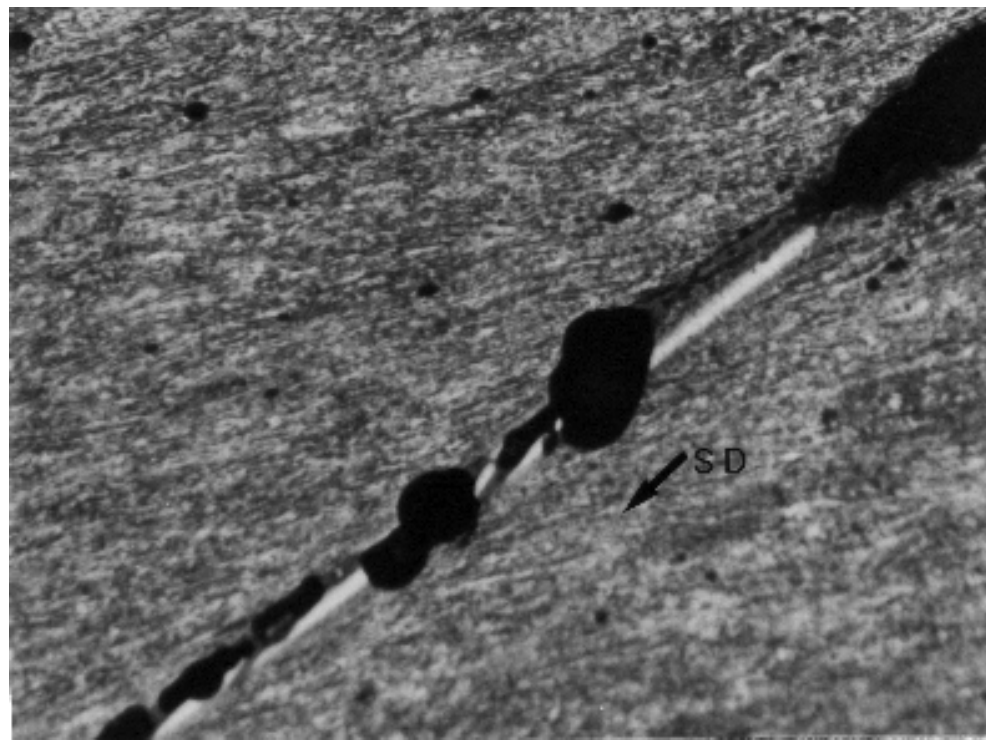


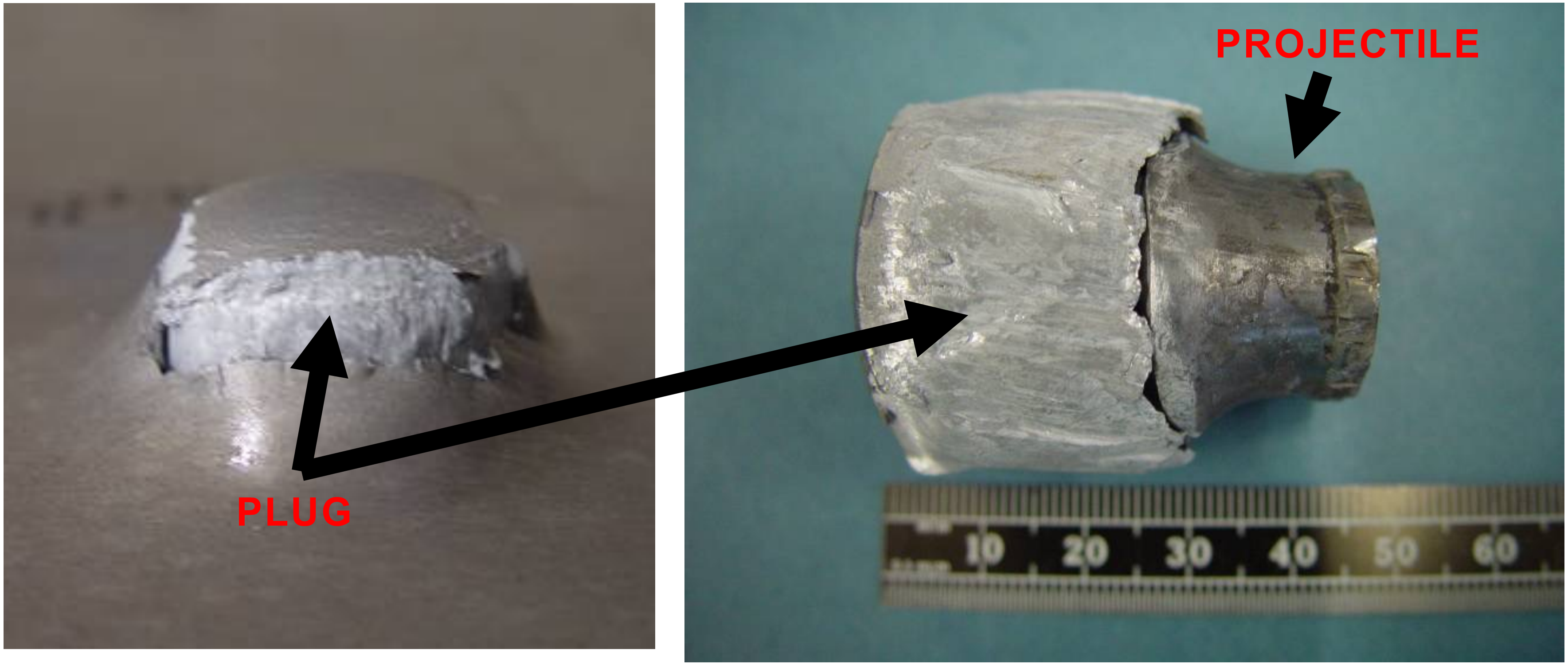
white etching ASB in 4340 steel x200

Artsi, Rittel and Roman, 1988

At the microscale.

ASB and crack x200



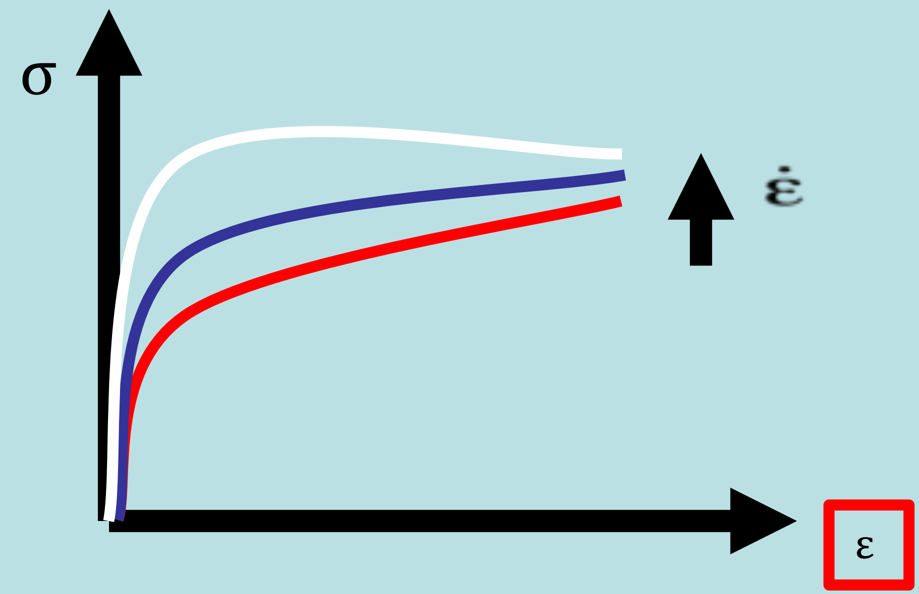


Plugging failure on the backside of an aluminum alloy armor plate (courtesy B. Dodd and F. Coghe)

In other words, the shear band is a local heterogeneity in an otherwise homogeneous neighborhood

Adiabatic shear

Competition between **strain-rate hardening and thermal softening** (Zener-Hollomon, 1944)



Accepted criterion: critical failure strain

THE ROLE OF T

- **Thermomechanical coupling** causes a **homogeneous temperature rise prior to localization**
- **Mechanical energy → Heat (PARTLY)**

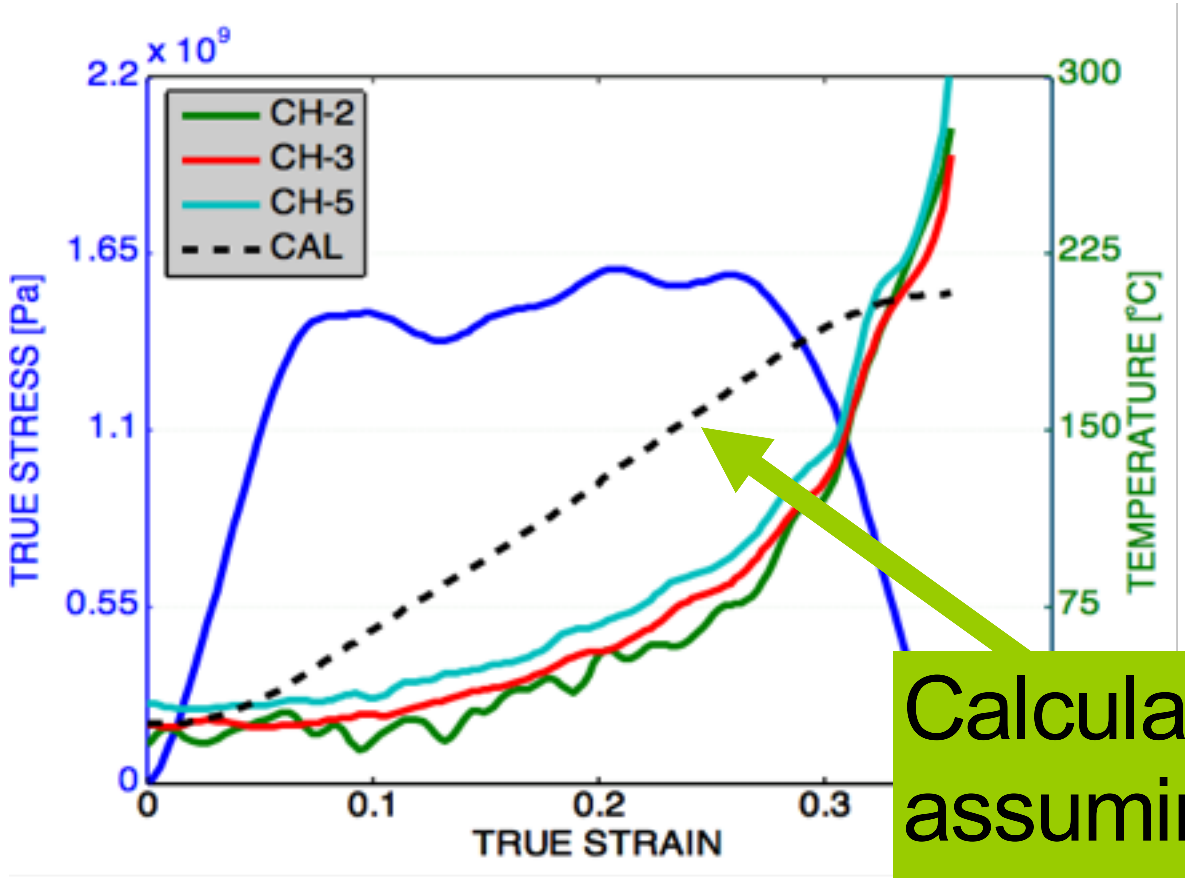
$$\beta_{diff}(\varepsilon,\dot{\varepsilon}) = \frac{\rho C_p \dot{T}}{\dot{W}_p} \qquad (1)$$

$$\beta_{int}(\varepsilon,\dot{\varepsilon}) = \beta = \frac{\rho C_p \Delta T}{W_p} \qquad (2)$$

G. I. Taylor, M. Quinney; *P. Roy. Soc. A-Math. Phy.* 307 (1934).

D. Rittel, "On the conversion of plastic work to heat during high strain rate deformation of glassy polymers", *Mechanics of Materials*, Vol. 31, No. 2, (1999), 131-139.

RESULTS: Ti6Al4V – *Real time T monitoring*

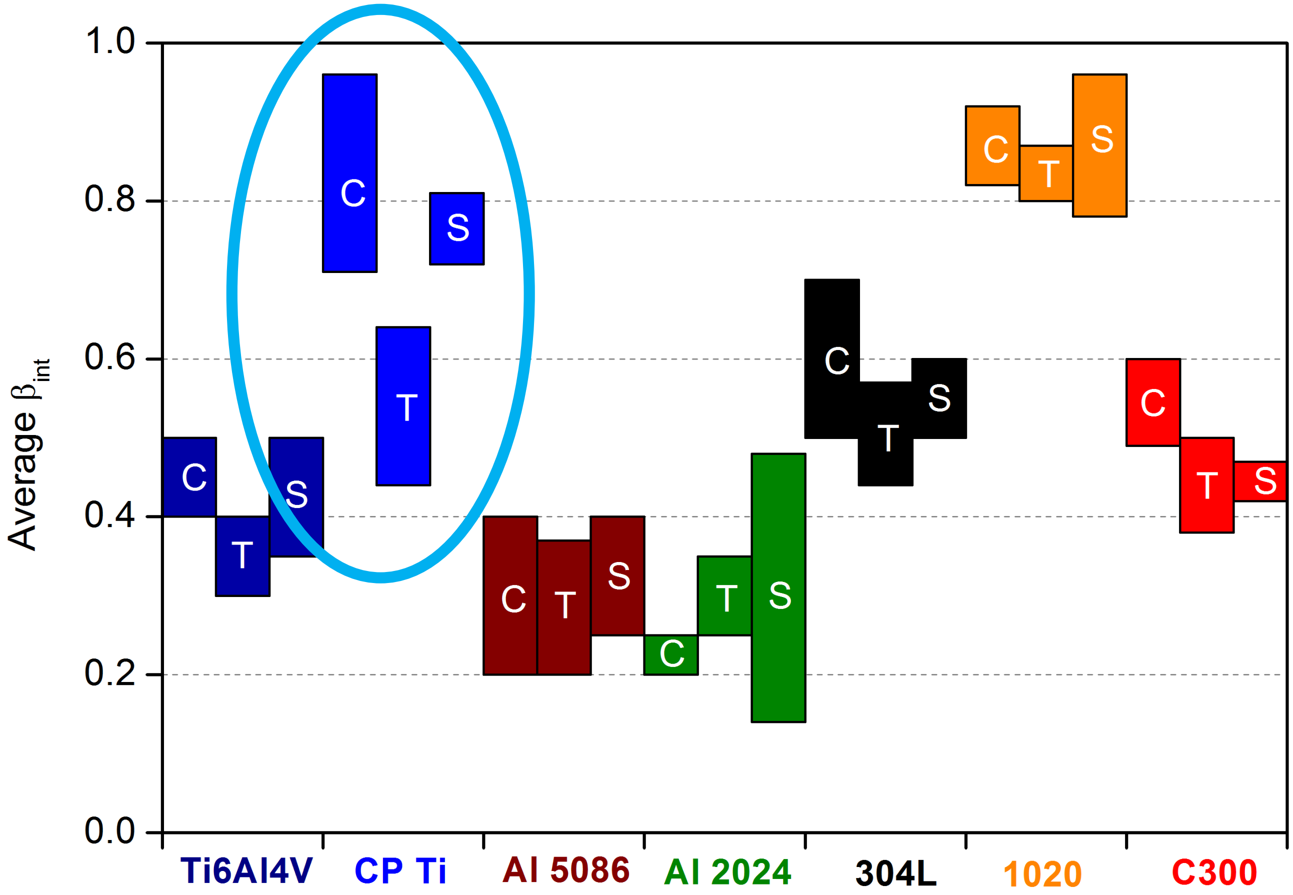


Calculated assuming β=1

NOTE THE MODEST ΔT PRIOR TO LOCALIZATION

More on thermomechanical coupling

LH Zhang and S. Osovski

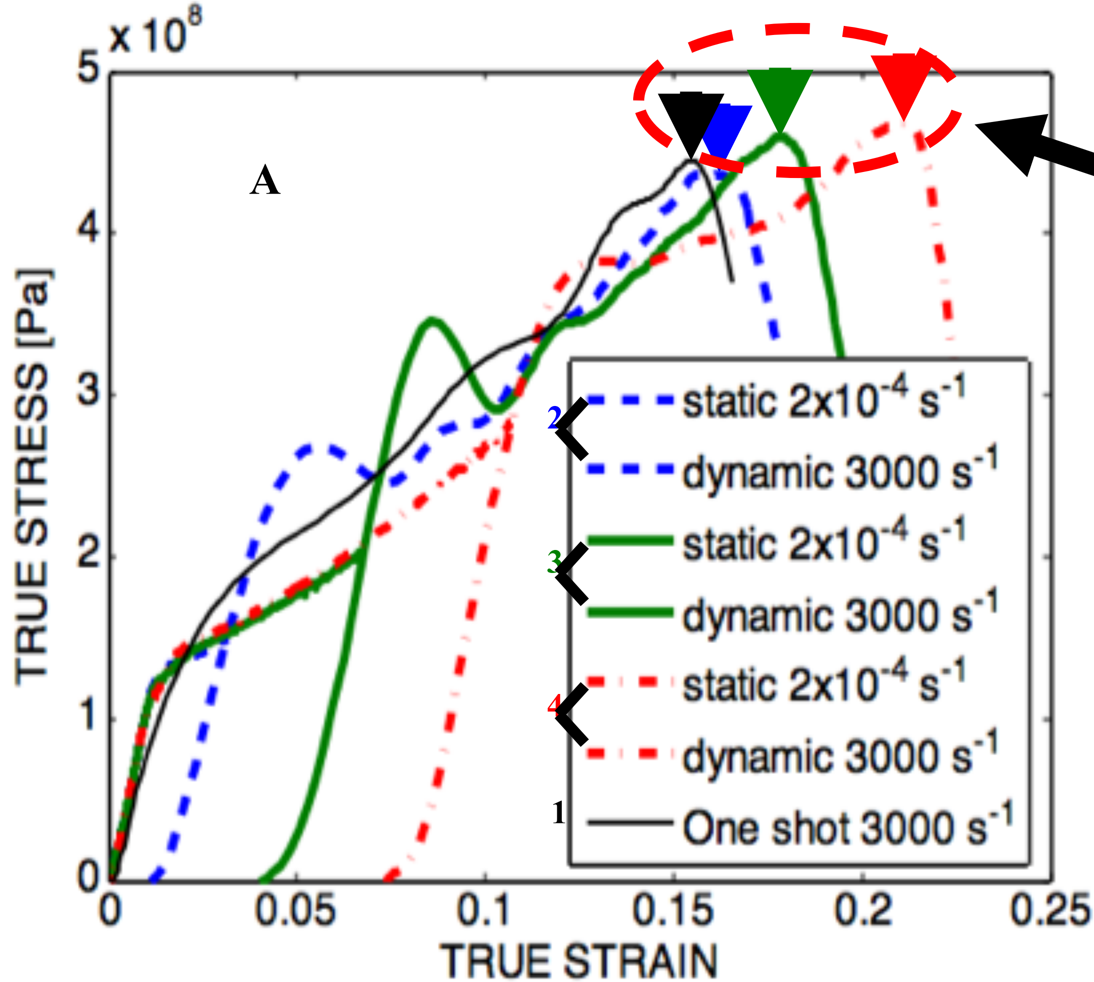


D. Rittel, LH. Zhang and S. Osovski, (2017), "The dependence of the Taylor-Quinney coefficient on the dynamic loading mode", J. Mech. Phys. Solids, 107, 96-114

- TQ coefficient is **not a constant 0.9**
- Recorded temperature rise **prior to localization** remains quite modest **(30-50 degrees)**
- Dependence on the **deformation micromechanism** (twinning vs. slip)
- **Thermal softening????**

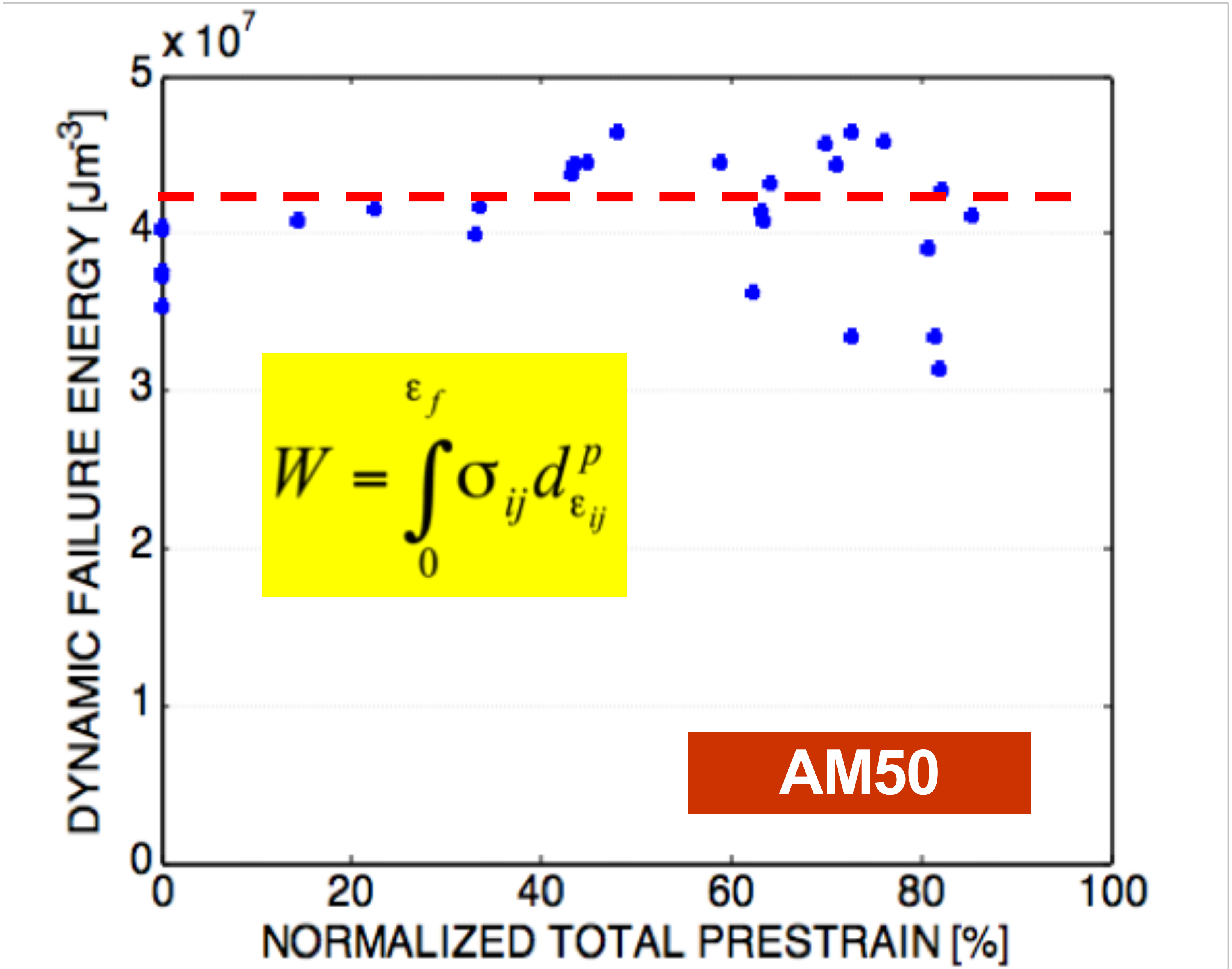
A NEW CRITERION FOR ASB

Quasi-static preload followed by dynamic tests



$\varepsilon^{c}_{failure}$??

Dynamic energy vs. normalized static pre-ε



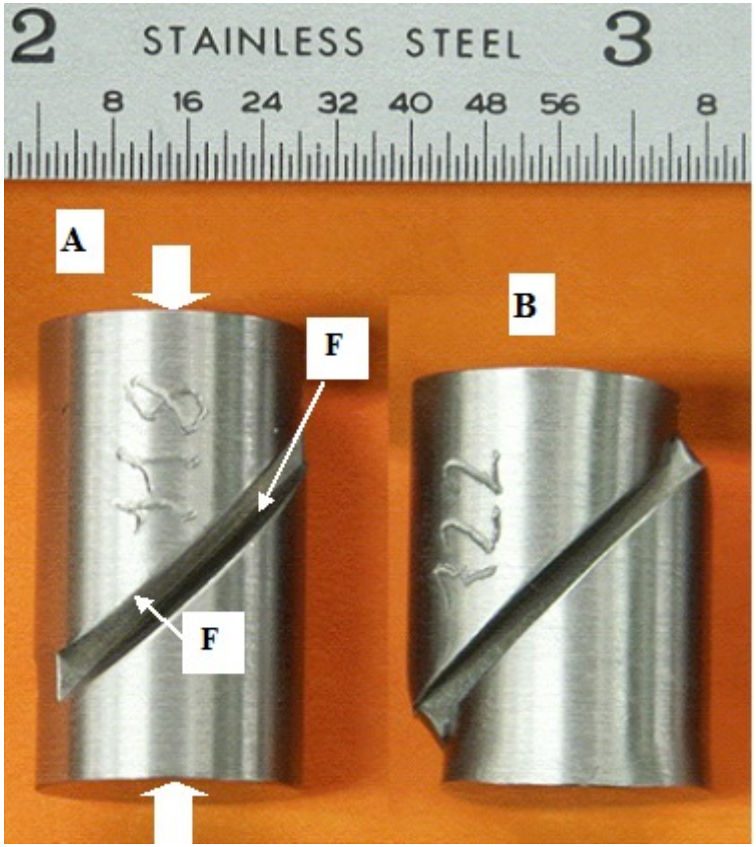
Interim Summary

- *Balance of **dynamic** energy*: $\mathbf{W_M = W_T + W_S}$
- $\mathbf{W_M}$: mechanical energy. **Observed constant**
- $\mathbf{W_T}$: thermal energy. **No significant role**
- $\mathbf{W_S}$: *stored energy of cold work*. **Relevant**
- $\mathbf{W_S}$: emphasis on **microstructural aspects** and **dynamic deformation only**

D. Rittel, Z. G. Wang and M. Merzer, "Adiabatic shear failure and dynamic stored energy of cold work", (2006), Physical Review Letters, 96(7), 075502:1-4 A.

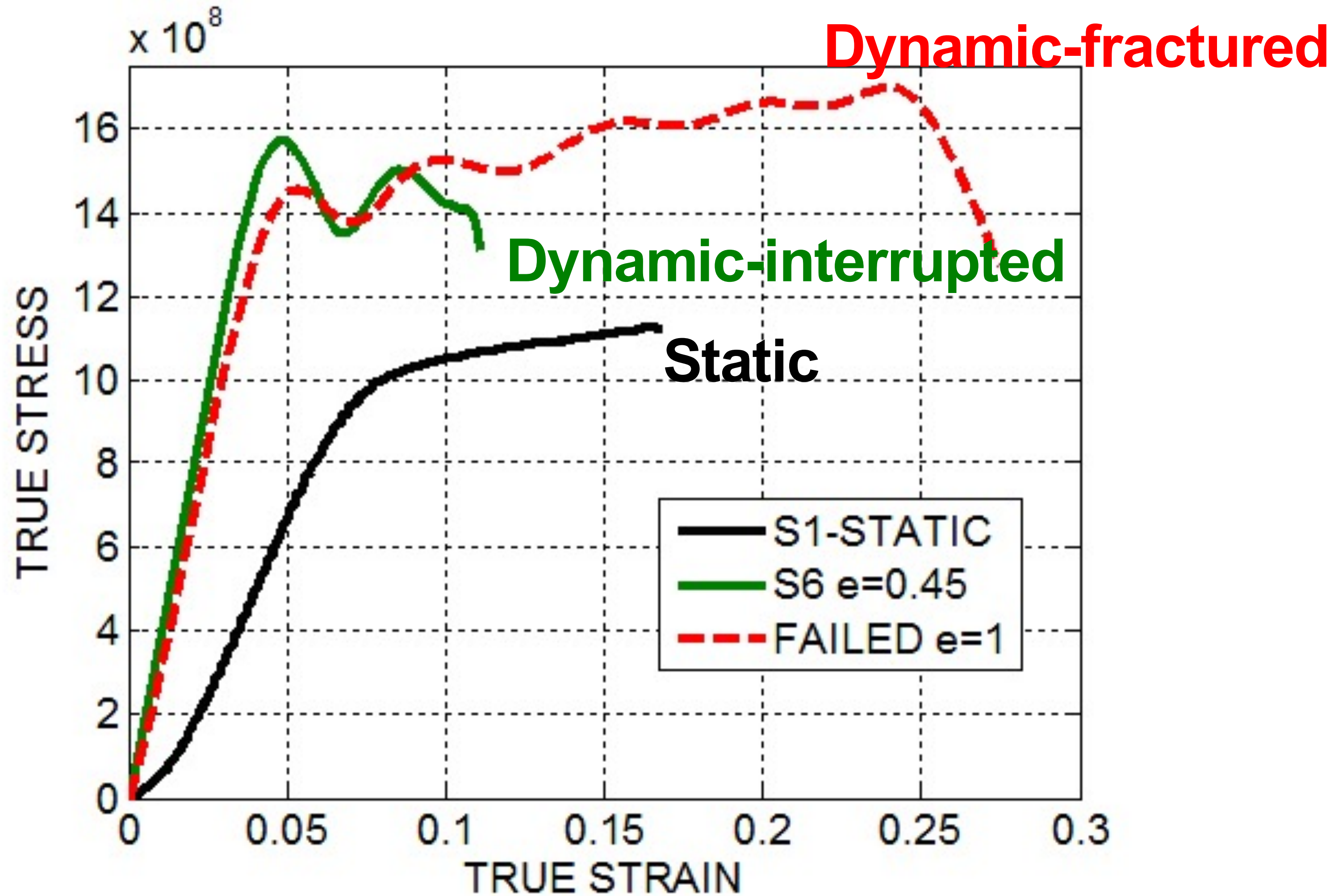
So, WHEN does localization start???

Central idea: Perform interrupted static and dynamic tests on a material (Ti6Al4V) that is prone to ASB shear localization, using the ***SCS specimen***

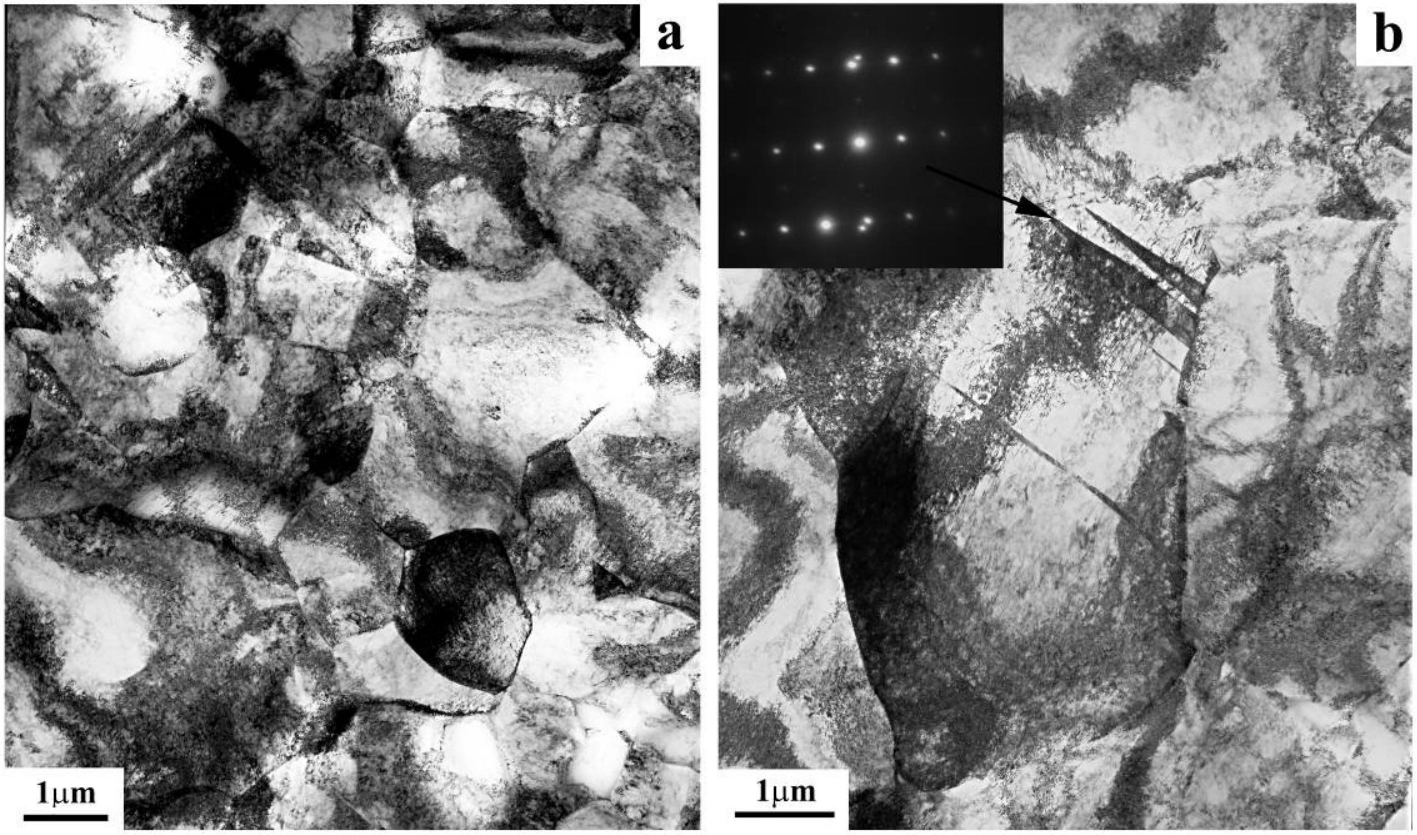


F: fillet where ASB usually form

Interrupted tests

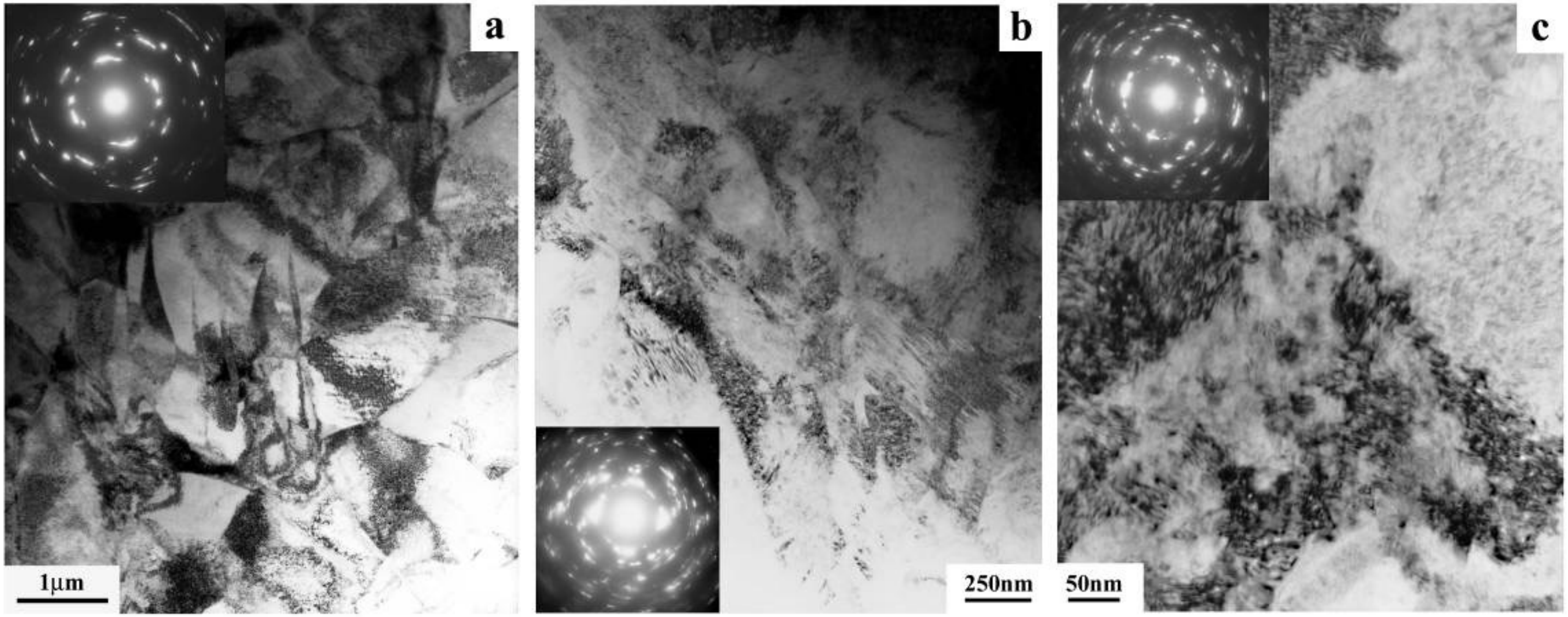


Quasi-static Ti6Al4Vspecimen - ε=0.17 not failed



(a) The typical microstructure consists of **dislocation cells**.
(b) Area showing **stress-induced (α”) martensite** (arrowed) transformed from the β phase, and its corresponding SADP.

Dynamically **failed specimen** ε=0.24

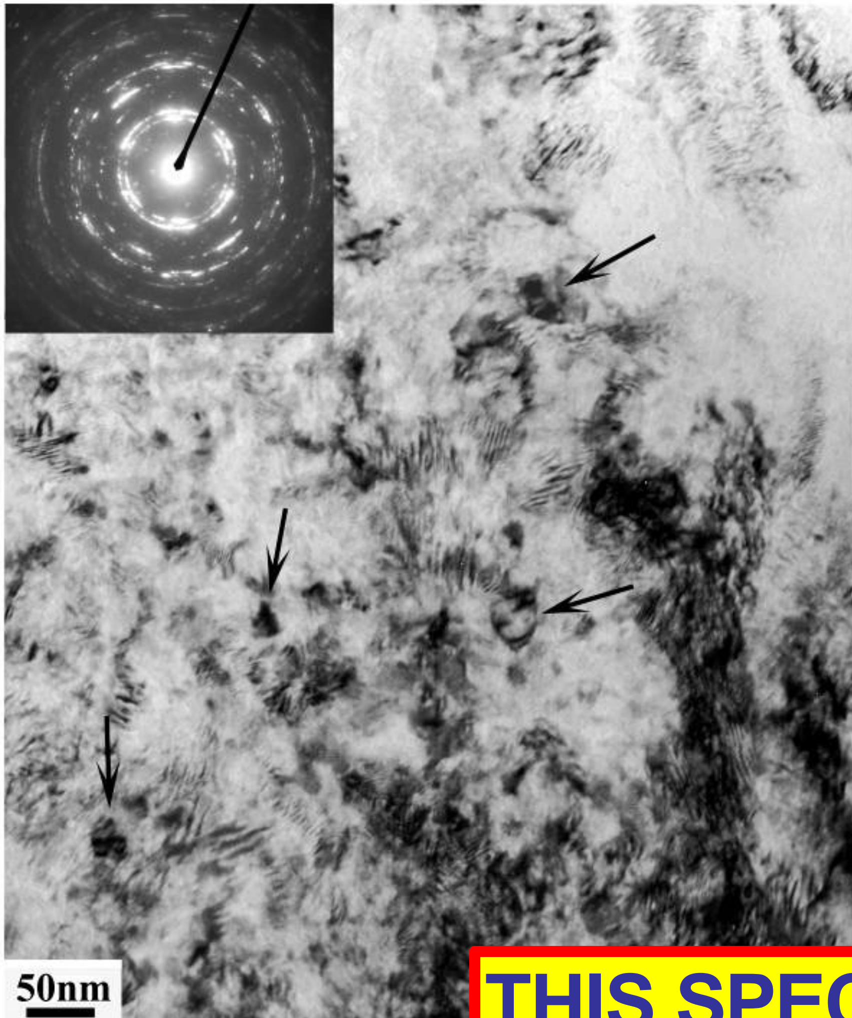


(a) Far from the ASB: Dislocation cells and stress-induced martensite. The typical SADP mainly contains misoriented α phase cells.

(b) **Within the ASB**: High dislocation density without any distinct morphology. The SADP shows **incomplete rings indicating the presence of very fine recrystallized grains**.

(c) Higher magnification of (b): The high dislocation density screens the fine grains revealed by the SADP.

Interrupted dynamic test – ε_r=0.45



Dynamically recrystallized grains (10-30 nm) formed in the highly dislocated area are indicated by arrows.

Free of dislocations. The corresponding SADP consists of ring patterns, typical of nanograined polycrystalline materials.

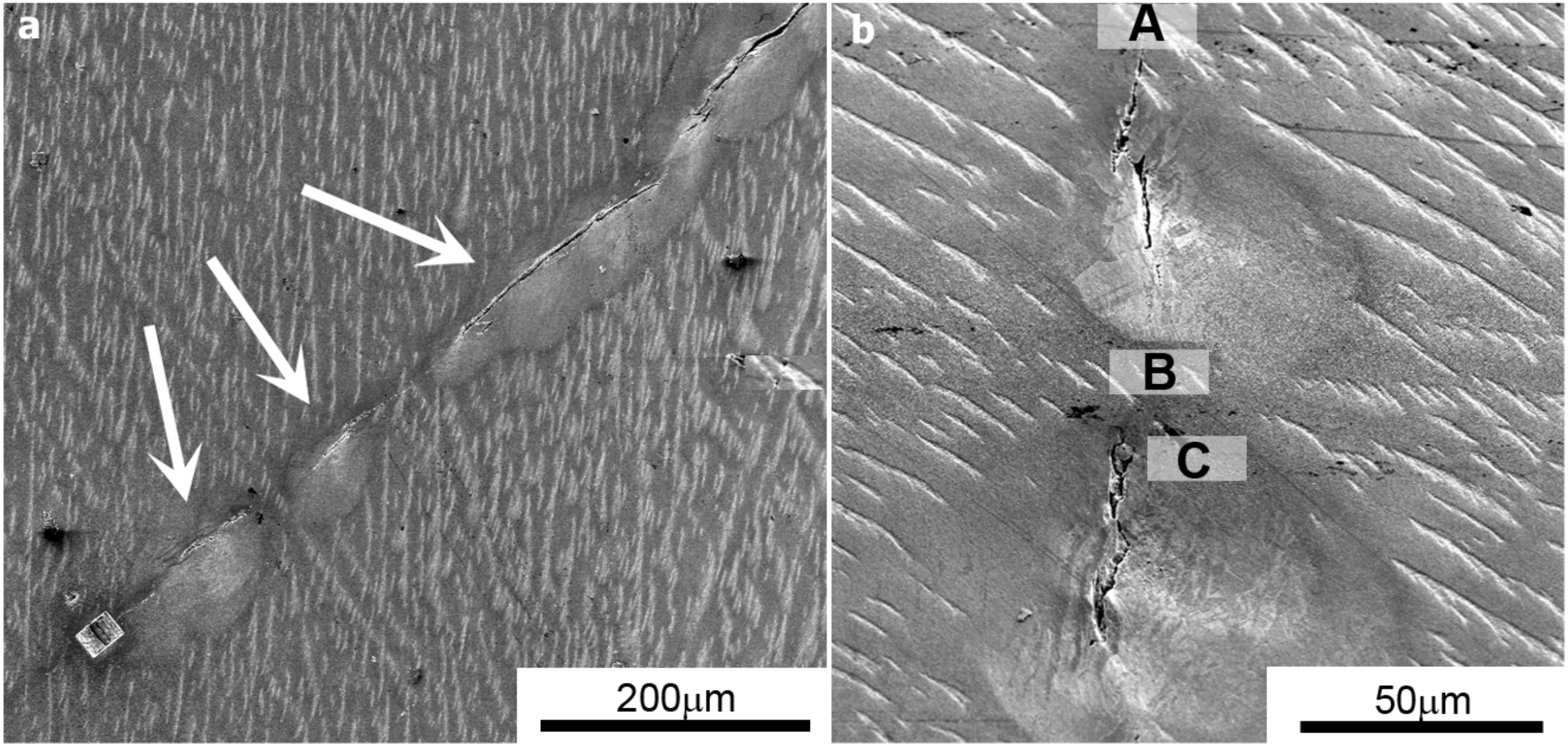
THIS SPECIMEN DID NOT FAIL!

An important observation (2008)

- Thorough TEM examination reveals a **qualitatively identical microstructure** for the interrupted and the fractured specimen.
- **No new mechanism** operates until failure
- One must therefore look for a **quantitative evolution** of the recrystallized phase. Difficult issue…. *Under progress*

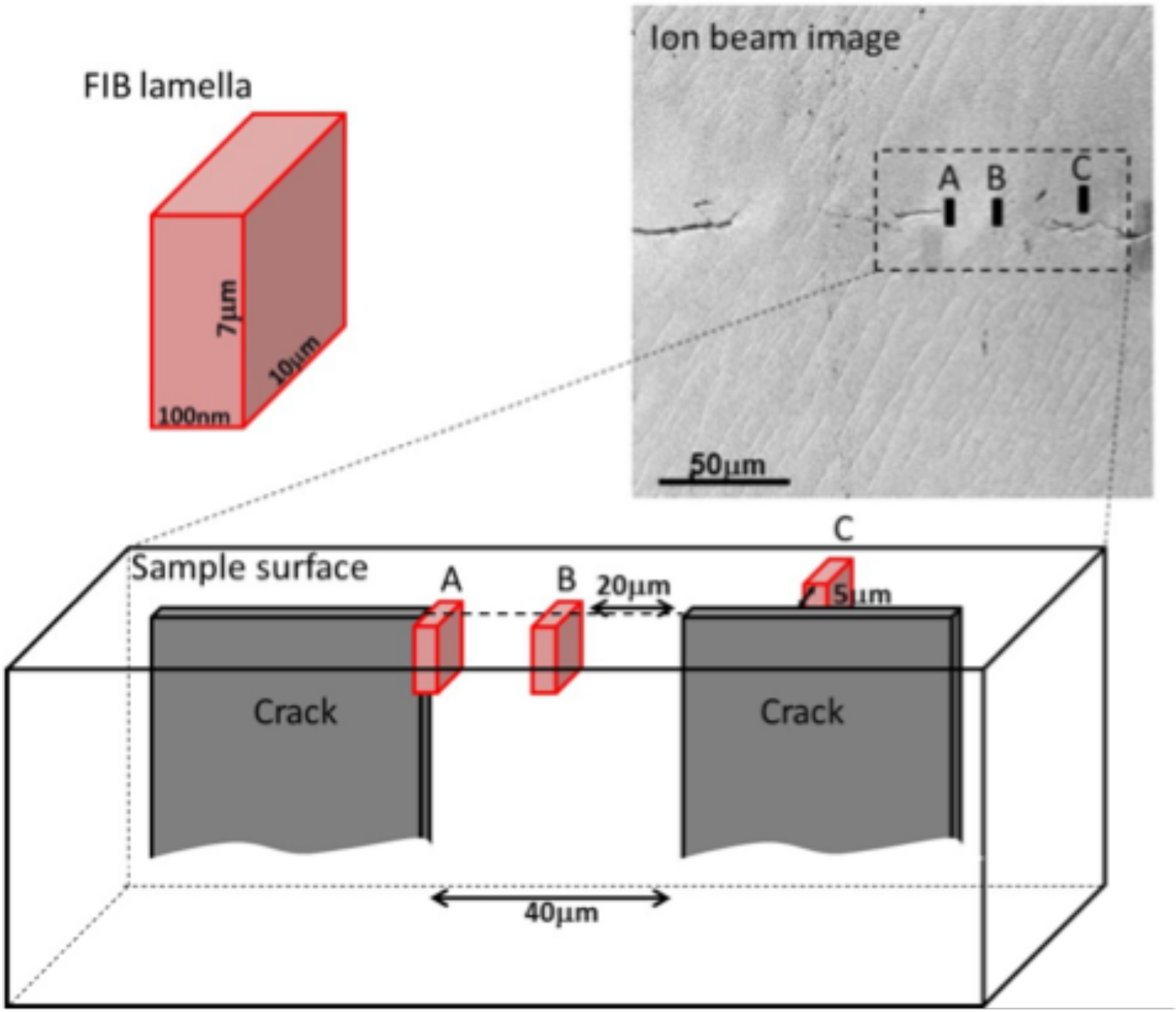
D. Rittel, P. Landau and A. Venkert, (2008), "Dynamic recrystallization as a potential cause for adiabatic shear failure", Physical Review Letters, 101 (16), 165501.

So, **HOW** does ASB progress? (2016)



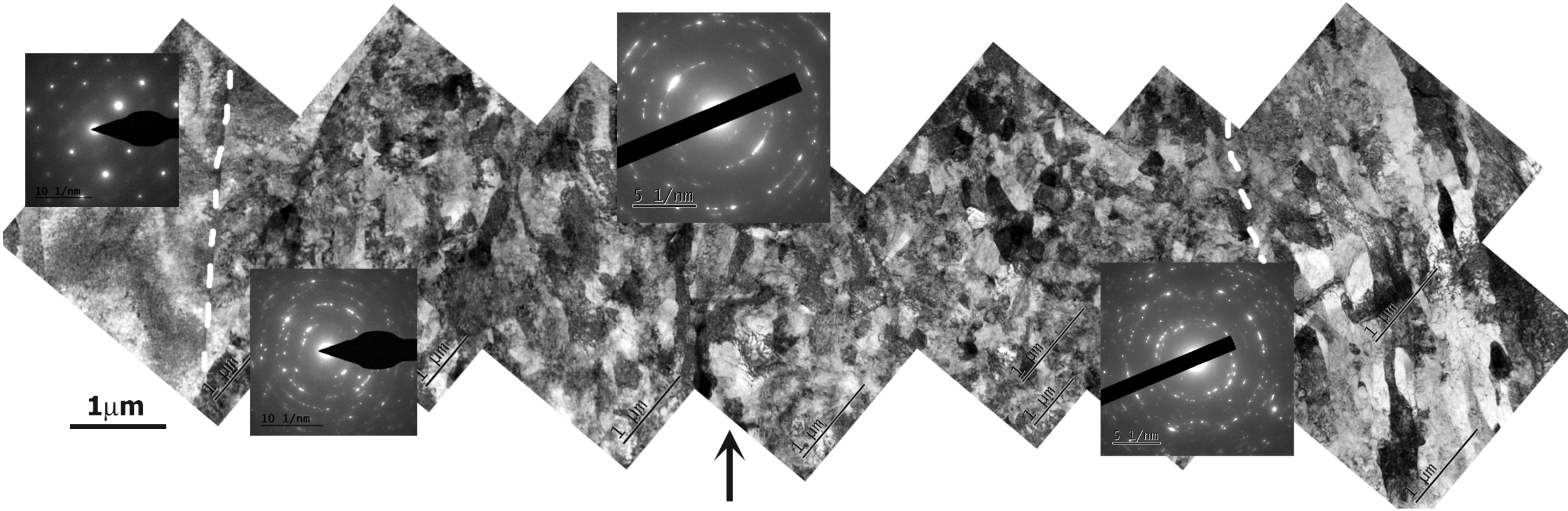
0.9 failure strain. Micro cracks in ASB

TEM (FIB) specimens



The cracks are located in islands of DRX

Coarse grains away from the crack

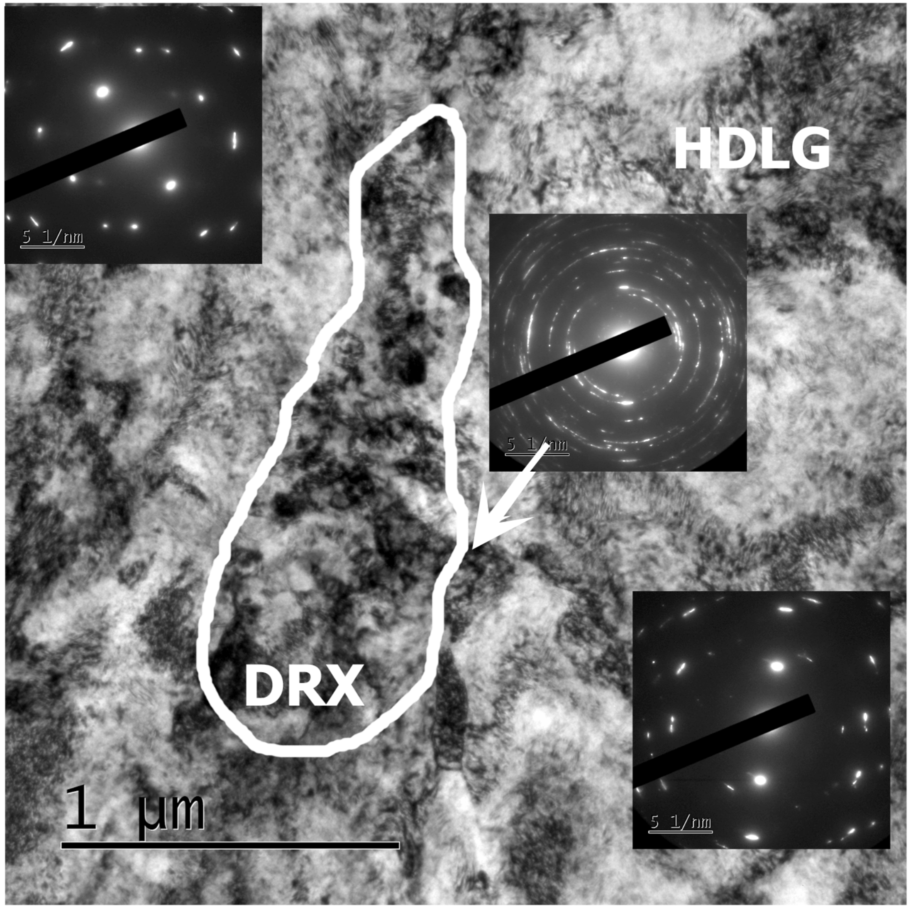


nano grains (DRX close to the crack)

Dynamically recrystallized grains at the tip of a crack (box A).

The crack is perpendicular to the image. The crack tip location is indicated by the black arrow, at the mid-bottom of the image.

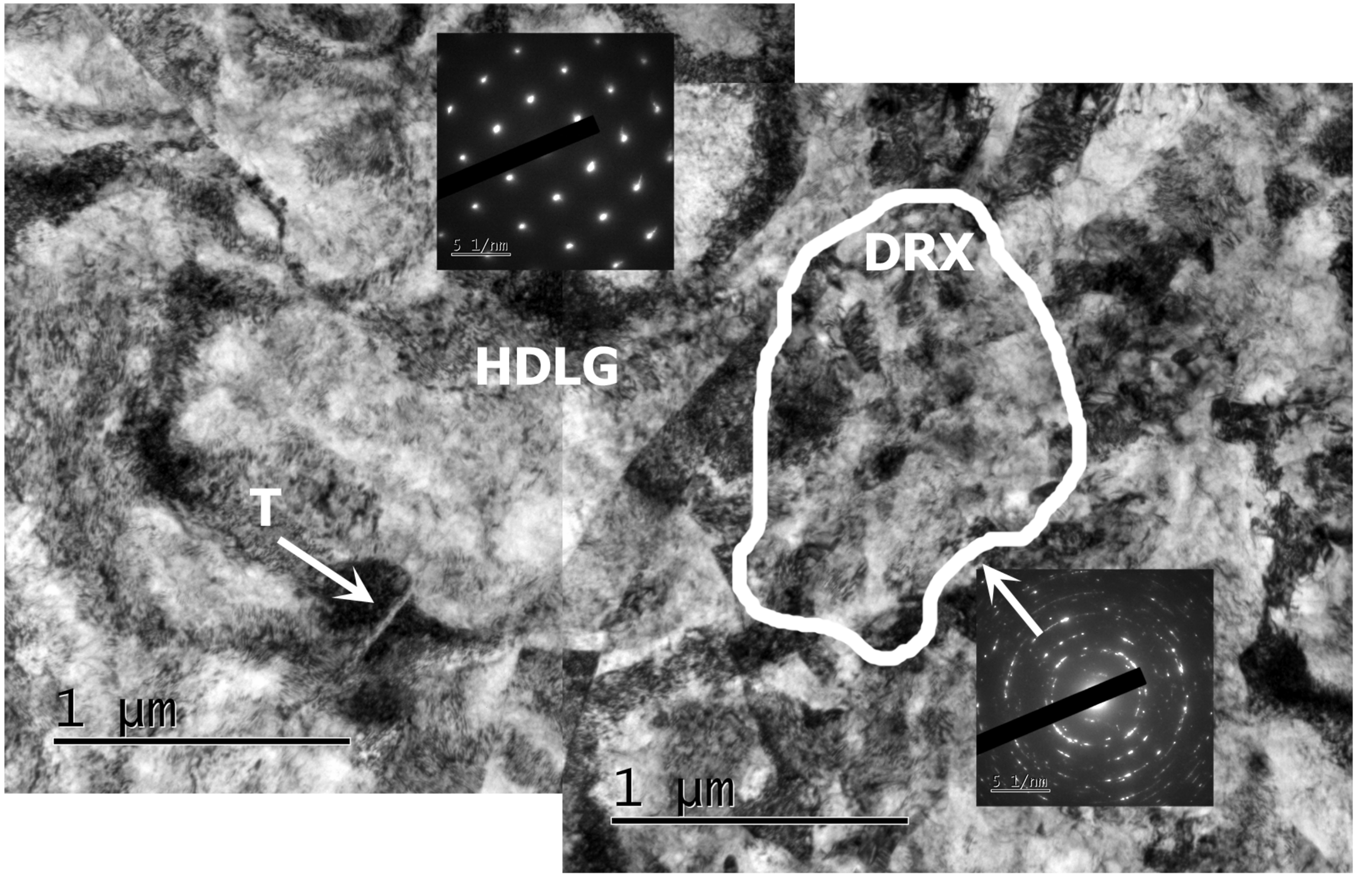
The dense DRX'ed region extends roughly **5 micron to each side**, with dashed lines delineating the extent of the DRX'ed region.



Sample between the cracks (box B): heavily deformed Ti matrix and small DRX'ed regions and highly deformed large grains (HDLG).

A single DRX island is bounded by a white line.

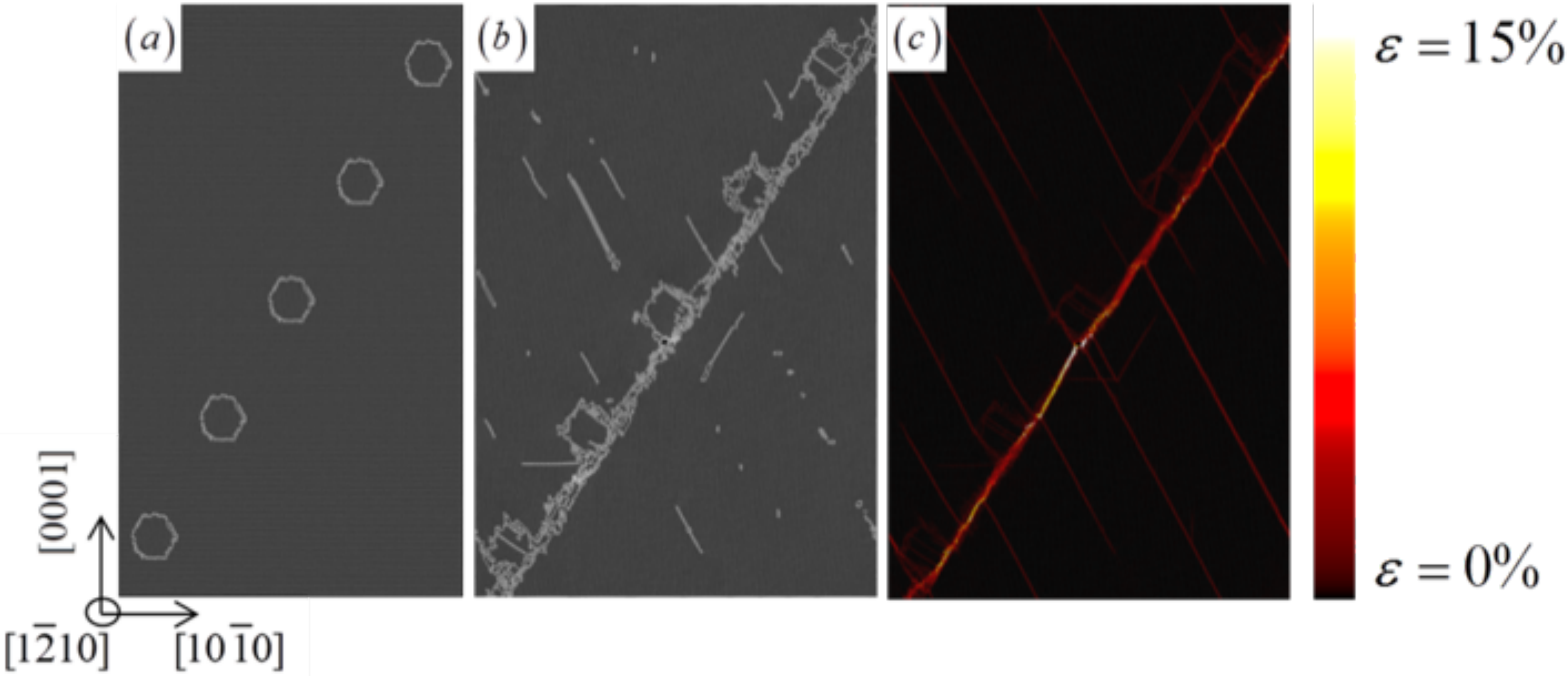
Corresponding diffraction patterns are inserted in the image.



(Box C), ~5 micron aside from the crack. Heavily deformed microstructure with a DRX island within it (marked by the white line), similar to the microstructure observed between the cracks (Box B). A twin is arrowed in the heavily deformed region.

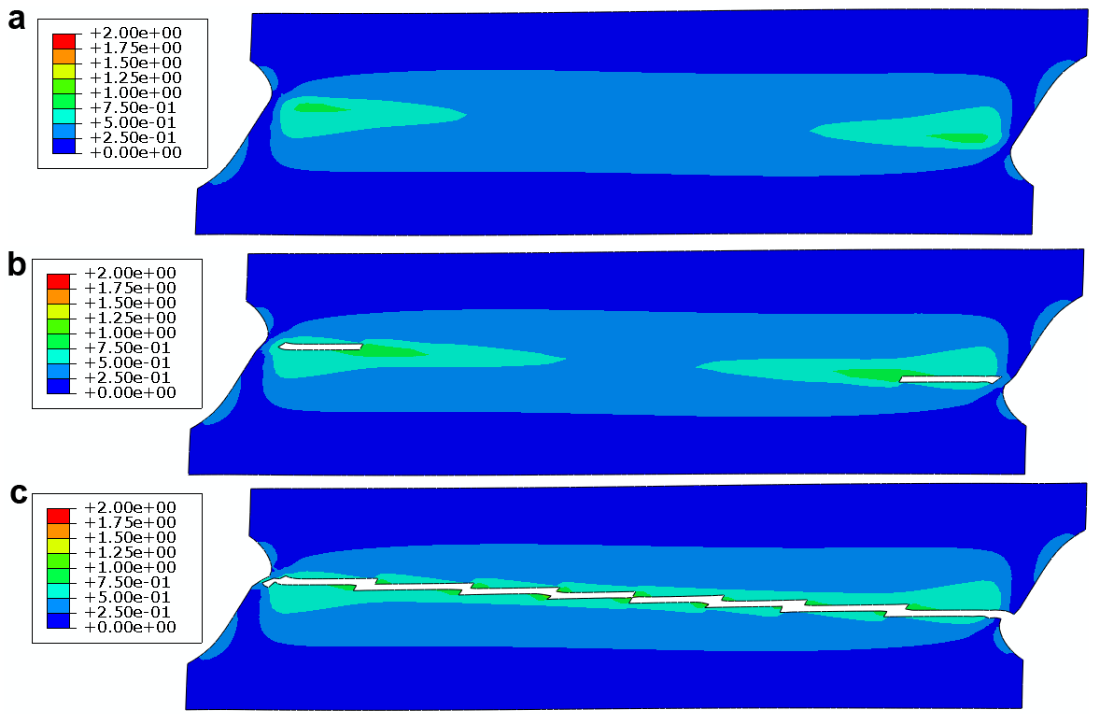
P. Landau, S. Osovski, A. Venkert, V. Gartnerova and D. Rittel, (2016), “The genesis of adiabatic shear bands”, *Scientific Reports*

Zooming: MD simulations

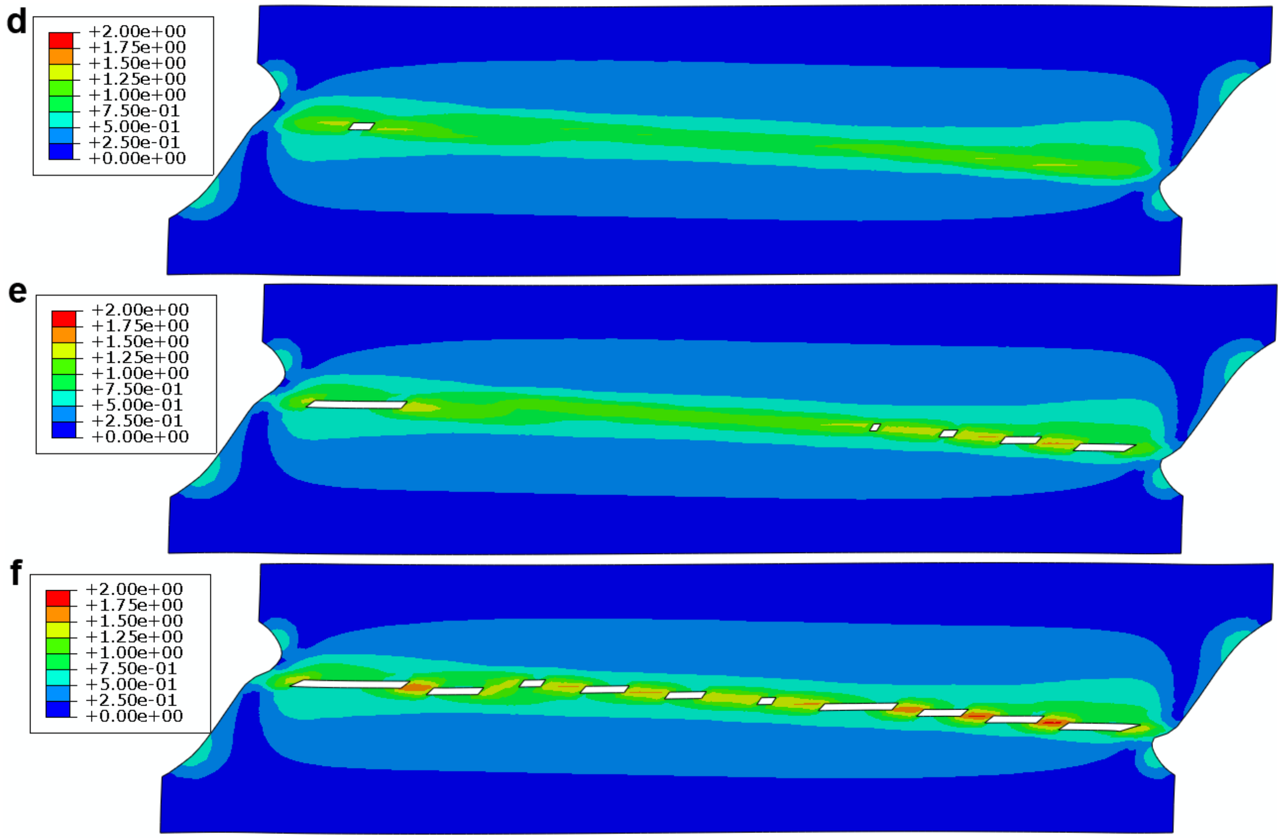


(Nanograins precipitate shear localisation (S. Chen, D. Mordechai and D. Rittel (2014), “Nanograins promote shear localization”, *Materials Res. Letters)*

A quick peek at modelling results



Homogeneous distribution of stored energy (= DRX propensity)



Heterogeneous distribution of stored energy.

MORE REALISTIC

P. Landau, S. Osovski, A. Venkert, V. Gartnerova and D. Rittel, (2016), "The genesis of adiabatic shear bands", *Scientific Reports*, 6:37226

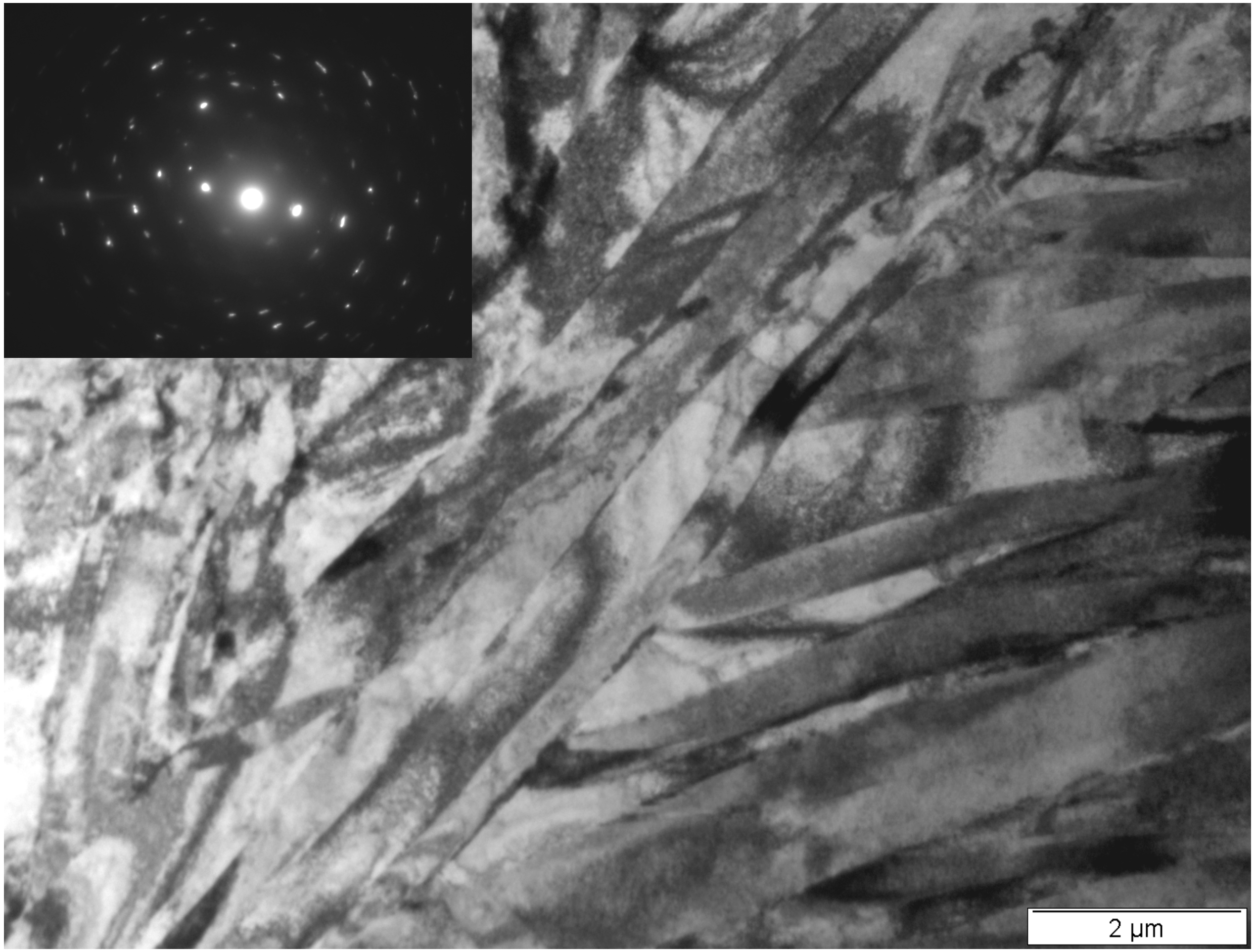
Is that all?

- Dislocation slip is important but not the only deformation micromechanism
- Twinning (shear) is also of prime relevance in **low stacking fault energy** (SFE) materials…..
- **Ti-6Al-4V** deforms by **slip only** **(high SFE)**
- **Pure Ti** deforms primarily by **twinning** and some slip (**lower SFE**)

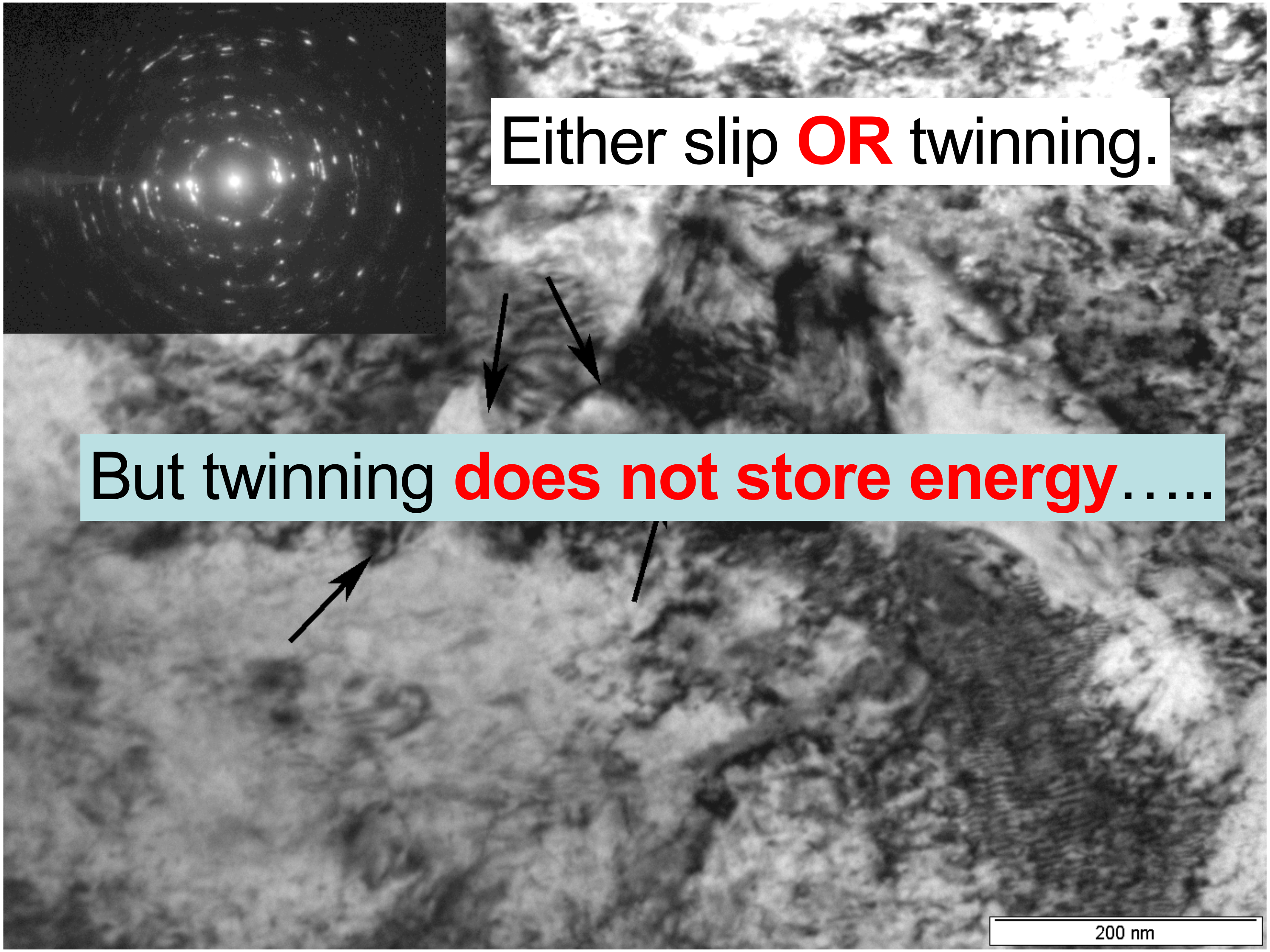
Some micrographs – **Pure Ti**

Ti sample deformed to $\varepsilon = 0.9\varepsilon_f$ showing twins .

No DRX found below that strain!



Same material at same strain. Different location.
DRX is obvious

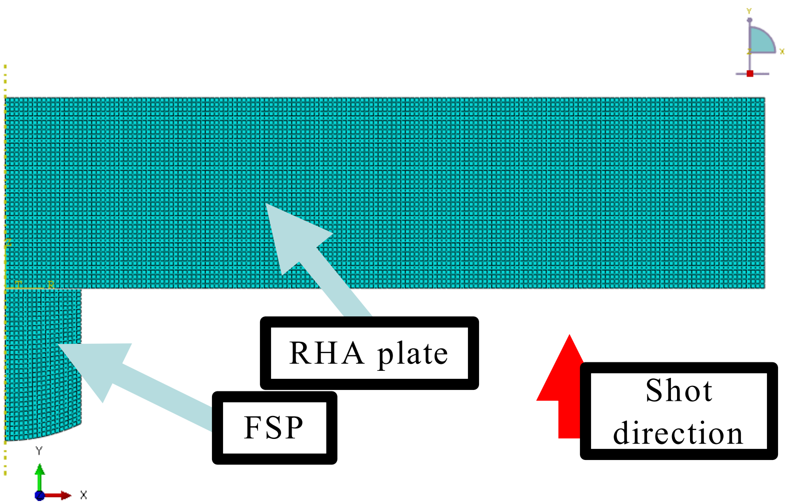


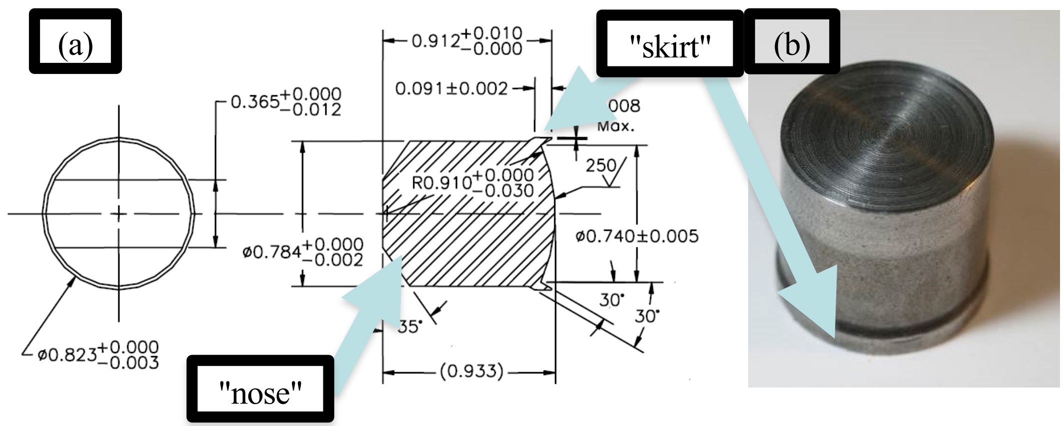
- Twinning must not be overlooked!
- Twinninig dissipates energy, thus delaying or precluding DRX.
- The coalescence of DRX islands with large local strain-rates leads to final failure (percolation?).
- Modeling (including microstructural evolutions.

Going MACRO: Numerical implementation

25[mm] RHA plate

Trimmed 20[mm] FSP





- 4340 steel -30[R_c] hardness
- Material constitutive behavior - JC[1]

- RHA steel -38[Rc] hardness
- σ_y=1500[MPa]

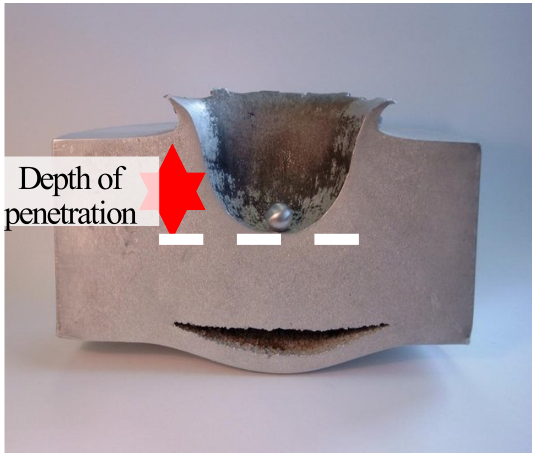
$$W_c = 450[MPa] \quad W_f = 1350[MPa]$$

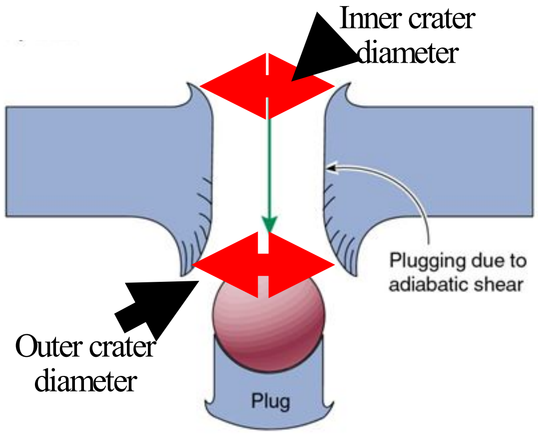
- Rate sensitive tensile failure criterion

Axi-symmetric simulation
Used mesh – element size 0.6[mm]
Initial condition of velocity

Experiments: RHA plate penetration

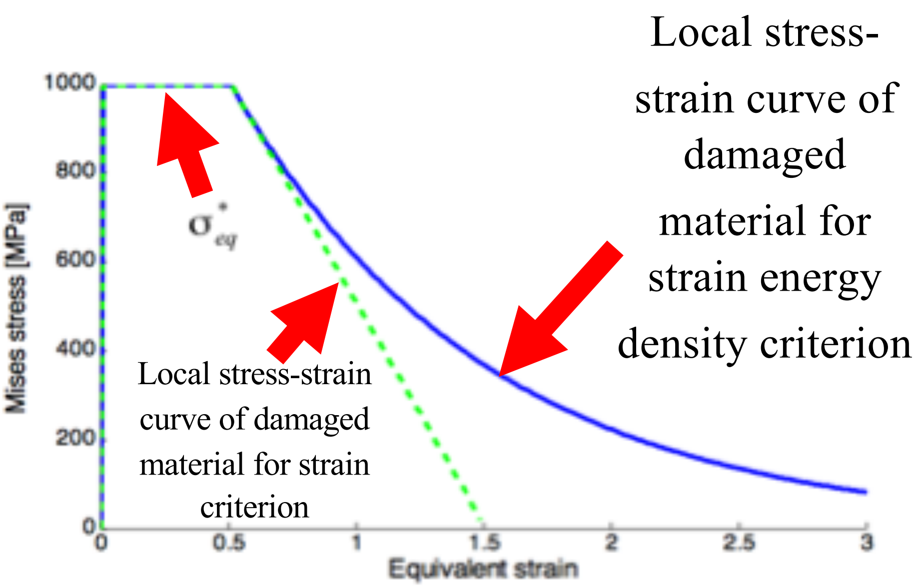
Shot Number	Measured impact velocity ±20[m/s]	Depth of penetration or (P) perforation ±0.05[mm]	FSP weight ±0.01[gr]	FSP length ±0.02[mm]	Inner crater diameter ±0.05[mm]	Outer crater diameter ±0.05[mm]
9	1151	11.05	46.79	20.32	36.30-37.40	-
6	1248	13.74	46.75	20.66	38.45-39.10	-
5	1256	14.09	46.89	20.73	39.45-41.15	-
7	1322	16.8	45.94	20.0	39.45-40.70	-
8	1394	P	46.51	20.58	39.85-41.70	21.35-26.90
3	1460	P	46.60	20.95	41.70-42.50	23.60-26.70
4	1466	P	46.36	20.5	41.05-43.90	22.65-24.75
2	1715	P	47.68	21.06	48.35-49.60	27.15-28.90
1	1920	P	46.74	20.68	49.20-54.05	28.95-30.45





Dolinski, M., Rittel, D., Experiments and modeling of ballistic penetration using an energy failure criterion. J. Mech. Phys. Solids , 2016.

Damage model parameters



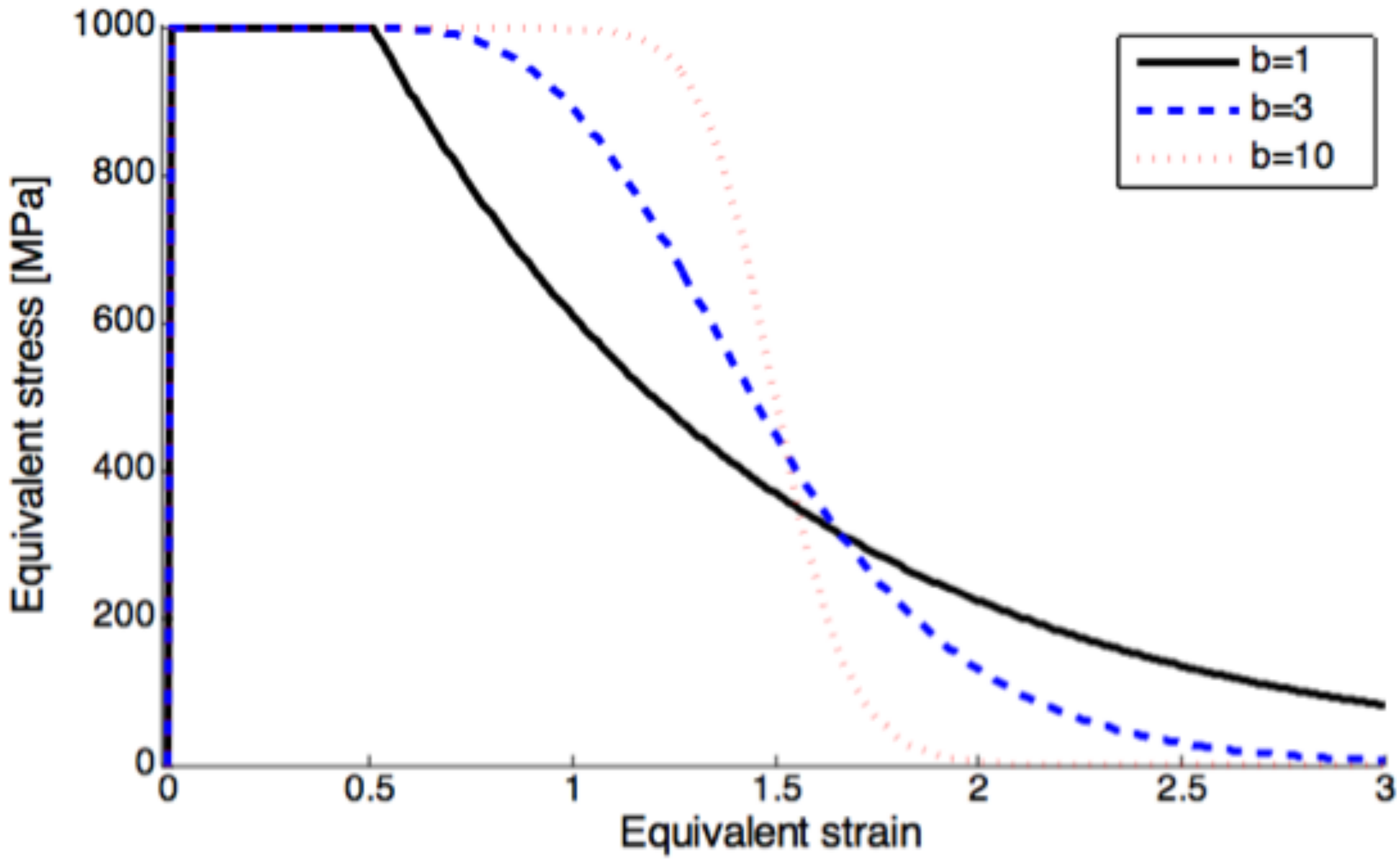
Strain criterion	PSED criterion
$\sigma^*_{eq} = 1000\ [MPa]$	$\sigma^*_{eq} = 1000\ [MPa]$
$D = \begin{cases} 0 & \varepsilon \le \varepsilon_{cr} \\ \dfrac{\varepsilon - \varepsilon_{cr}}{\varepsilon_f - \varepsilon_{cr}} & \varepsilon \ge \varepsilon_{cr} \end{cases}$	$D = \begin{cases} 0 & W \le W_{cr} \\ \dfrac{W - W_{cr}}{W_f - W_{cr}} & W \ge W_{cr} \end{cases}$
$\varepsilon_{cr} = 0.5$	$W_{cr} = 500\ [MPa]$
$\varepsilon_f = 1.5$	$W_f = 1500\ [MPa]$

$$\sigma = \sigma^*\left(1 - D^b\right)$$

Parameters are determined experimentally

- Very high strains can be achieved
- Simplified material model

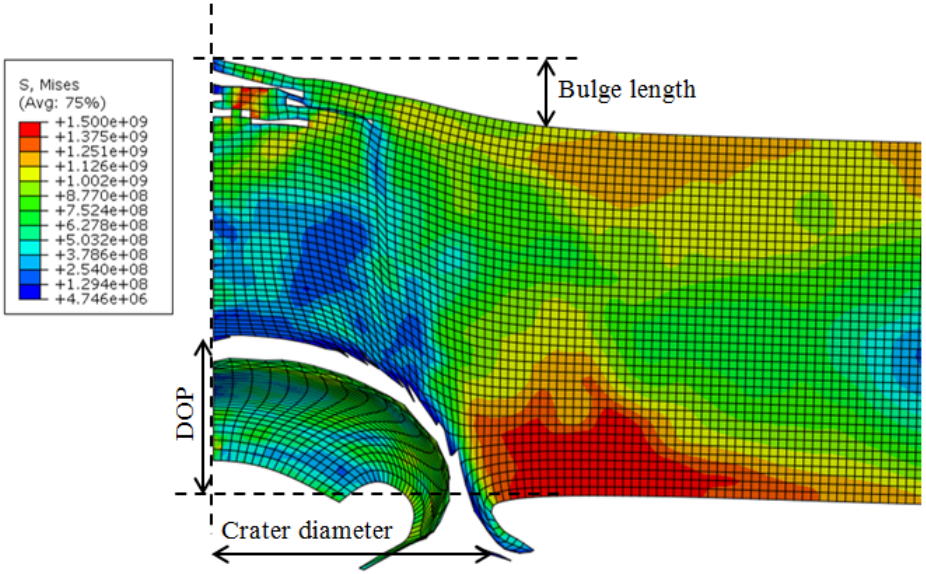
Dolinski, M., Merzer, M., Rittel, D., 2015. Plastic strain energy density as a criterion for dynamic failure – IJIE, 2015.



“Shear band toughness”

Comparison of impact velocity 1150[m/s]

	Experiment	Simulation
Impact velocity	1151±20[m/s]	1150[m/s]
DOP	11.05±0.1[mm]	11.1[mm]
Crater diameter	36.3-37.4±0.1[mm]	37.34[mm]
Bulge length	4.97±0.1[mm]	5.04[mm]

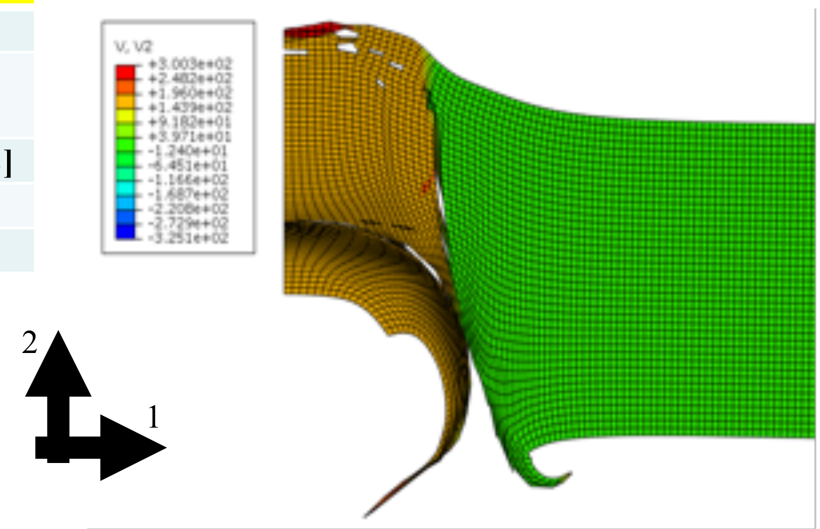


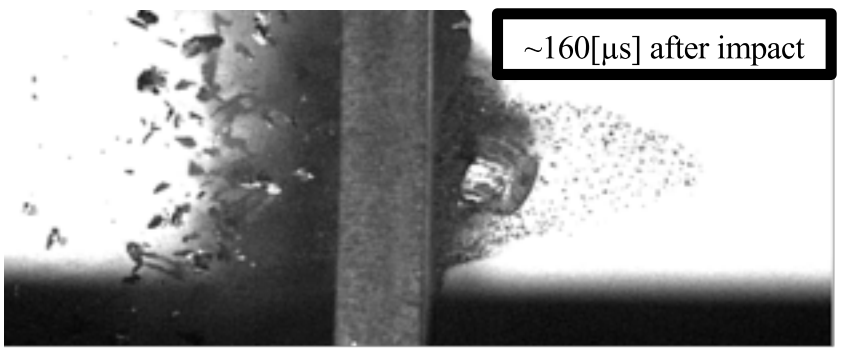

Penetration crater

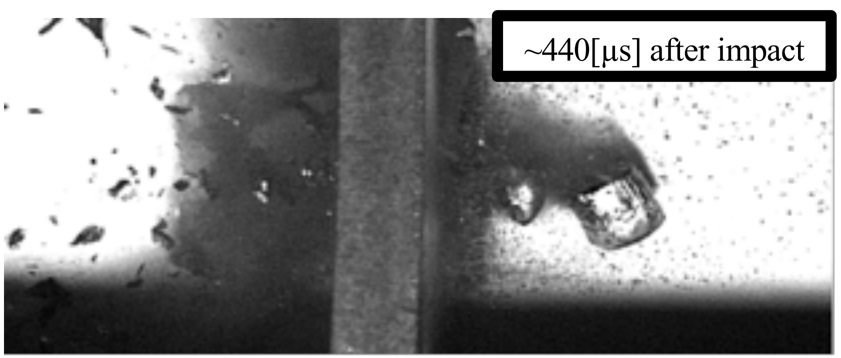

Plate's rear side

Comparison of impact velocity 1400[m/s]

	Experiment	Simulation
Impact velocity	1394±20[m/s]	1400[m/s]
Crater maximal diameter	39.45-40.7±0.1[mm]	39.53[mm]
Plug exit velocity	196±20[m/s]	180±20[m/s]
Plug diameter	20.9-26.2±0.1[mm]	26.05[mm]
Plug height	22.2±0.1[mm]	20.1[mm]





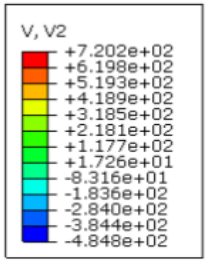


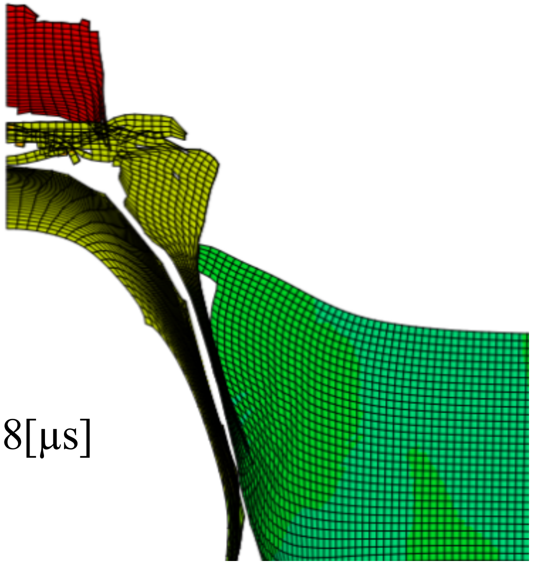
Plate's front side

plug

Comparison of impact velocity 1900[m/s]

	Experiment	Simulation
Impact velocity	1920±20[m/s]	1900[m/s]
Crater maximal diameter	49.20-54.05±0.05[mm]	49.24[mm]
Crater minimal diameter	28.95-30.45±0.05[mm]	28.99[mm]
Fastest fragment velocity	723±20[m/s]	700±10[m/s]





t=58[μs]

Plate’s rear side

Plate’s front side

M. Dolinski and D. Rittel, (2015), “Experiments and modeling of ballistic penetration using an energy failure criterion”, *J. Mech. Phys. Solids*, 83, 1-18.

Conclusions

- Adiabatic shear has **microstructural origins**.
- DRX evolution and kinetics must be further studied and modeled, taking twinning into account.
- DRX is driven by stored strain energy (microstructure).
- Macro-modeling can be based on a strain energy density + damage criterion.

Thank you for your attention.