How to Make Strong Metals With High Ductility?

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Outline

1. How do we try to do it?

    First way: fragmentation

    Second way: consolidation

2. How do we try to explain and to predict it?

    Mechanics of the processing

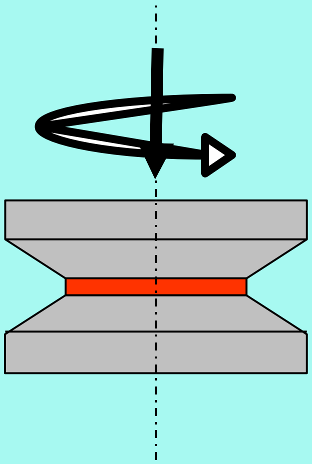
    Structure, ductility, strength

3. Final Thoughts

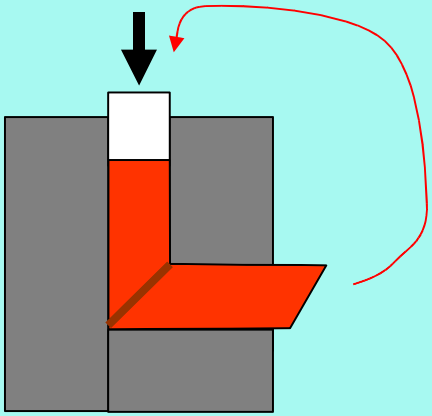
How do we try to do it?

- Severe plastic deformation (SPD)
- Twist Extrusion
- First way: Fragmentation
- Second way: Consolidation

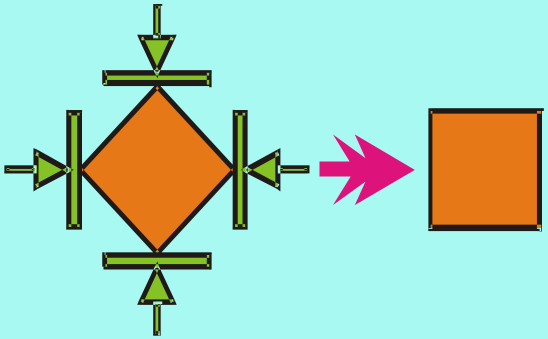
Some of the SPD Techniques



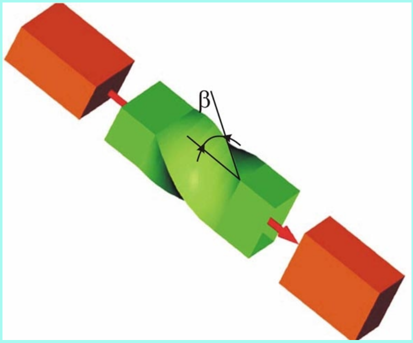
High Pressure Torsion



Equal Channel Angular Extrusion

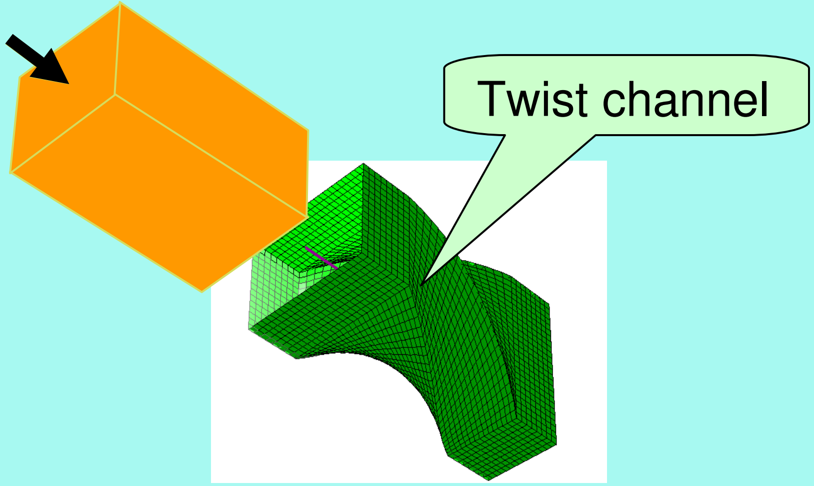


3d Forging

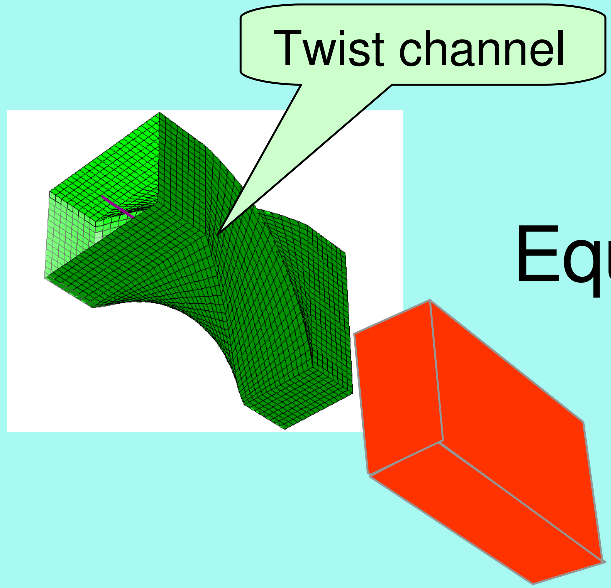


Twist Extrusion
(*Y.Beygelzimer, 1999*)

The idea of TE:



The idea of TE:

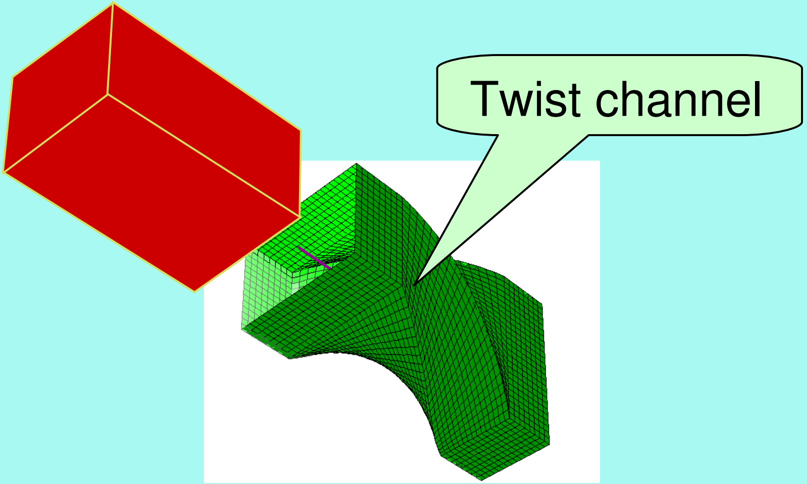


Equivalent strain e~1

The shape and the dimensions of the work-piece do not change!

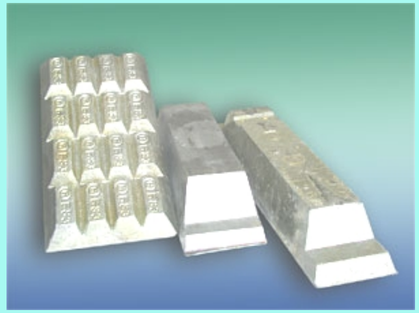
The idea of TE:

Equivalent strain e~2



Repeated twist extrusion leads to grain refinement

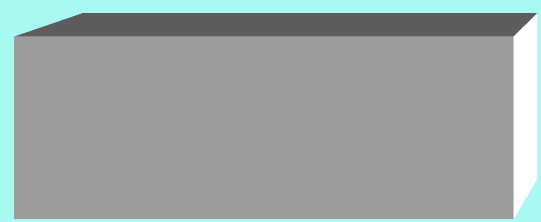
Twist Extrusion: Two in One



Fragmentation

Twist Extrusion

Consolidation



Fragmentation

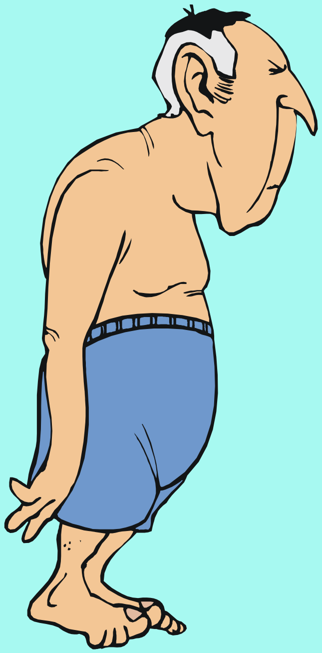
- Grains refinement. UFG materials
- Breaking of a brittle particles

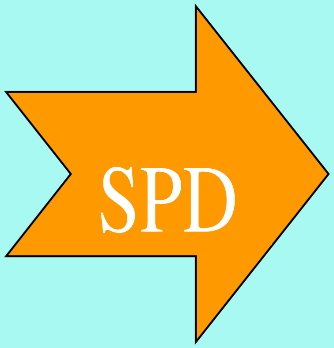
Why should we care about grain refinement during severe plastic deformation?

This is one of few effective techniques for obtaining ultrafine-grained (UFG) materials

Grain refinement

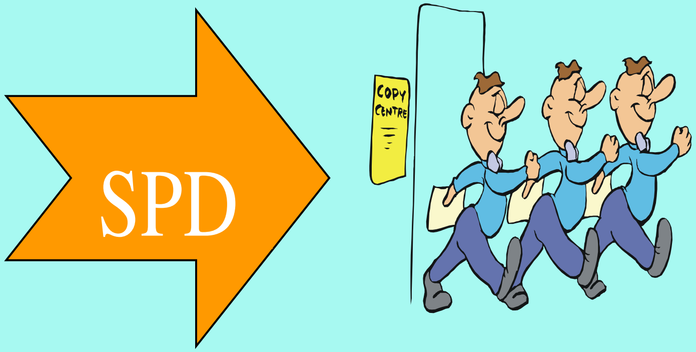
Coarse





Grain refinement

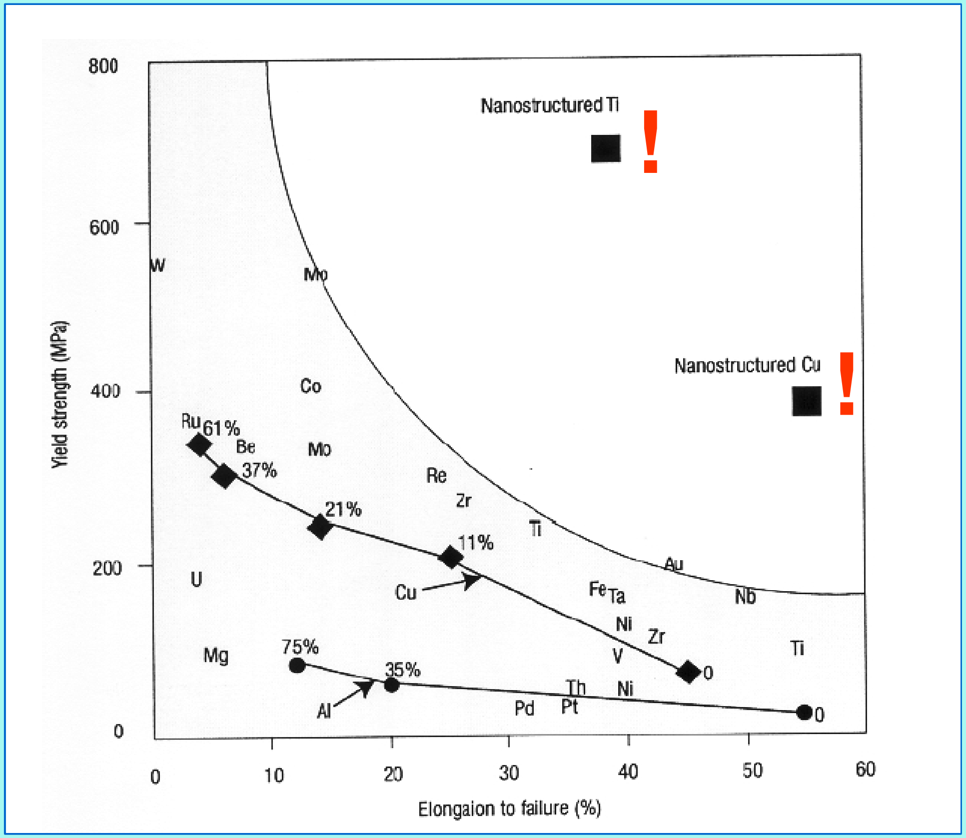
UFG



Ultrafine-Grained Materials

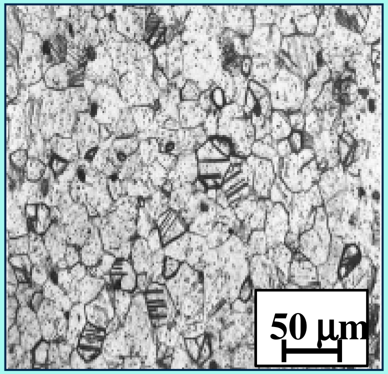
- What are they?
  - Metals with grain size ~10-1000 nm
- Why are they appealing?
  - Significantly improved properties
  - Qualitatively different properties not seen in conventional materials

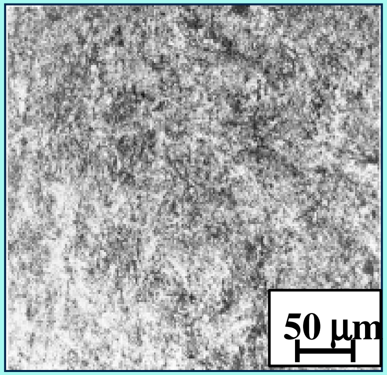
High strength and ductility of UFG materials

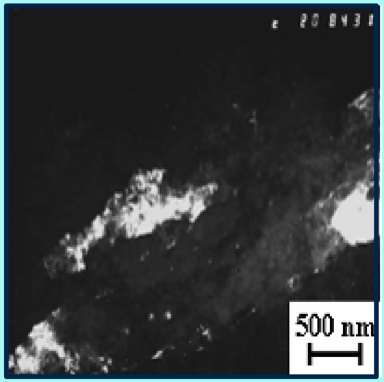


R.Z. Valiev, I.V. Alexandrov, Y.T. Zhu and T.C. Lowe, “Paradox of Strength and Ductility in Metals Processed by Severe Plastic Deformation,” J. Mater. Res. 17, 5-8 (2002).

Twist extrusion of the Ti







Initial state

After 3 passes

Twist extrusion of the Ti

Table 1. Mechanical properties of titanium after TE, subsequent annealing, and cold rolling

State	Direction of tests relative to the extrusion axis	σ_u, MPa	$\sigma_{0.2}$, MPa	δ, %	H_V, MPa
As-delivered	Longitudinal	505	375	36	1800
	Transverse	500	360	46	1850
TE (three passes)	Longitudinal	505	463	31	2300
	Transverse	835	765	17	2800*
					2400**
TE (three passes) + 1-h annealing	Longitudinal	500	441	37.5	–
	Transverse	865	737	37.5	–
TE (three passes) + cold rolling (reduction 50%)	Longitudinal	780	750	30	2700
	Transverse	795	760	27	2750*
					3300**

* Butt end of plate.
** Plane of plate.

The Physics of Metals and Metallography, Vol. 99, No. 2, 2005, pp. 204–211. Translated from Fizika Metallov i Metallovedenie, Vol. 99, No. 2, 2005, pp. 92–99.
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SPD of the Ti

Table 2. Mechanical properties of titanium obtained by different SPD methods

SPD method	T_{SPD}, °C	Degree of deformation	P_{SPD}, GPa	Direction of tension	σ_u, MPa	$\sigma_{0.2}$, MPa
HPT [2]	20	5 rev., $\varepsilon = 5$	5	Transverse to the twist axis	950	790
TE	20	Three cycles, $\varepsilon = 3.45$	0.75	Transverse to the extrusion axis	835	765
				Along the extrusion axis	505	463
ECAP [3]	450–400	Eight cycles, $\varepsilon = 9.2$	1.2	Transverse to the pressing axis	805	765
				Along the pressing axis	710	640

The Physics of Metals and Metallography, Vol. 99, No. 2, 2005, pp. 204–211. Translated from Fizika Metallov i Metallovedenie, Vol. 99, No. 2, 2005, pp. 92–99.
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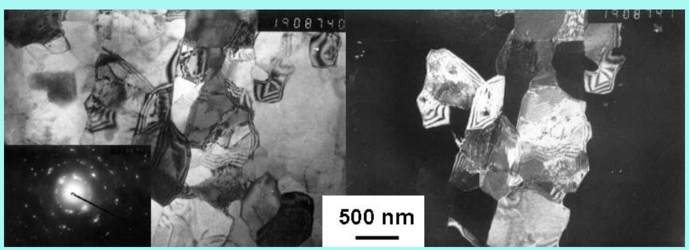
Plates for traumatology are made of UFG Ti

Twist extrusion of the Al-Mg-Sc-Zr alloy

Chemical composition:
Al - 3 wt.%Mg - 0,3 wt.%Sc – 0,10 wt.%Zr

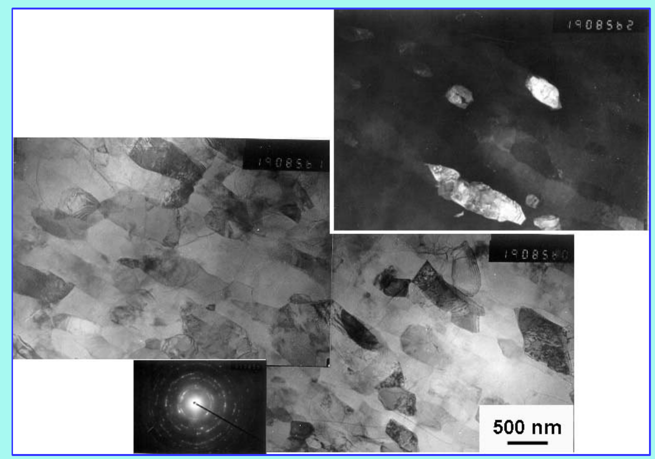
Initial grain size d_{av}=100 μm

Standard direct extrusion:
T=280-300ºC



d_{av}= 0.455 μm
d_{min}= 0.129μm
d_{max}=1.032 μm

Twist extrusion: T=280-300ºC
5 passes CW + 1 pass CCW



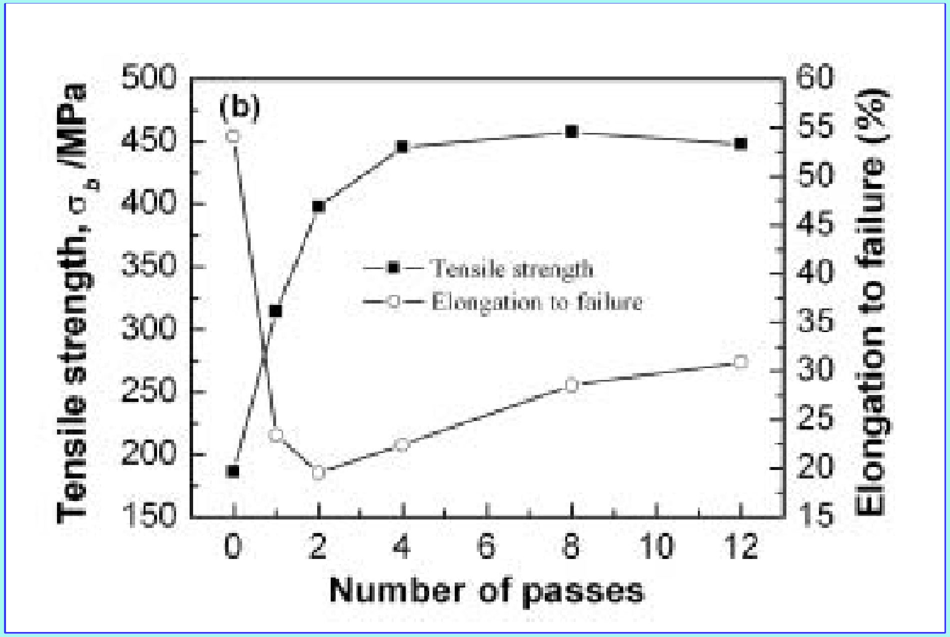
d_{av}=0.325 μm
d_{min}= 0.077μm
d_{max}=0.671 μm

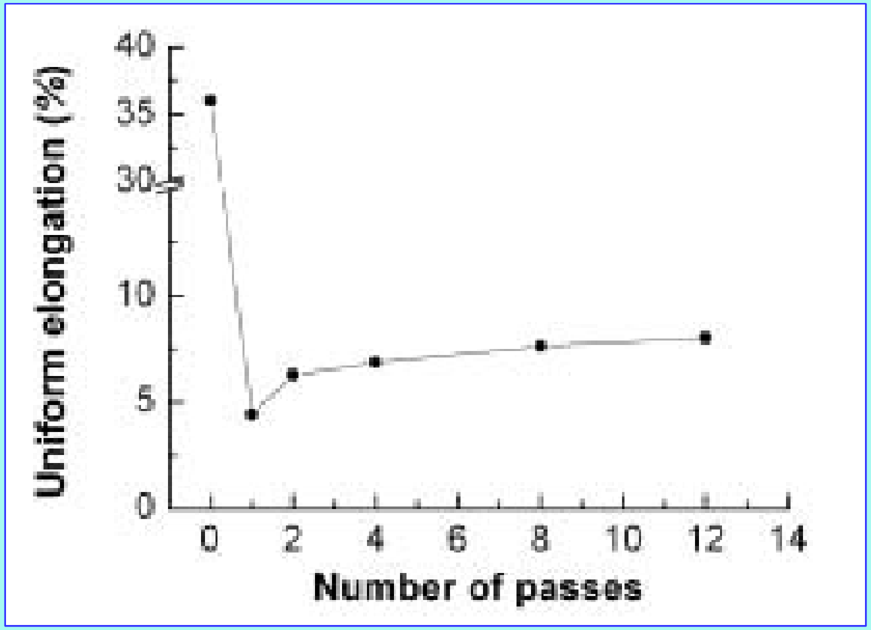
SPD of the Cu

State	Yield stress, MPa	Tensile strength MPa	Uniform elongation, %
As received	80	145	40
TE, 3 passes, with BP	393	426	18
* ECAE, 2 passes	320	360	14
* ECAE, 16 passes, without BP	420	440	15
* ECAE, 16 passes, with BP	440	470	25

*N. Krasil'nikov, R.Valiev

ECAE of the Cu





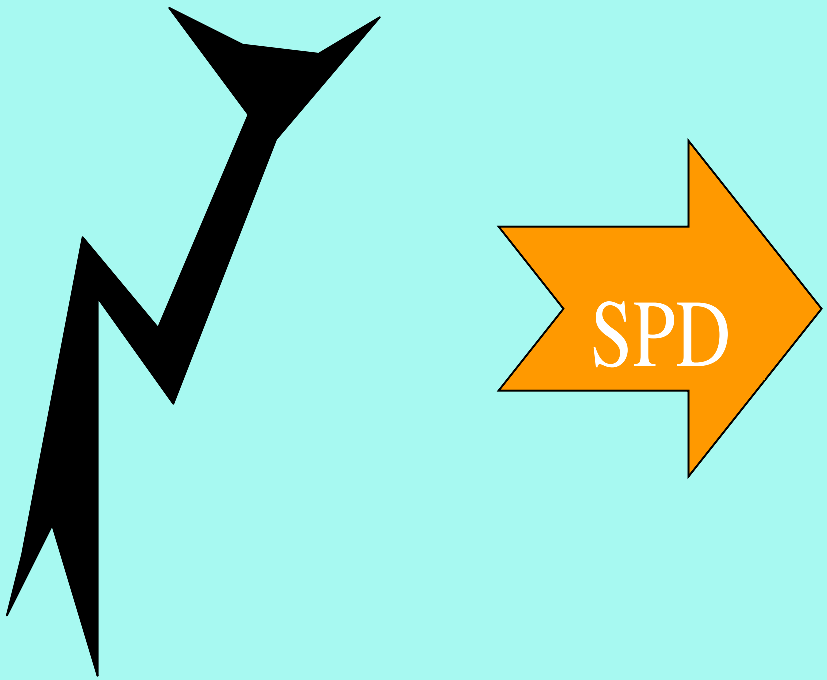
Wei Wei, Guang Chen, Jing Tao Wang, Guo Liang Chen

Journal of Advanced Materials 2005 (in press)

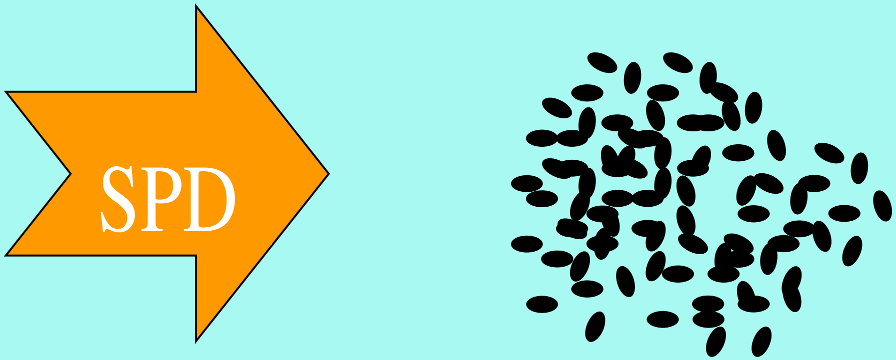
Three present-day ways to increase strength and ductility of UFG materials

- Cryogenic processing to produce a bimodal grain structure
- Formation of second-phase particles to modify the propagation of shear bands
- Developing aging and annealing treatments that can be applied to the UFG materials in the post-processed condition

Breaking of a brittle particles



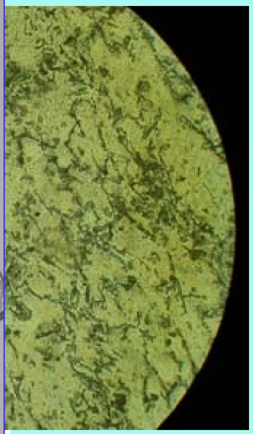
Breaking of a brittle particles

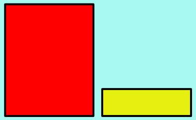


TE of secondary Al alloy

Al-88%; Si-9,5% …

ass





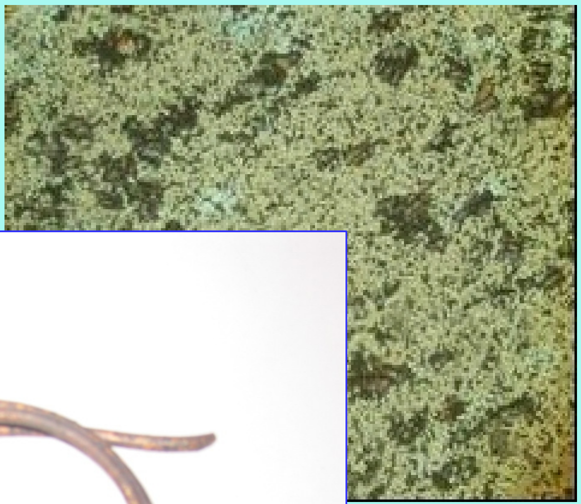
σ_y=50MPa 4%

a

Twist Extrusion of phosphorous Cu (P 9%)

Initial state

1 pass



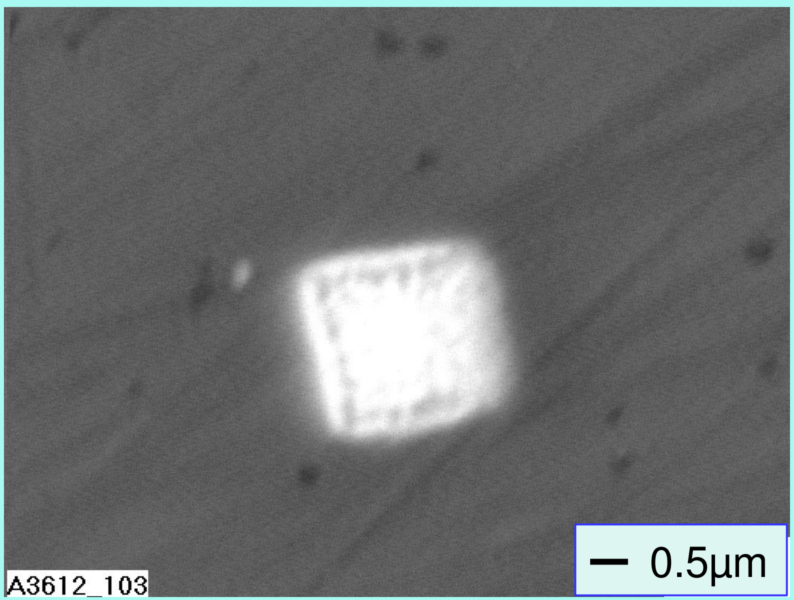
	δ, %
Dire	4
T	11

Back pressure = 200 MPa, T= 623 K

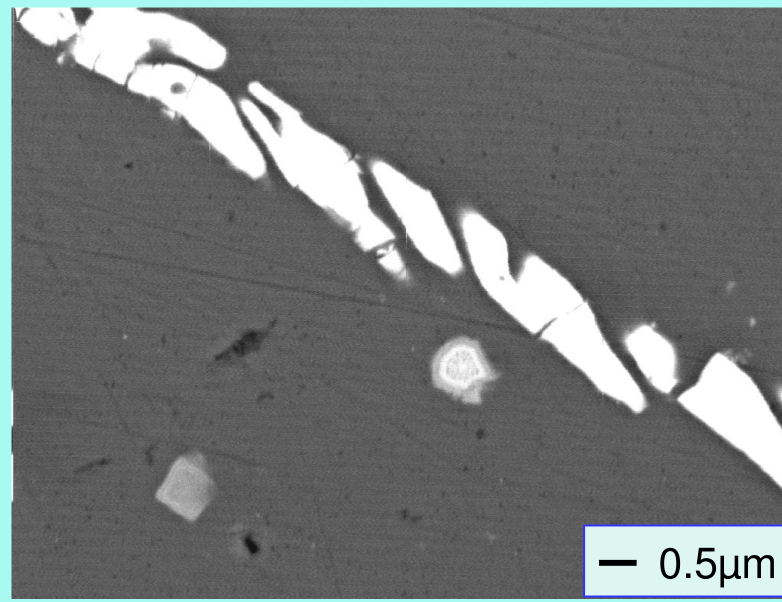
Twist extrusion of the Al-Mg-Sc-ZR alloys

Chemical composition:
Al – 3 wt.%Mg - 0,3 wt.%Sc – 0,15 wt.%Zr

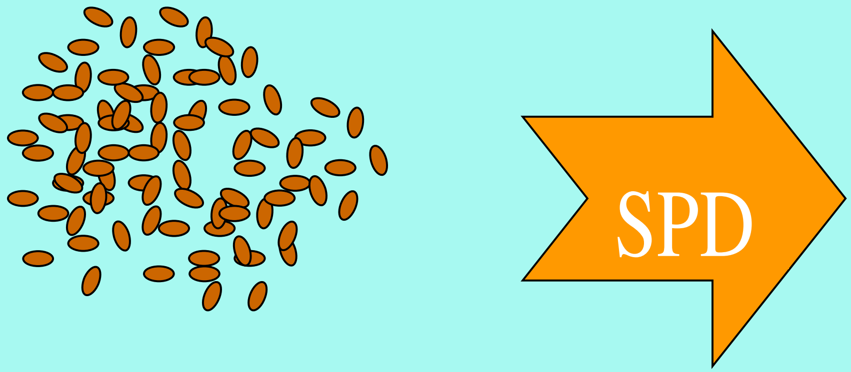
SEM, As-cast structure
Cross-section



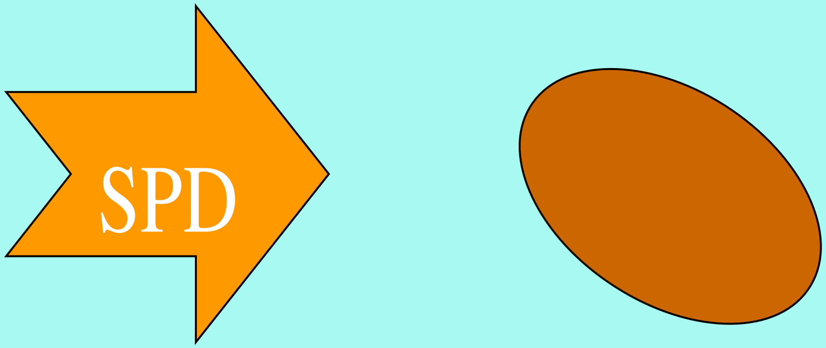
SEM, As-deformed structure,
TE – 5 passes, T_{def}=280-300ºC
Longitudinal section



Consolidation

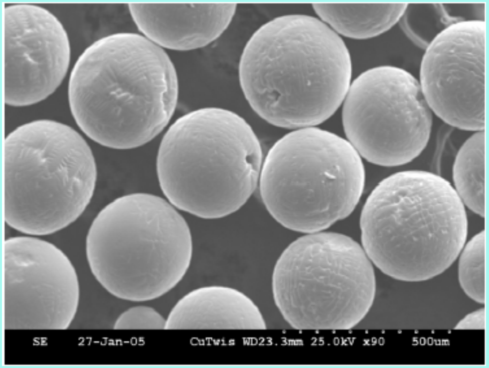


Consolidation

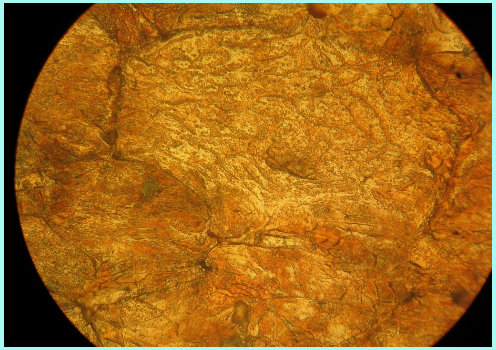


Consolidation of nanostructural Cu powder by Twist Extrusion

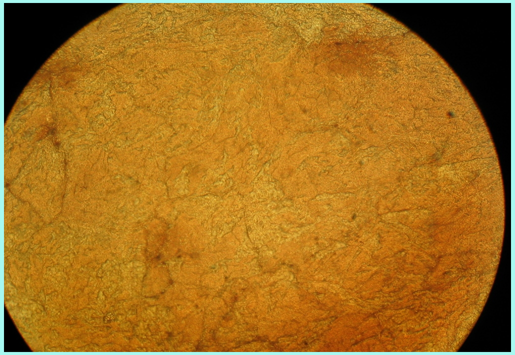
Back pressure = 200 MPa, T= 473 K



Initial powder, D=250 μm



1 pass



2 passes

Compression test
after 2 passes:

Yield stress = 450 MPa
Breaking strain = 28%

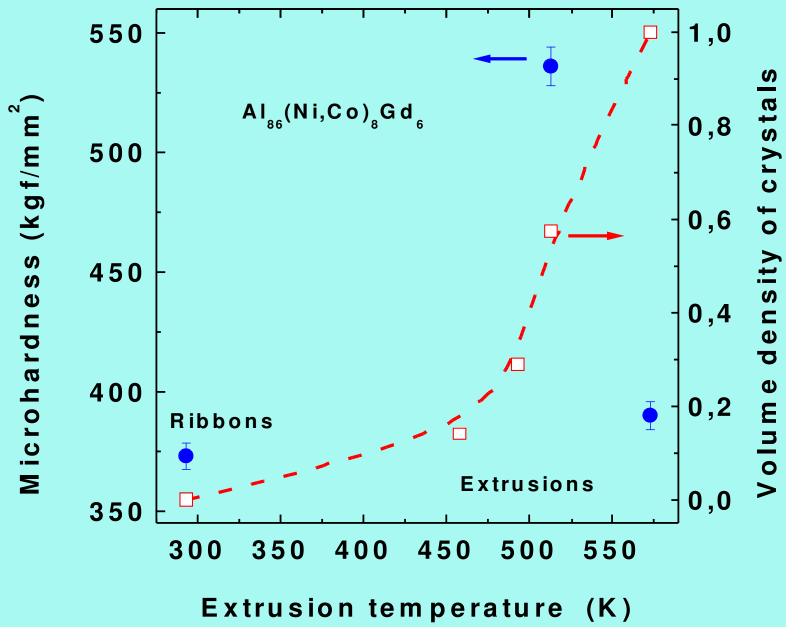
Tensile test
after 2 passes:

Yield stress = 200 MPa
Breaking strain = 15%

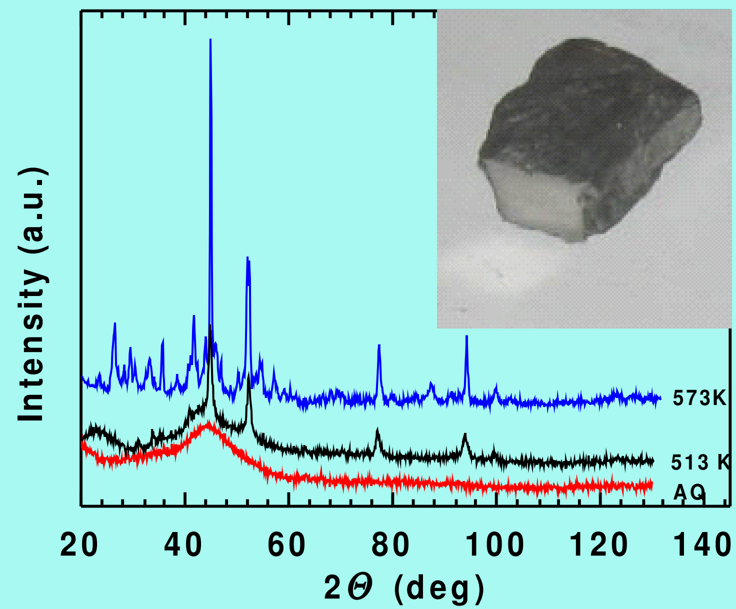
Consolidation of nanostructural Cu powder by Twist Extrusion

State	**Density, %**	**Diameter of the coherent-scattering region L, nm**
powder	-	100
TE, 1 path	99.2	36
TE, 2 paths	99.6	55

Consolidation of amorphous Al86Ni6Co2Gd6 melt-spun ribbons by Twist Extrusion

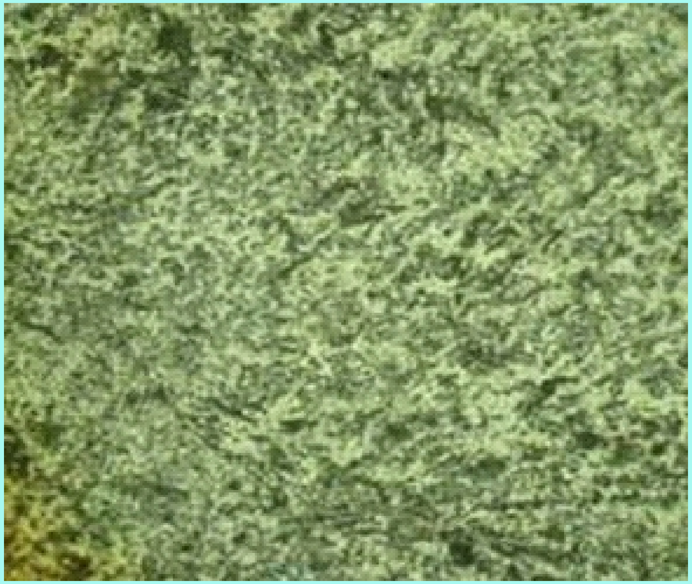


Microhardness and the volume fraction of the amorphous phase in the compacted samples.



X-ray diffraction patterns

Consolidation of the cutting of the secondary Al alloy by Twist Extrusion



Yield stress =180-220 MPa; δ= 20-24%

How do we try to explain and to predict it?

- The questions
- Mechanics of the processing
- The Problem
- The Model
- Predictions

The questions

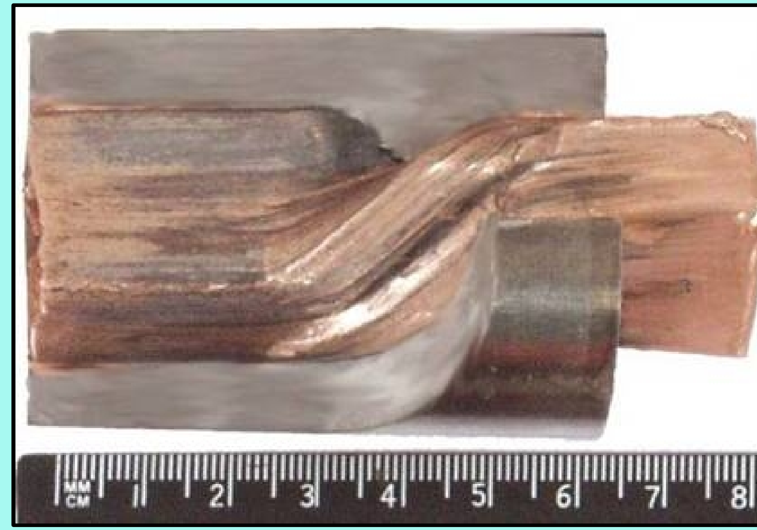
- Parameters of the process?
- Strength and Ductility of the materials?
- Structure of the materials?

Mechanics of metal flow

Stream lines

1

4



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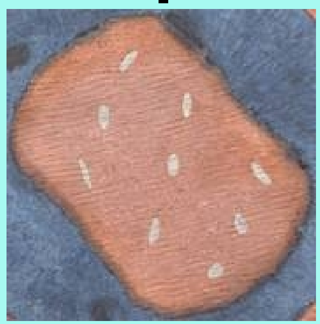


5

3

6

7

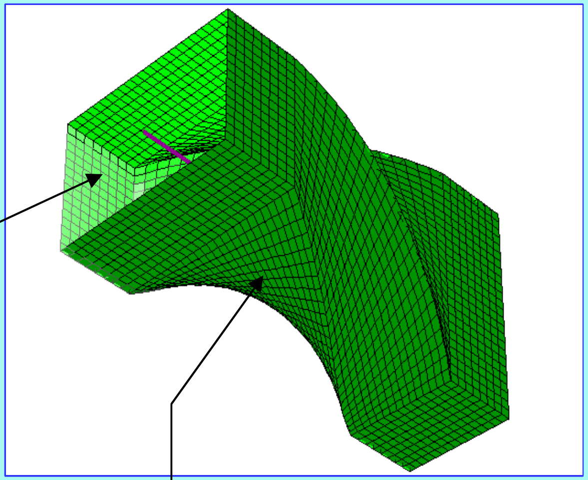
8

Kinematically-admissible velocity field

1. Volume constancy condition

$$divV = 0$$

2. Boundary condition



$$V = V_0$$

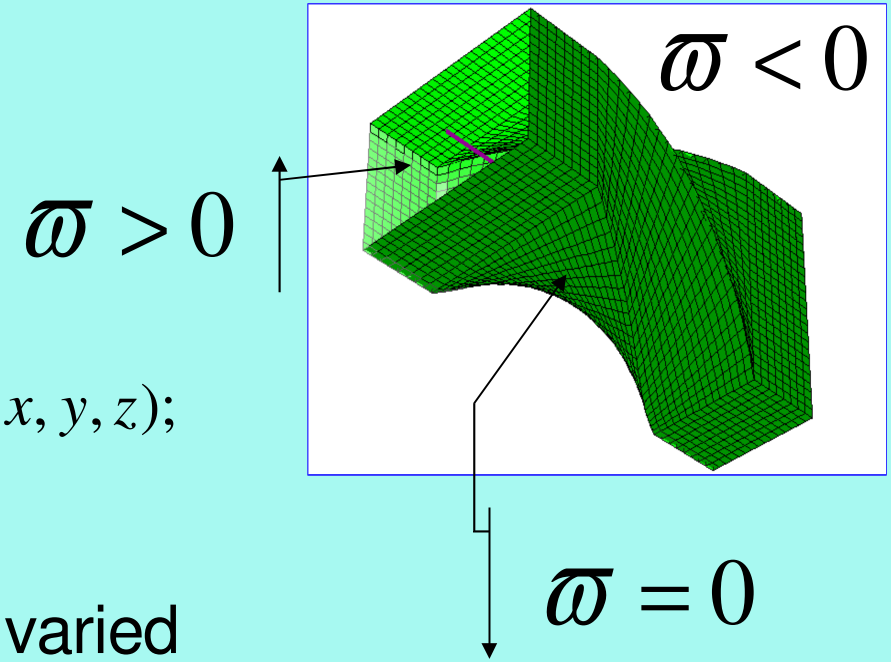
$$V \cdot n = 0$$

Kinematically-admissible velocity field

$$V = rotA$$

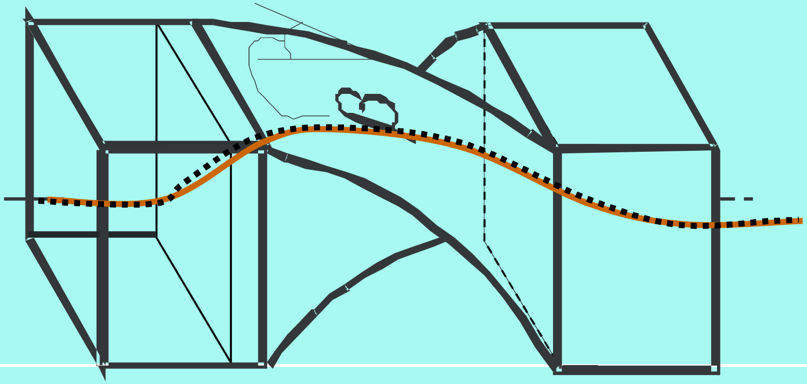
ϖ- form function

$$\begin{cases} A_x = 0.5V_0 y; \\ A_y = -0.5V_0 x; \\ A_z = -\dfrac{V_0 tg\beta}{R} xy + \varpi(x,y,z)P(x,y,z); \end{cases}$$



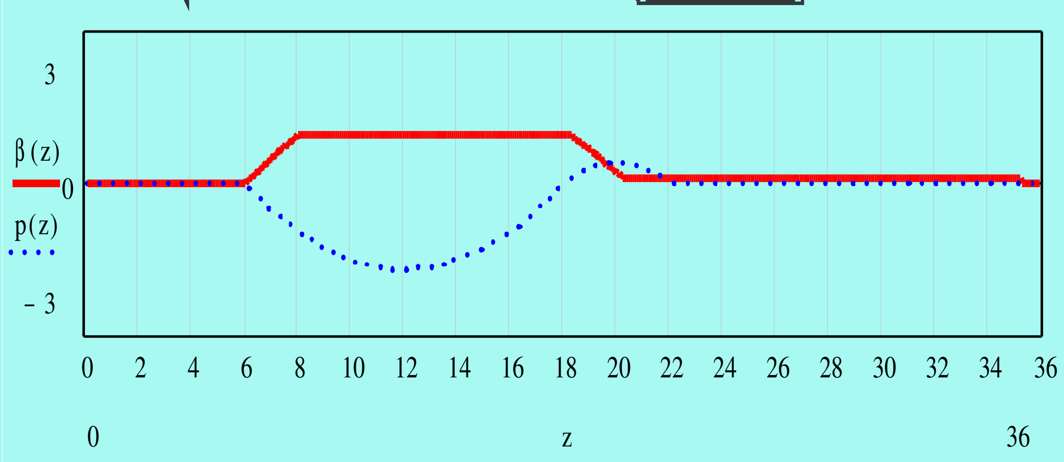
P- function which is varied

Finding function P on the experimental stream lines

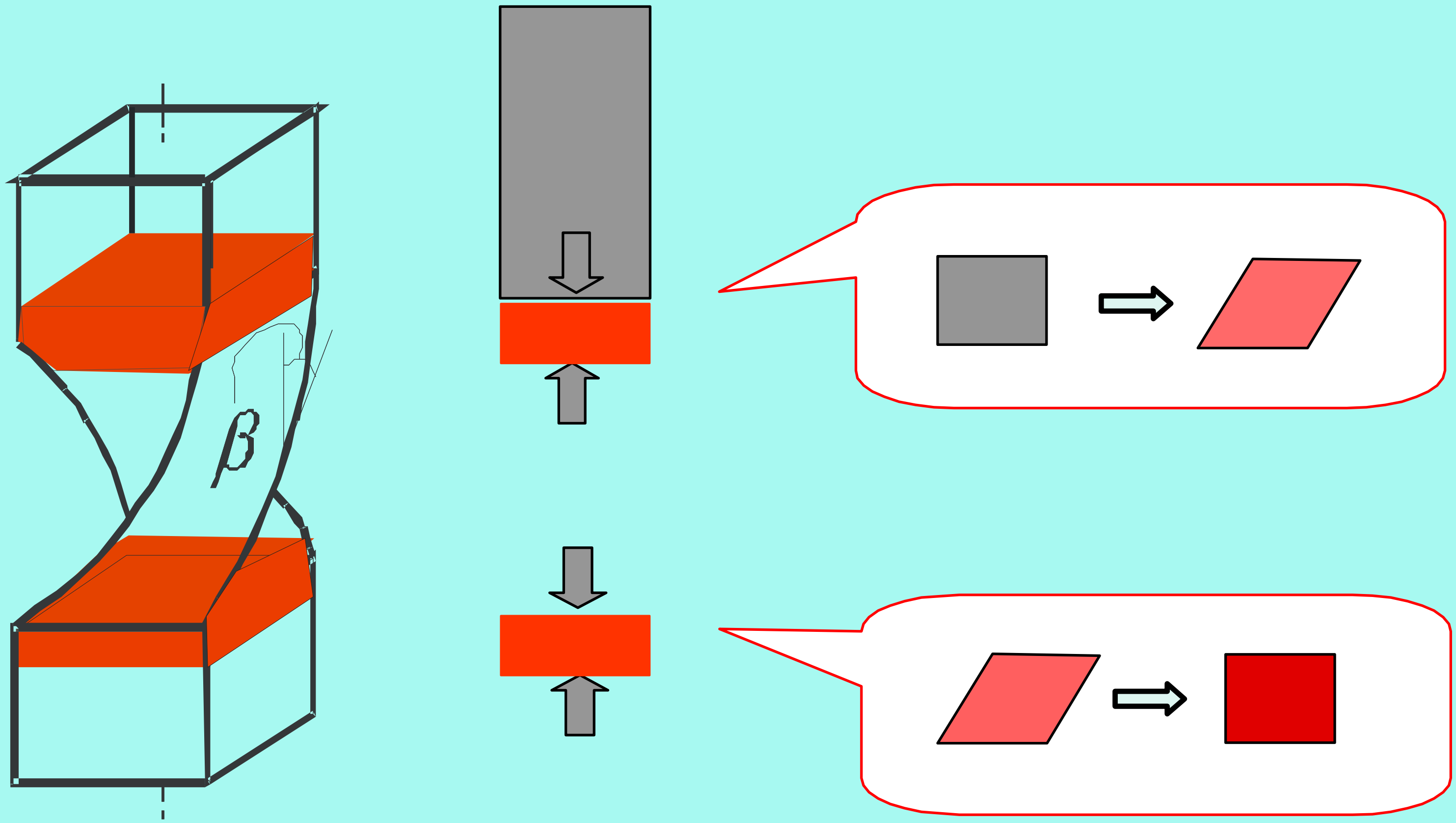


Experimental stream line

Theoretical stream line



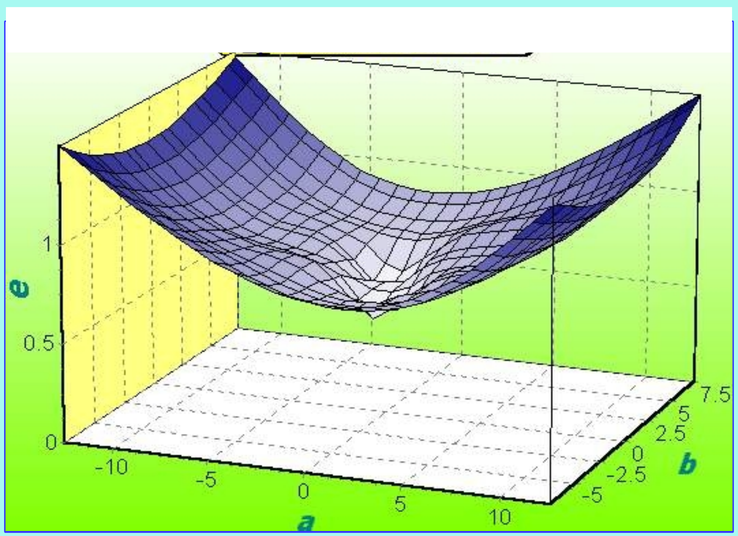
Metal Deformation under Twist Extrusion



We showed that most of the deformation achieved by Twist Extrusion is Simple Shear at the ends of the twist channel

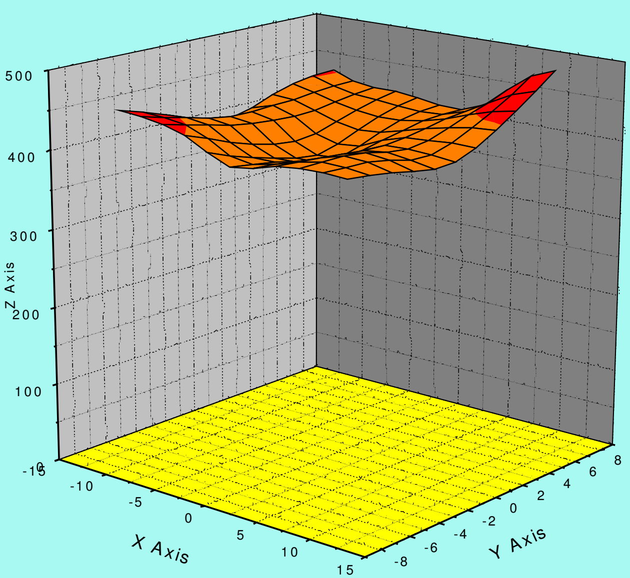
Equivalent strain for TE pass

The average equivalent strain during one pass e=tan(β)



Distribution of the strain

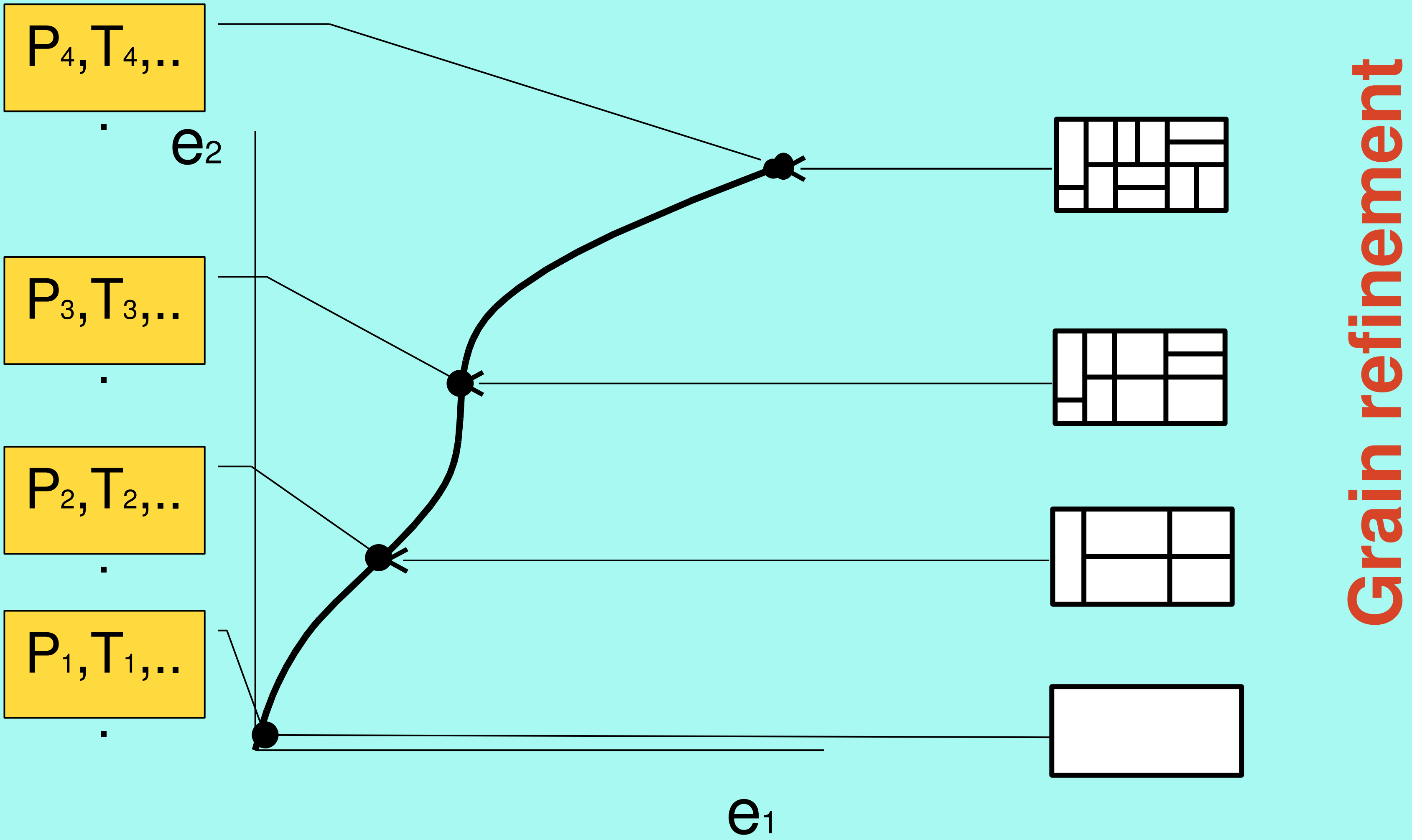
Yield stress, Cu



The Problem with Theoretical Model

One of the main problems faced by any theoretical model is the need to capture the multi-level character of plastic deformation

Metal Structure is Determined by the Image of the Loading Process



But … The Image of The Loading Process depends on this structure

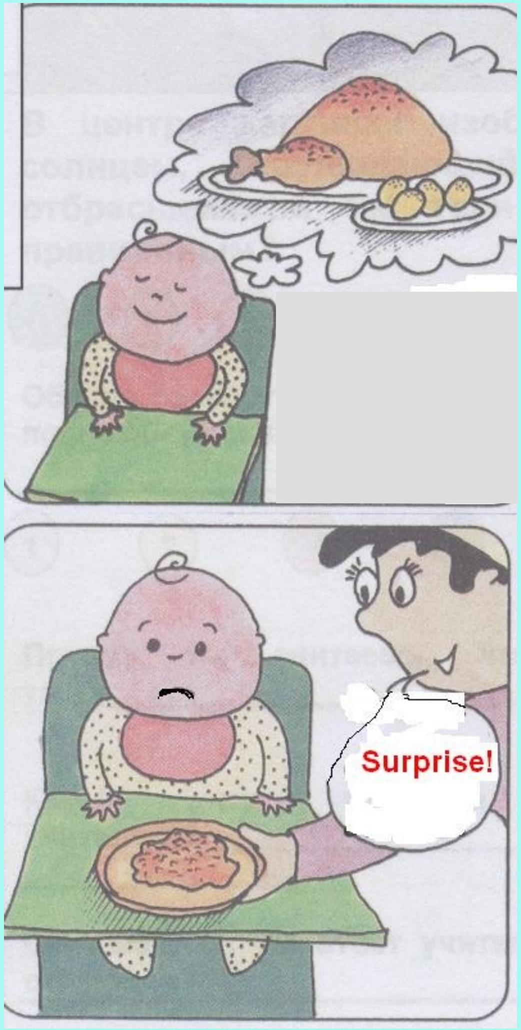
The reason is that the structure defines the mechanical properties of the materials.

Macro-Micro Interdependency

Metal Structure

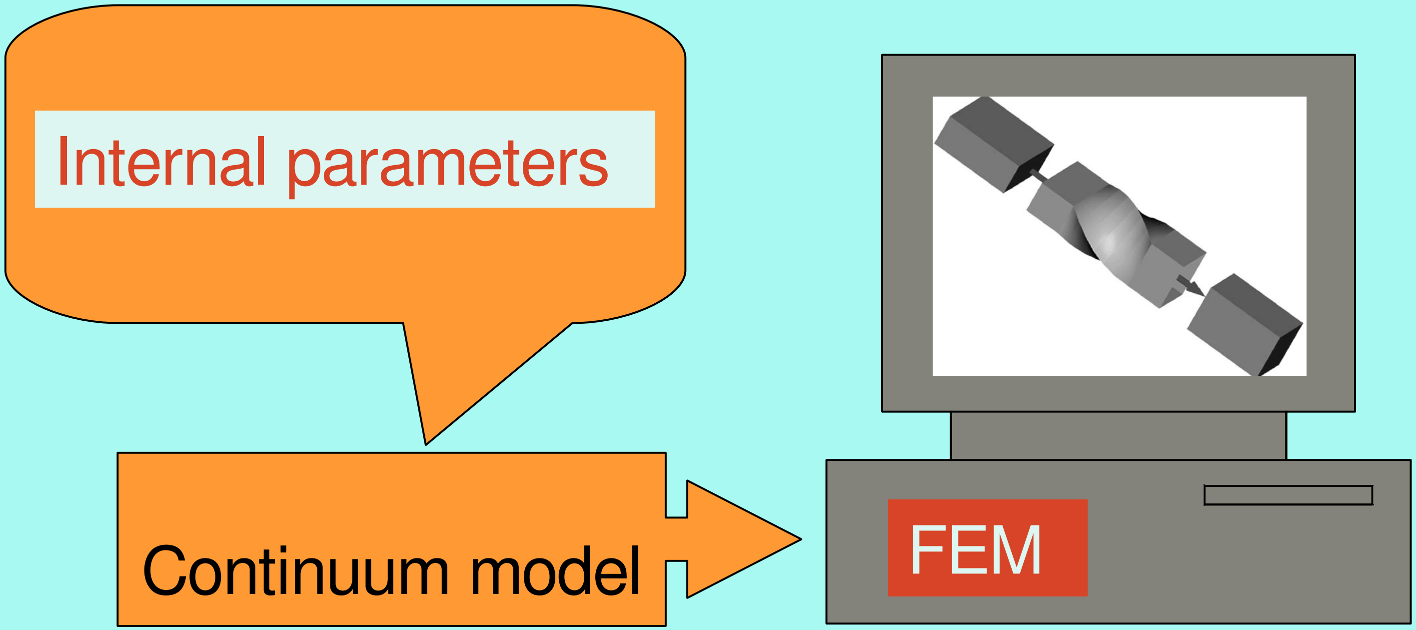
Image of the Loading Process

The Problem



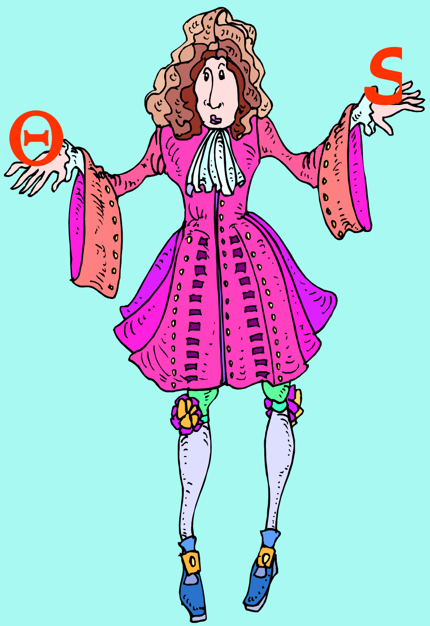
- We are trying to produce a given ultrafine homogeneous structure
- In reality, however, the specimen may respond with a number of bad things: highly inhomogeneous structure, deformation localization or fracture.
- The reason why this happens is precisely the **"Interdependency"**.

Our approach to capture the interdependency



Internal parameters will allow us to account for the interdependency between the stress-strain state and the structure.

Internal parameters serve as special envoys representing the micro-level processes at the macro-level



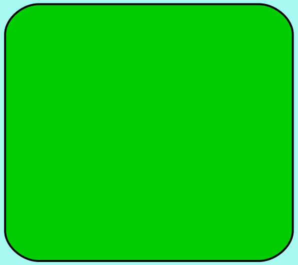
Model of the material

Constitutive equations of the Mises's model

$$f\left(\sigma_{ij}\right)=0, \qquad \dot{e}_{ij}=\lambda\frac{\partial f\left(\sigma_{ij}\right)}{\partial\sigma_{ij}}$$

RVE

$$f\left(\sigma_{ij}\right)=\tau^2-\left(\frac{\sigma_s}{\sqrt{3}}\right)^2 \qquad \dot{e}=0$$



$$\sigma=\frac{1}{3}\sigma_{ik}\delta_{ik} \qquad \tau=\sqrt{\left(\left(\sigma_{ik}-\frac{1}{3}\sigma\delta_{ik}\right)\left(\sigma_{ik}-\frac{1}{3}\sigma\delta_{ik}\right)\right)}$$

Porous body with structurally inhomogeneous matrix

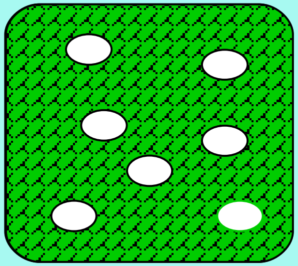
$$f\left(\sigma_{ij}\right)=\frac{\sigma^2}{\psi(\Theta)}+\frac{\tau^2}{\varphi(\Theta)}-(1-\Theta)\left(\frac{\sigma_s}{\sqrt{3}}-\alpha\sigma\right)^2$$

$$f\left(\sigma_{ij}\right)=\tau^2-\left(\frac{\sigma_s}{\sqrt{3}}\right)^2$$

$$\dot{e}=0$$

$$\frac{\dot{e}\tau}{\varphi(\theta)}=\dot{\gamma}\left(\frac{\sigma}{\psi(\theta)}+\alpha(1-\theta)(k_0-\alpha\sigma)\right)$$

RVE



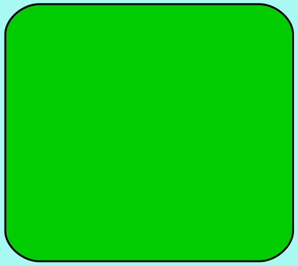
Beygelzimer Y. et al., (1994) Engin. Fracture Mech., **48**, N5

Beygelzimer Y. Proceedings of International Workshop on Modelling of Metal Powder Forming Processes, Grenoble, France, July 21-23, 1997

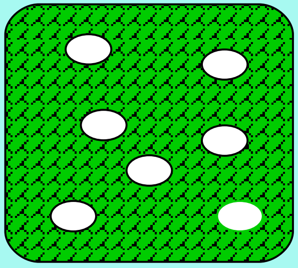
Plausible reasoning

RVE

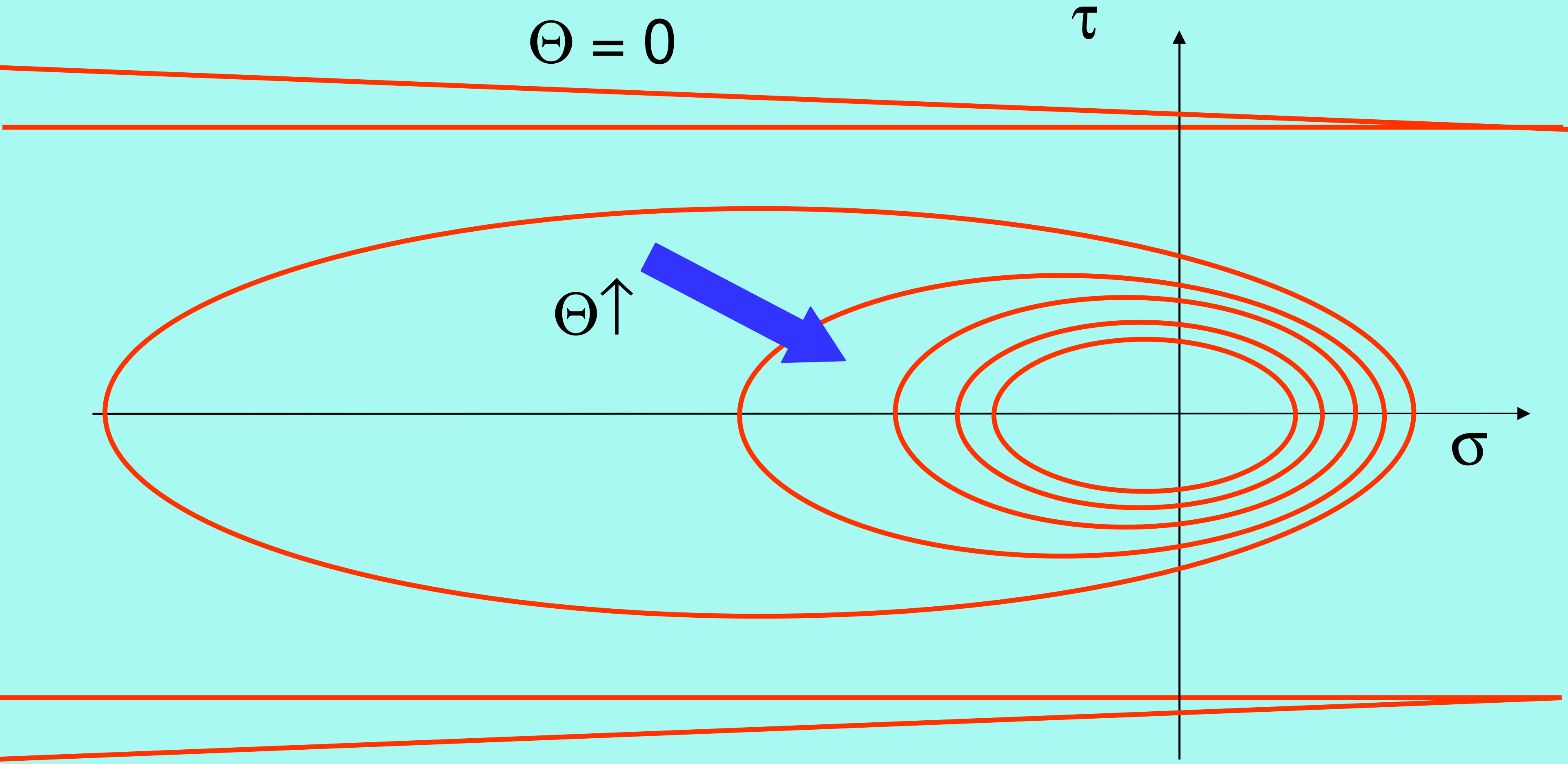
$$f\left(\sigma_{ij}\right) = \tau^2 - \left(\frac{\sigma_s}{\sqrt{3}}\right)^2$$



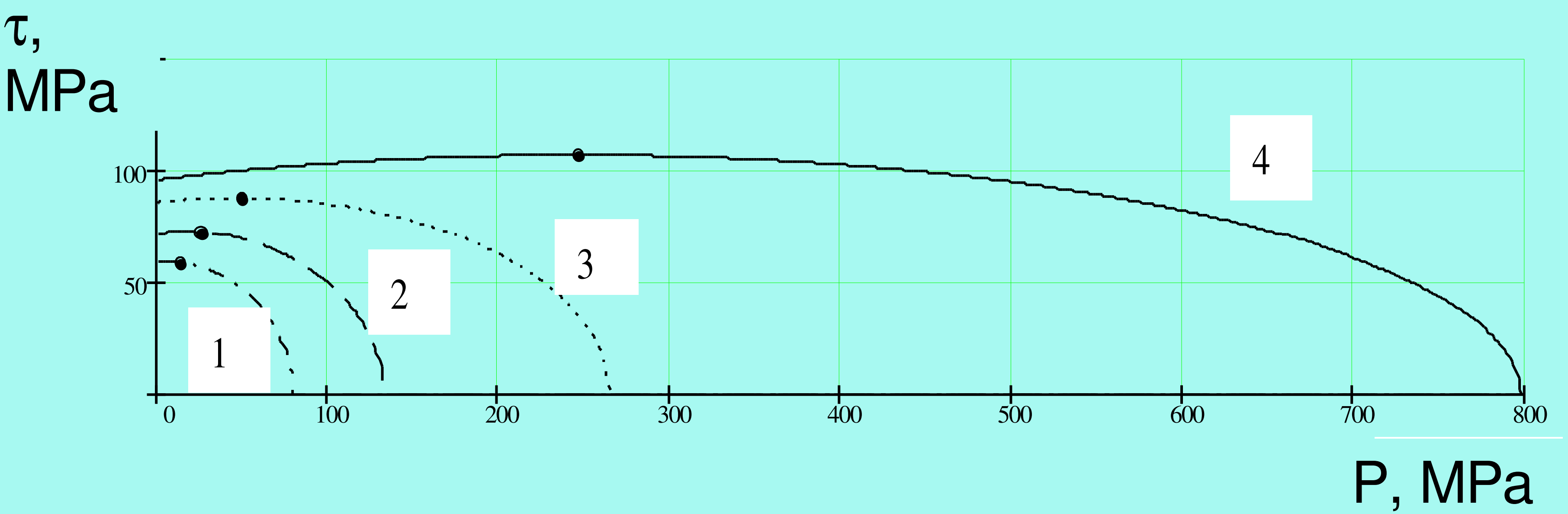
$$f\left(\sigma_{ij}\right) = \frac{\sigma^2}{\psi\left(\Theta\right)} + \frac{\tau^2}{\varphi\left(\Theta\right)} - \left(1-\Theta\right)\left(\frac{\sigma_s}{\sqrt{3}} - \alpha\sigma\right)^2$$



Loading surfaces



Loading surfaces of the cutting of the secondary Al alloy

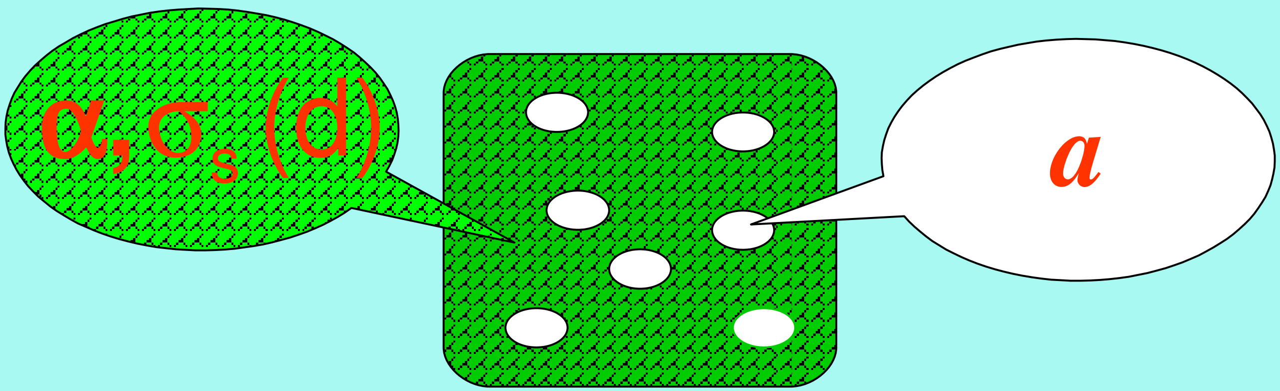


Θ: 1- 30%, 2- 20%, 3- 10%, 4- 3%.

Porous body with structurally inhomogeneous matrix at Θ<<1

$$f\left(\sigma_{ij}\right) = 6a\Theta\sigma^2 + \tau^2 - \left(\frac{\sigma_s}{\sqrt{3}} - \alpha\sigma\right)^2$$

$$\frac{d\Theta}{d\gamma} = \alpha + 6\sqrt{3}a\frac{\sigma}{\sigma_s}\Theta$$



Breaking of a brittle particles

$$\alpha = \alpha_1 \exp(-\lambda\gamma) + \alpha_2\left(1 - \exp(-\lambda\gamma)\right)$$

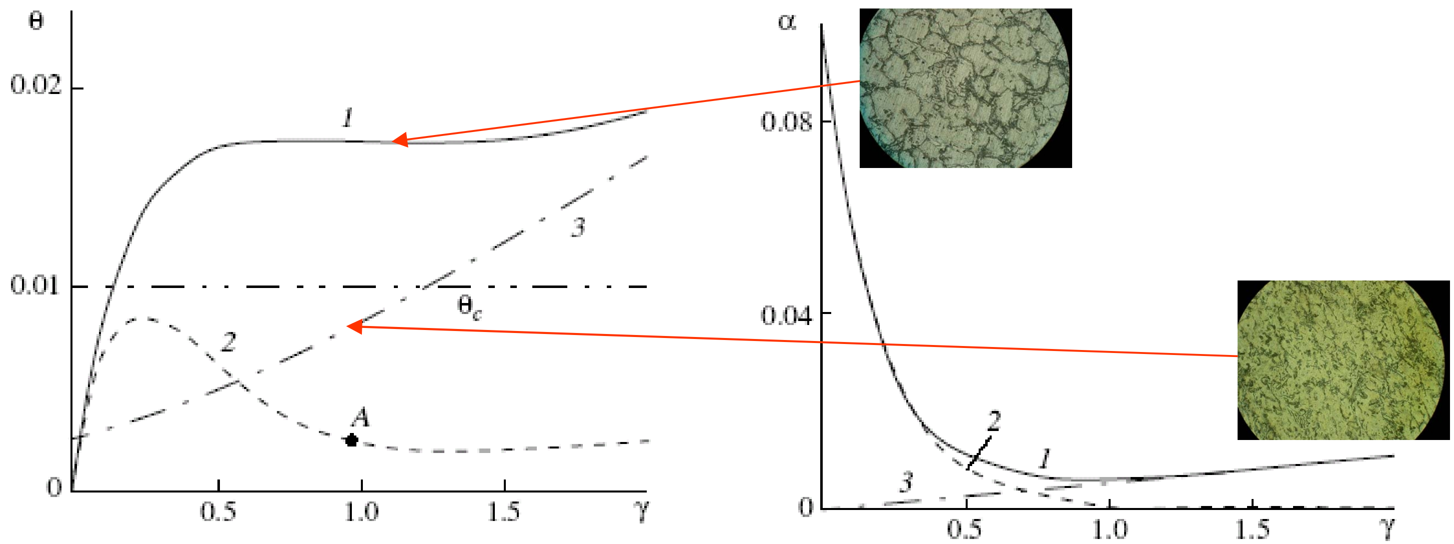


Fig. 3. Deformation-induced porosity θ vs. the degree of deformation γ for (*1*, *2*) as-cast and (*3*) predeformed metal with the rigidity indices $\eta = -3^{-1/2}$ (*1*, *3*) and –4 (*2*). θ is the critical value of porosity.

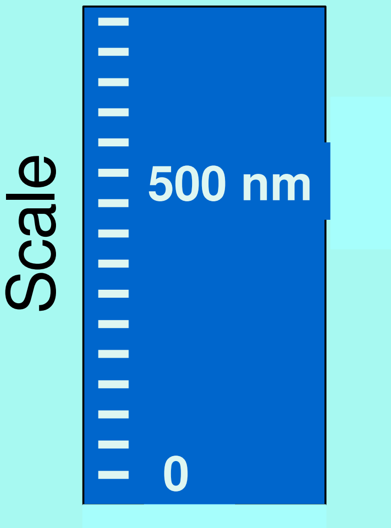
Fig. 4. Accommodation parameters (*1*) α, (*2*) α_1, and (*3*) α_2 vs. the degree of deformation.

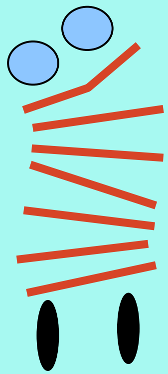
Beygelzimer Y., Shevelev A. On the Development of Fracture Models for Metal Forming// *Russian Metallurgy (Metally), Vol.,* N*5,* p. 452–456, 2003

The model of grain refinement and viscous fracture

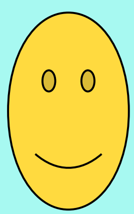
Beygelzimer Y. Grain refinement versus voids accumulation during severe plastic deformations of polycrystals: Mathematical simulation, *Mechanics of Materials*, V. 37, N7, p. 753-767, 2005

Main characters of the Model

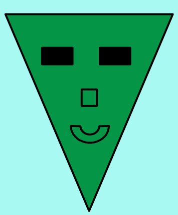




- **Accumulative Zone** – a “spring”, the part of crystals in which dislocation charges accumulate during plastic deformation; AZs emerge due to the inhomogeneity of shear along the sliding plane.

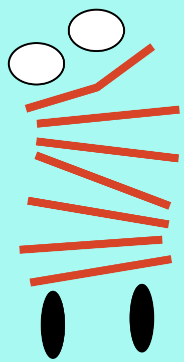


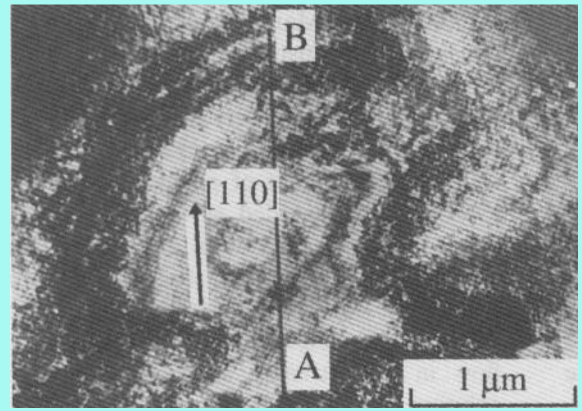
- **Void –** a bit of an emptiness

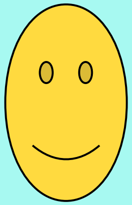


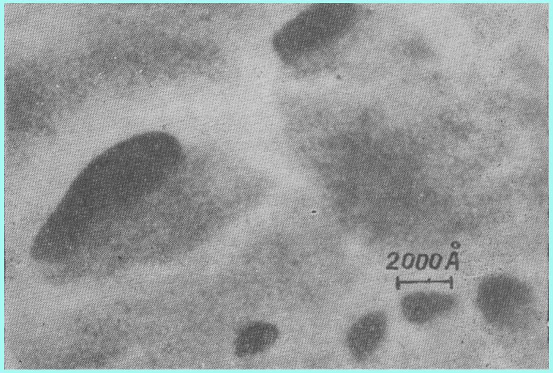
- **Embryo –** an embryo of high-angle boundary (a partial disclination)

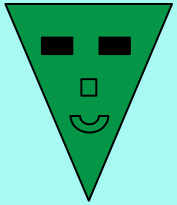
Pictures of Main Characters

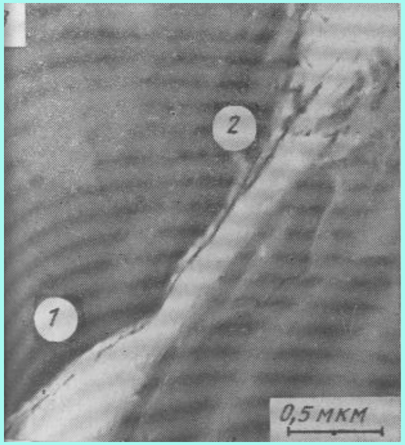




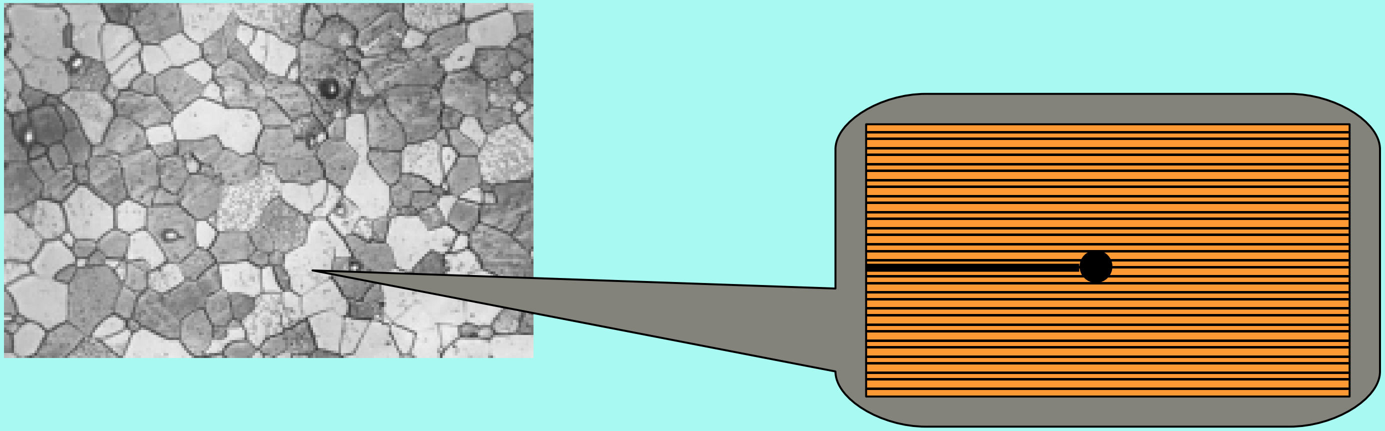








The Birth of an Accumulative Zone



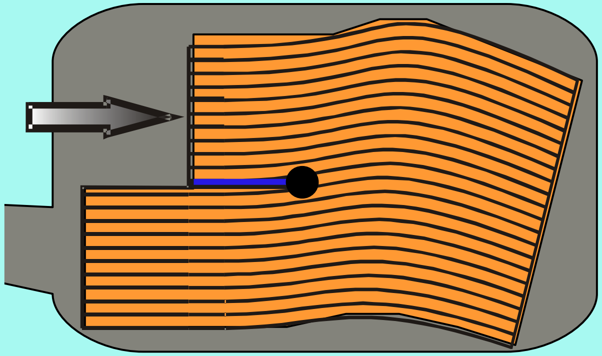
There are regions of polycrystals where dislocations get plugged during plastic deformation. Such regions cause bendings of the crystalline lattice.

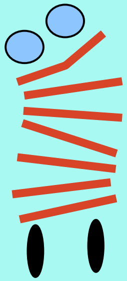
The Birth of an Accumulative Zone

The model postulates that AZs emerge in two places:

3. hurdles that exist in polycrystals before deformation

5. high-angle boundaries that emerge during deformation.



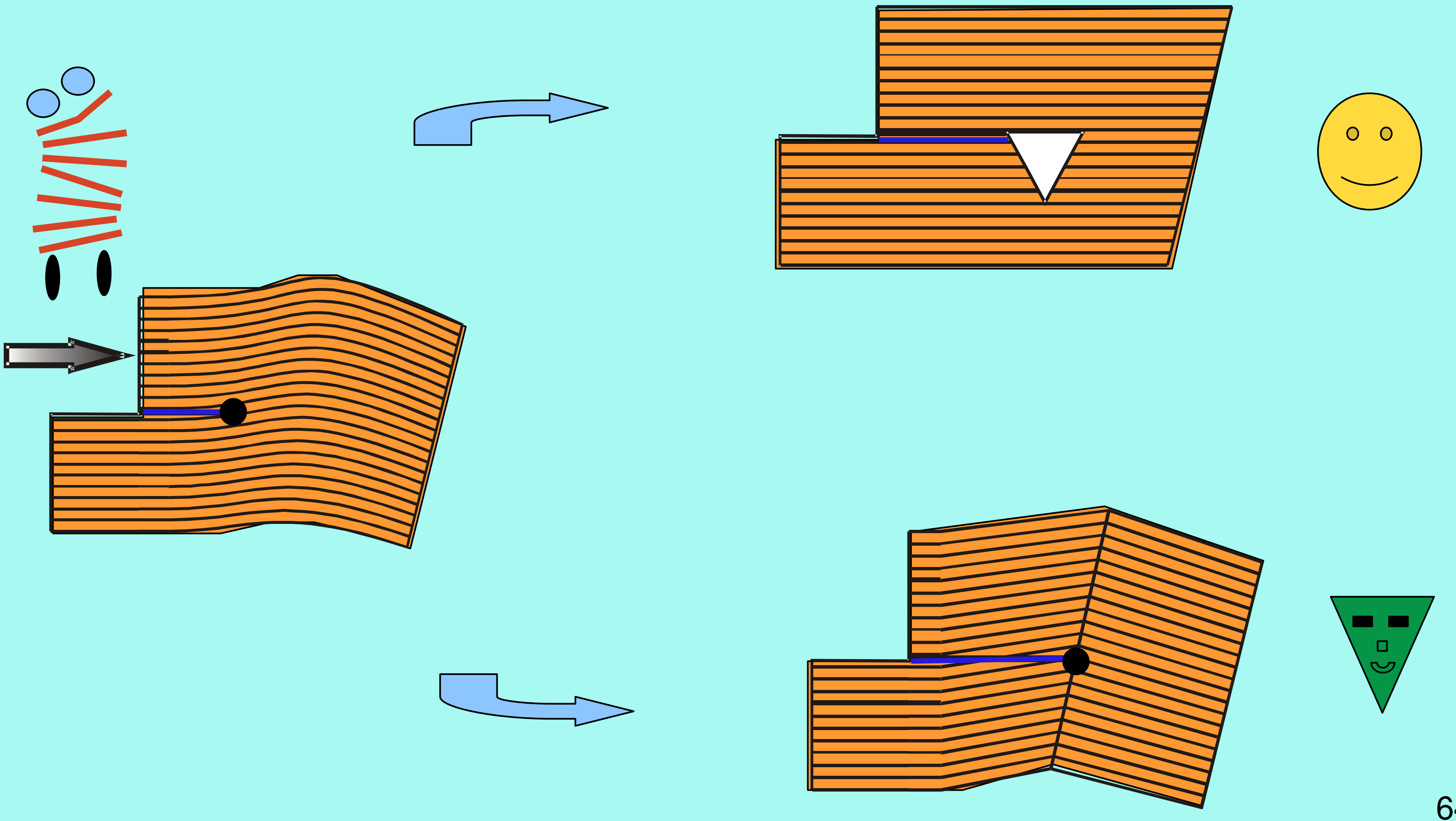


Relaxations of Accumulative Zones in coarse grained materials

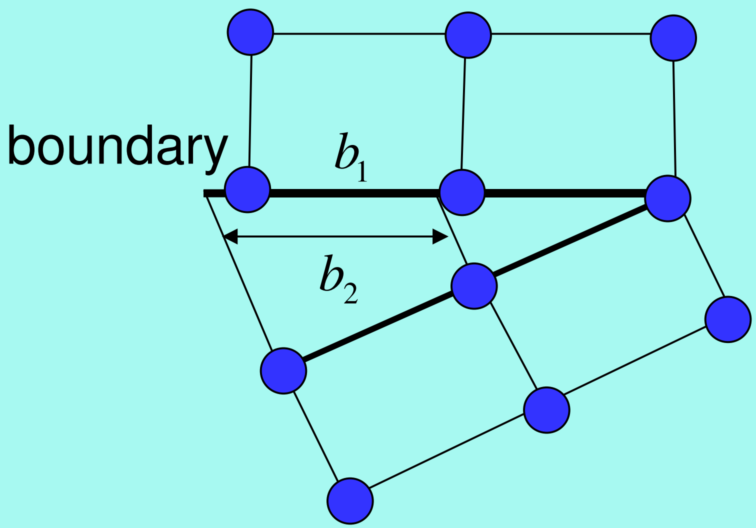
There are different relaxation mechanisms for accumulative zones. When talking about large cold deformations, we will distinguish two main mechanisms:

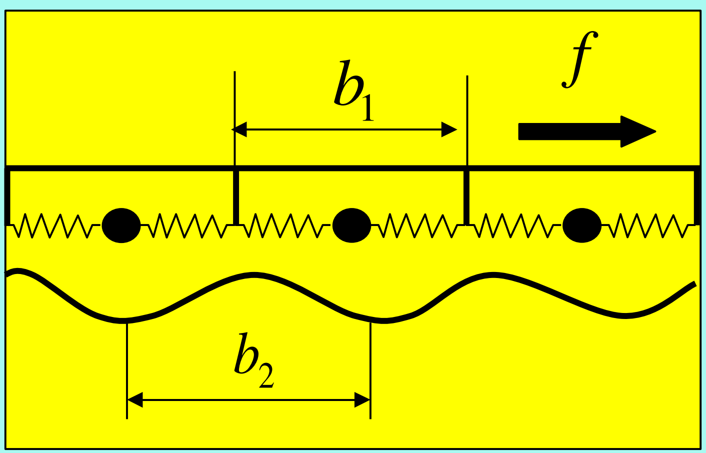
3. **Emergence of high angle boundaries** **(**leading to grain refinement)
4. **Emergence of voids** (leading to fracture)

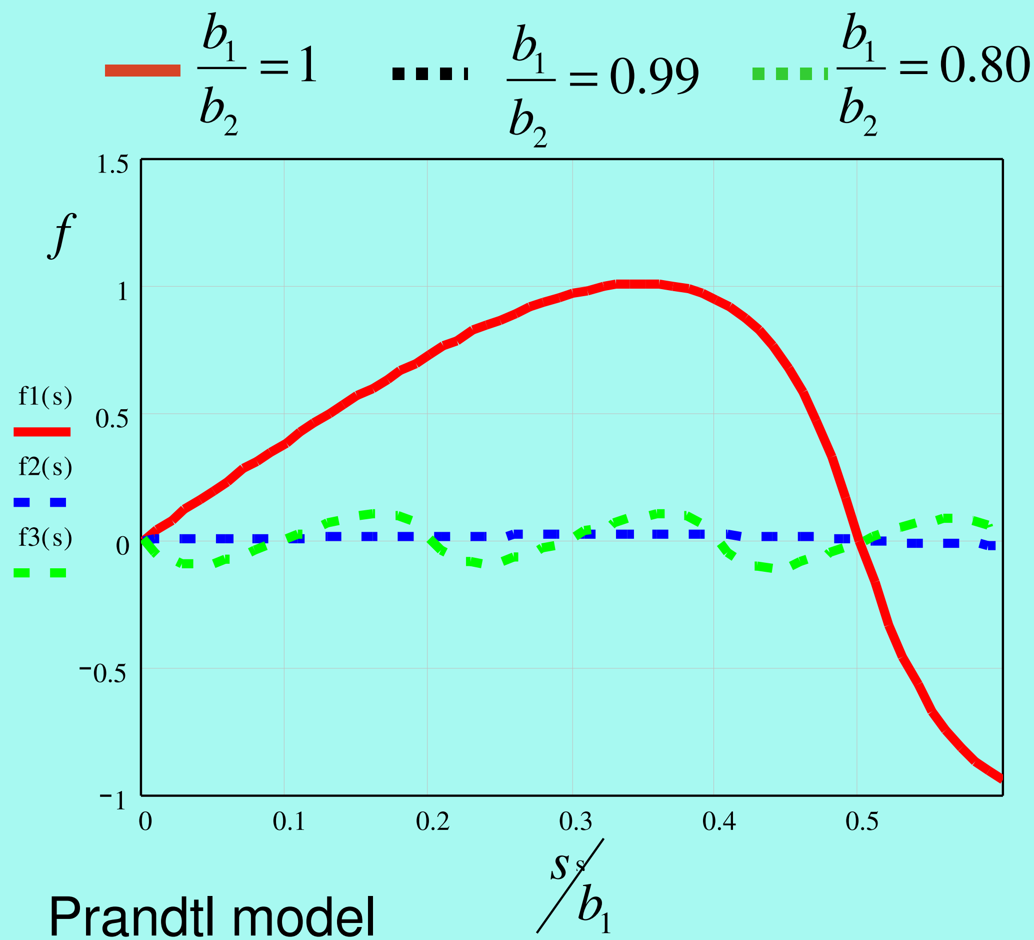
Relaxations of Accumulative Zones in coarse grained materials



Boundary sliding

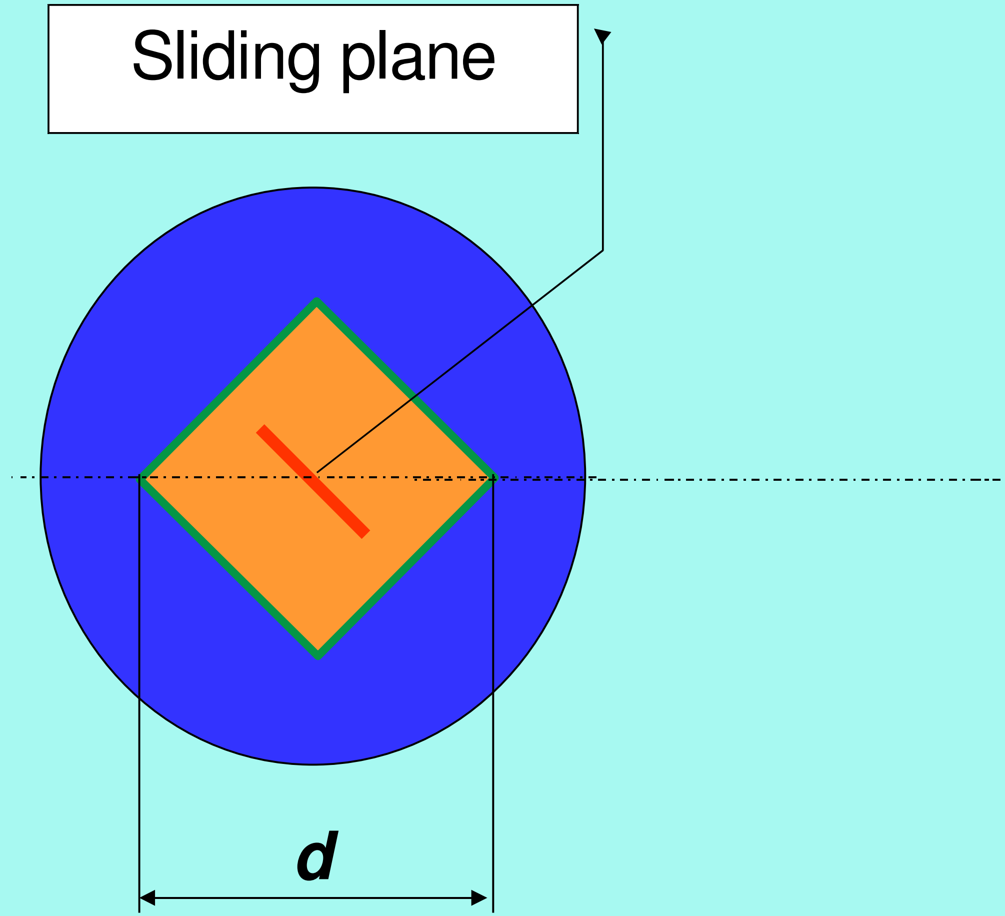




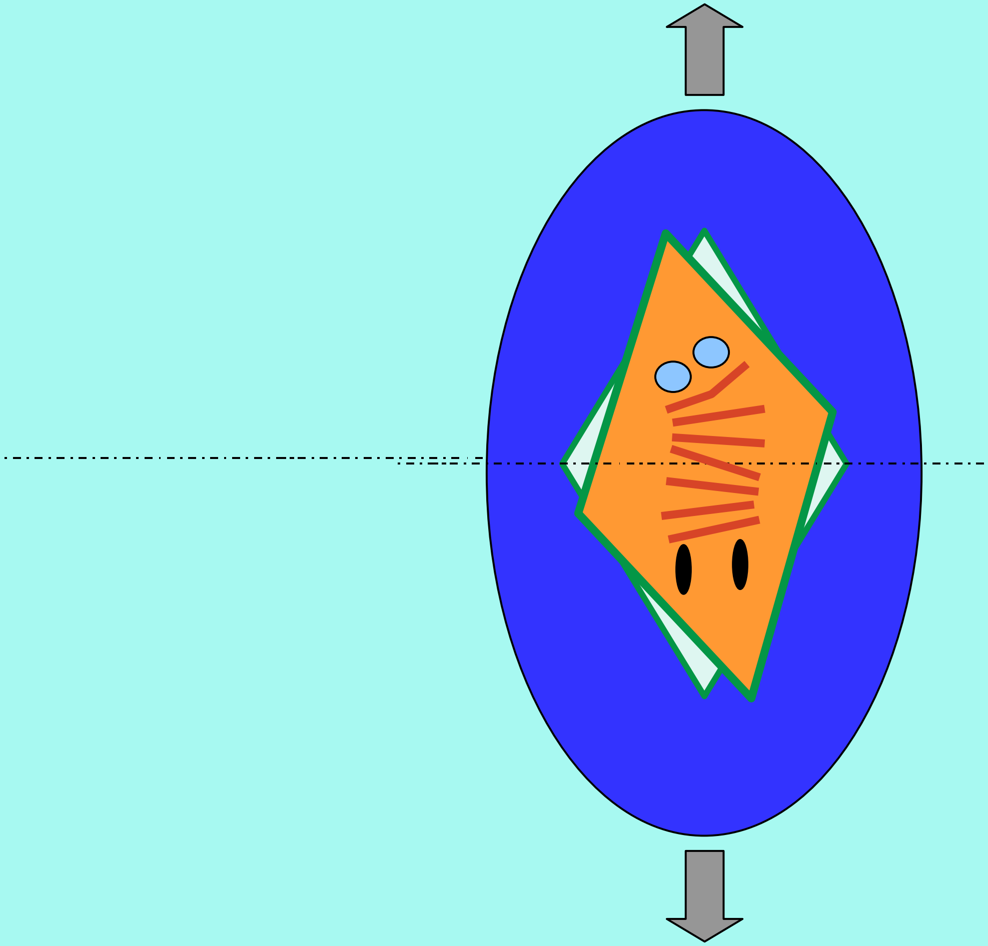


Prandtl model

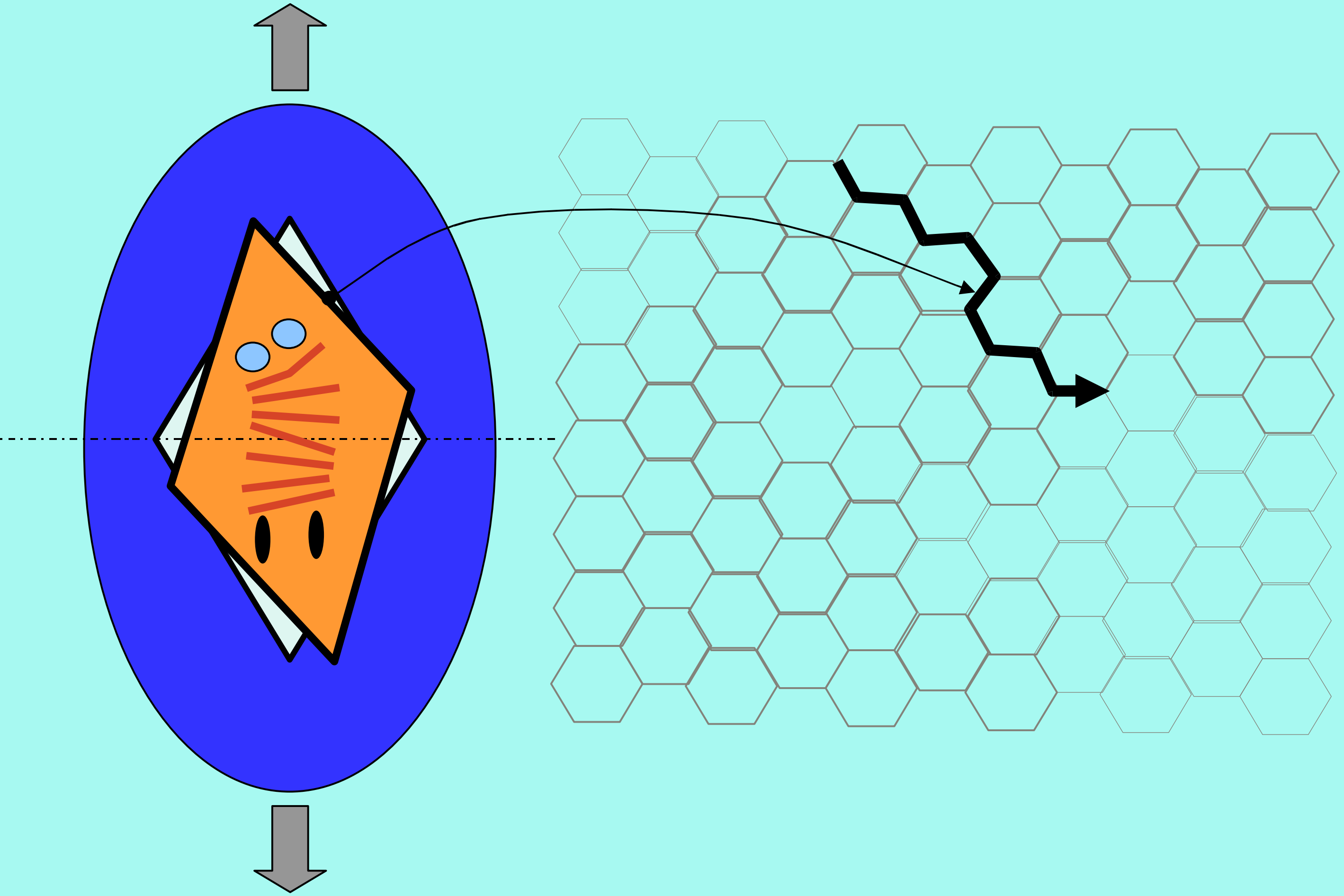
Relaxations of Accumulative Zones in ultrafine grained materials



Relaxations of Accumulative Zones in ultrafine grained materials



Relaxations of Accumulative Zones in ultrafine grained materials



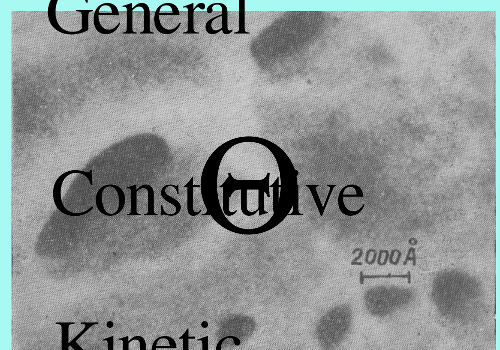
Equations of the Model

Classical Plasticity Theory:

$$\begin{cases} G(\sigma,\varepsilon)=0 & \text{General} \\ P(\sigma,\varepsilon;\mu)=0 & \text{Constitutive} \end{cases}$$

Proposed model with internal parameters capturing the structure:

$$\begin{cases} G(\sigma,\varepsilon)=0 & \text{General} \\ P(\sigma,\varepsilon; S,\Theta; \mu)=0 & \text{Constitutive} \\ K(S,\Theta,\sigma,\varepsilon;\mu)=0 & \text{Kinetic} \end{cases}$$



Loading function

$$f\left(\sigma_{ij};\Theta,S\right)=6a\Theta\sigma^{2}+\tau^{2}-\left(\frac{\sigma_{s}\left(S\right)}{\sqrt{3}}-\alpha^{*}\sigma\right)^{2}$$

$$\alpha^{*}=C_{3}\overline{N}^{\frac{3}{2}}d_{c}^{-3}v$$

Kinetic equations

$$\begin{cases} \dfrac{d\bar{N}}{d\gamma} = \left(C_1 + C_2 C_5 \bar{N}_b\right) F\left(\bar{S}\right) - \left(C_3 + C_4\right)\bar{N} \\[2ex] \dfrac{d\bar{N}_b}{d\gamma} = C_4 \bar{N} - C_5 \bar{N}_b \\[2ex] \dfrac{d\bar{S}}{d\gamma} = \dfrac{C_5 \bar{N}_b}{\bar{S} + \bar{S}_0} \\[2ex] \dfrac{d\Theta}{d\gamma} = C_3 \bar{N}^{\frac{3}{2}} d_c^{-3} v - C_6 \Theta \end{cases}$$

$\bar{N} = 0 \quad \bar{N}_b = 0$

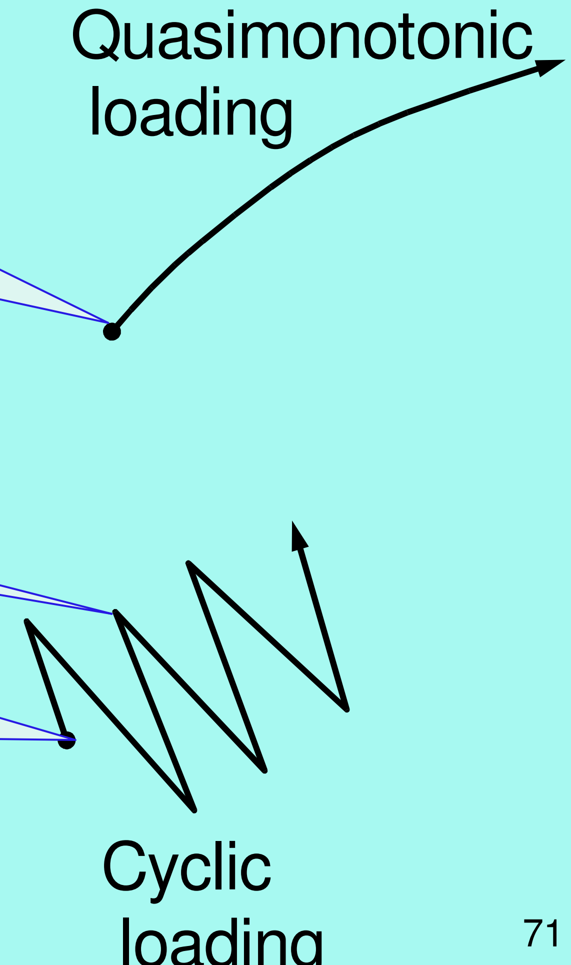
$\bar{S} = 0 \quad \Theta = 0$

$\bar{N}_{n+1} = 0 \quad \bar{N}_{b(n+1)} = \bar{N}_{b(n)}$

$\bar{S}_{n+1} = \bar{S}_n \quad \Theta_{n+1} = \Theta_n$

$\bar{N} = 0 \quad \bar{N}_b = 0$

$\bar{S} = 0 \quad \Theta = 0$



Prediction

Prediction (i)

As $\gamma \to \infty$:

$N \to 0,$ $N_b \to 0,$

$\bar{d} \to d_c,$ $\Theta \to 0$

Ideal Plasticity Land

Metals don't fracture and don't harden under sufficiently high pressure when equivalent strain is very large, i.e., metals become ideally plastic.

The reason is boundary sliding

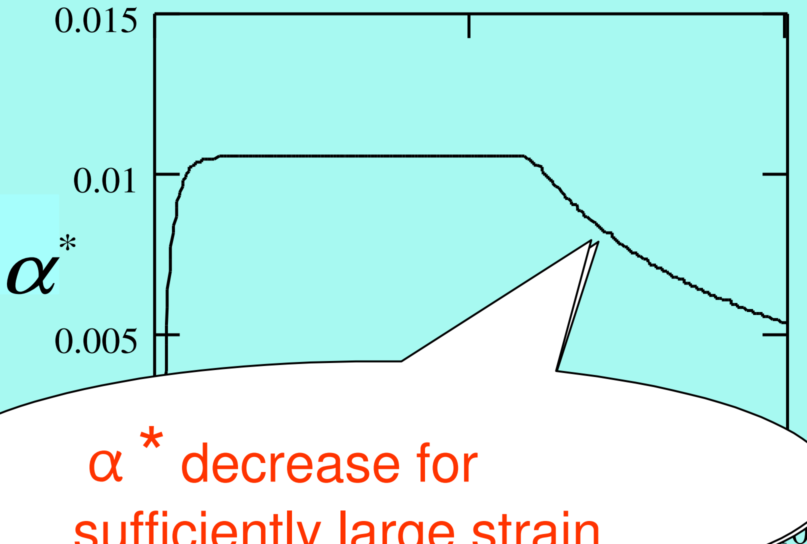
Prediction (ii)

Ductility grows
for sufficiently large equivalent strain

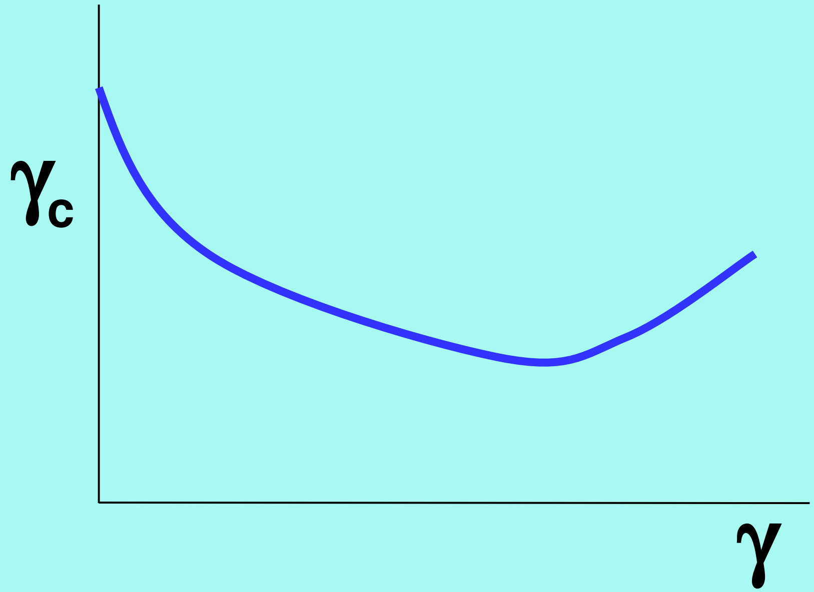
The reason is boundary sliding

The term responsible for the birth of voids

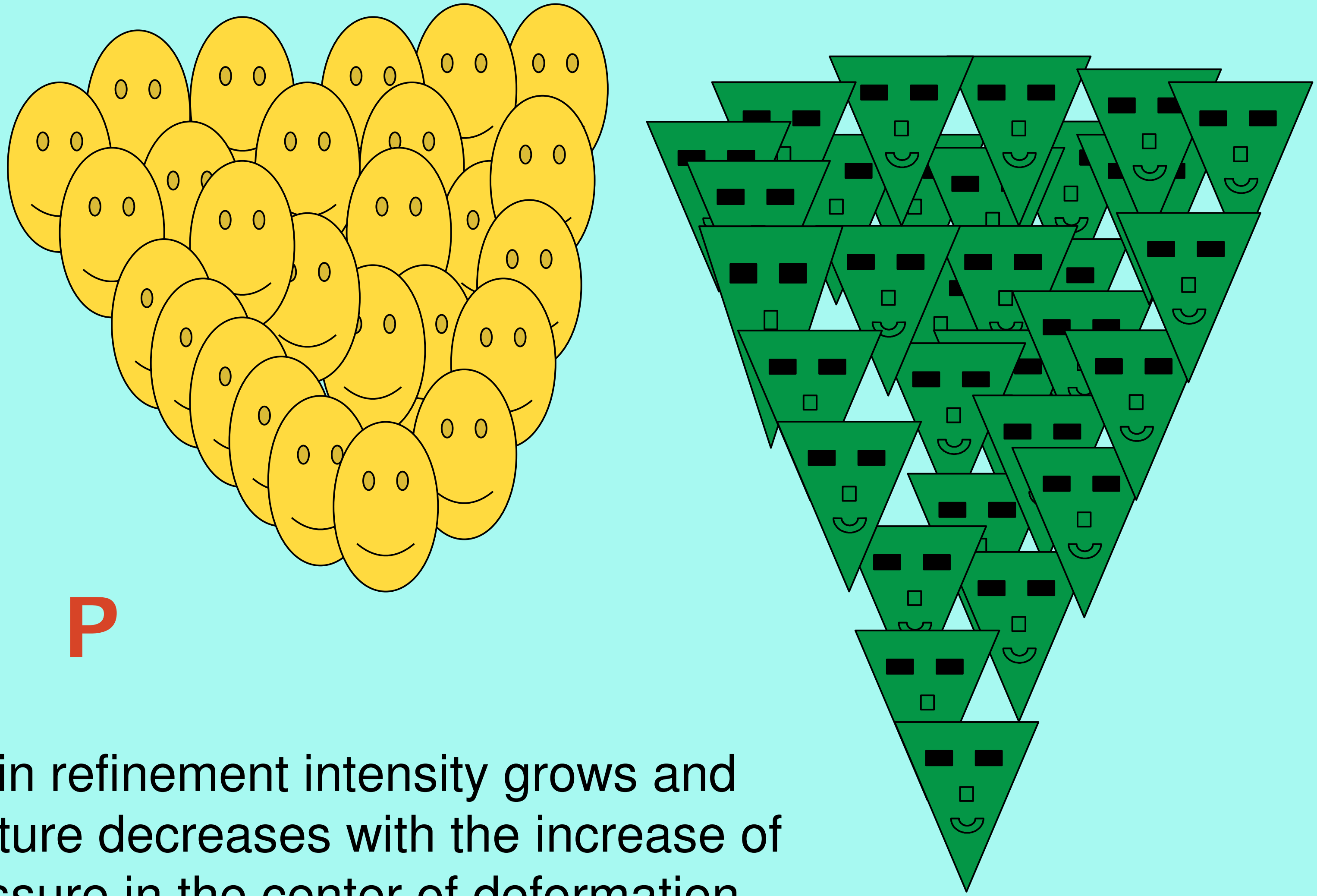
$$\frac{d\Theta}{d\gamma} = \alpha^*(\gamma) - B\frac{p}{\sigma}\Theta \qquad \alpha^*(\gamma) = C_3 \overline{N}^{\frac{3}{2}}(\gamma) d_c^{-3} v$$



α * decrease for sufficiently large strain.

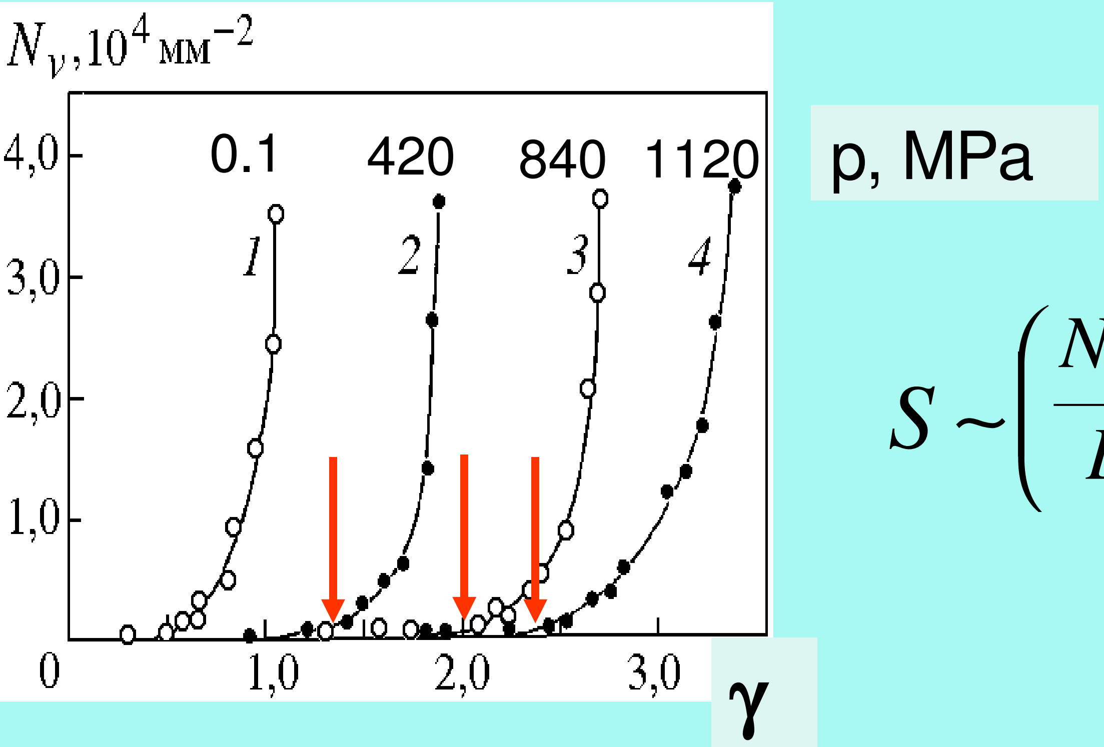


Prediction (iii)



Grain refinement intensity grows and fracture decreases with the increase of pressure in the center of deformation.

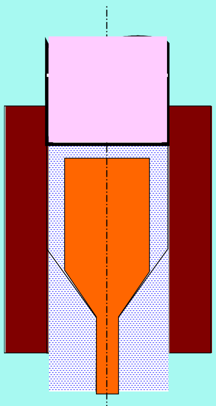
The reason is γ_p grows with pressure increase

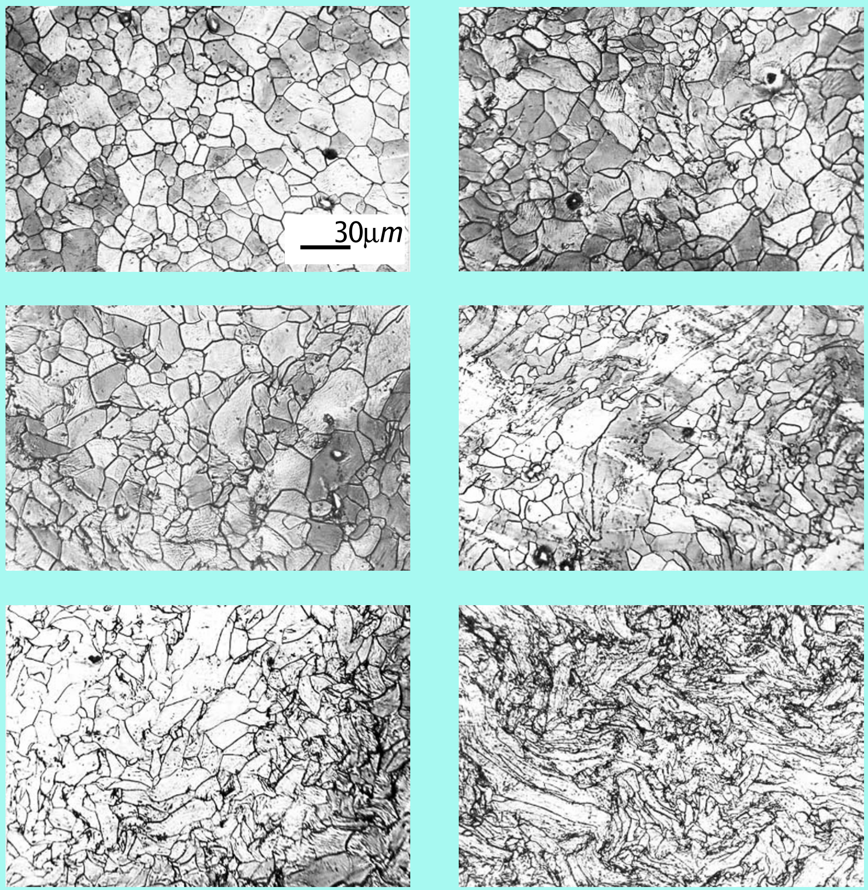


$$S \sim \left(\frac{N_c \cdot \gamma_p(p)}{D \cdot \gamma_c(0)} \right)^{\frac{1}{3}} \sqrt{\gamma}$$

Correspondence with experimental results:

Influence of pressure on the microstructure of molybdenum at hydroextrusion:

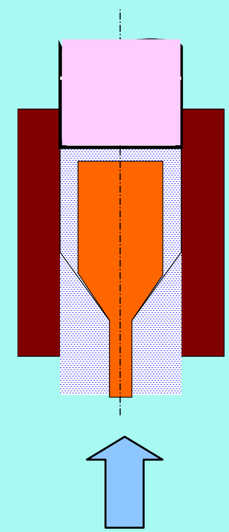




e=0.36

e=0.60

e=0.92

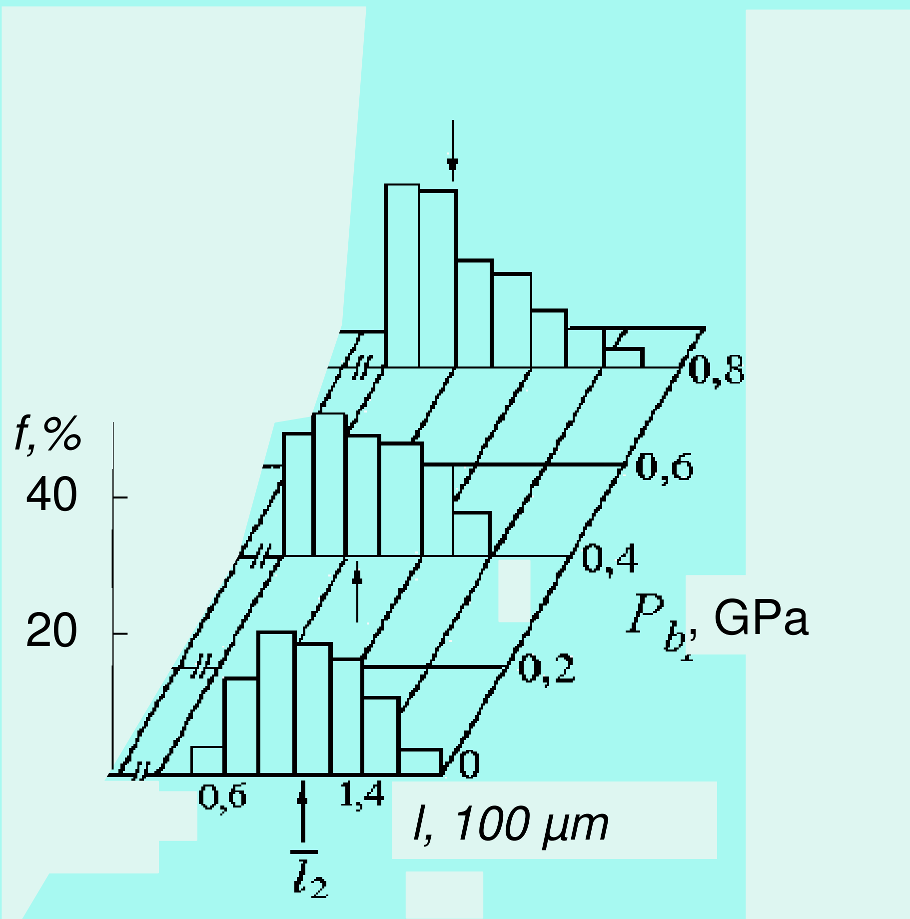


P_b

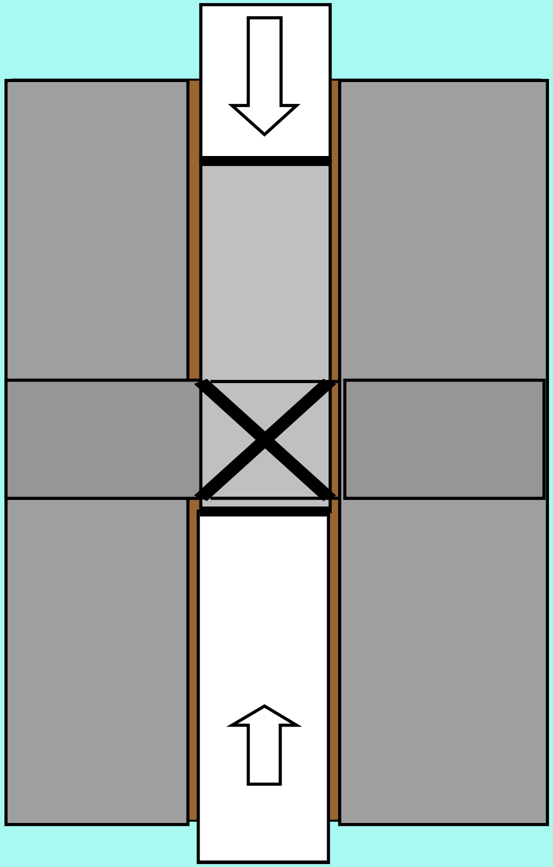
P_b = 0,1 MPa P_b = 800 MPa

Correspondence with experimental results:

Effect of pressure on fragment size distribution Hydroextrusion of molybdenum *(e=0.6)*.

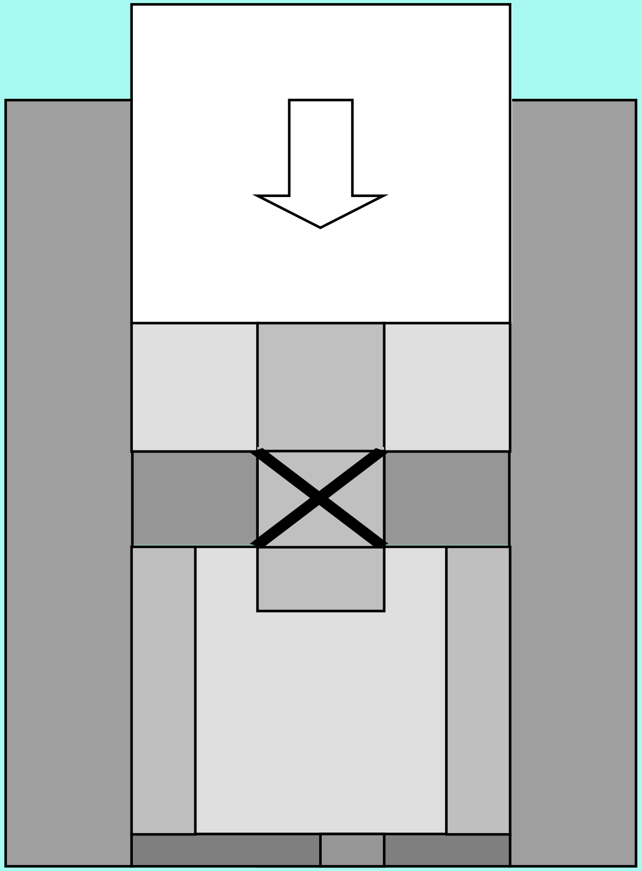


Use in Twist Extrusion

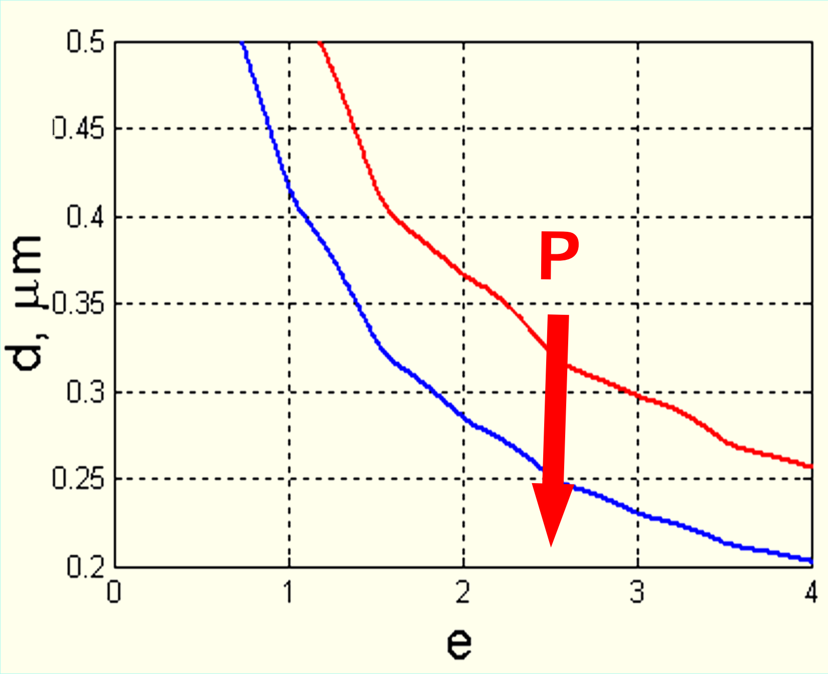


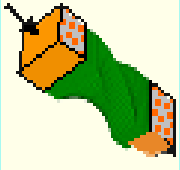
Twist Extrusion based on mechanical extrusion with backpressure

Twist Extrusion based on hydro-mechanical extrusion



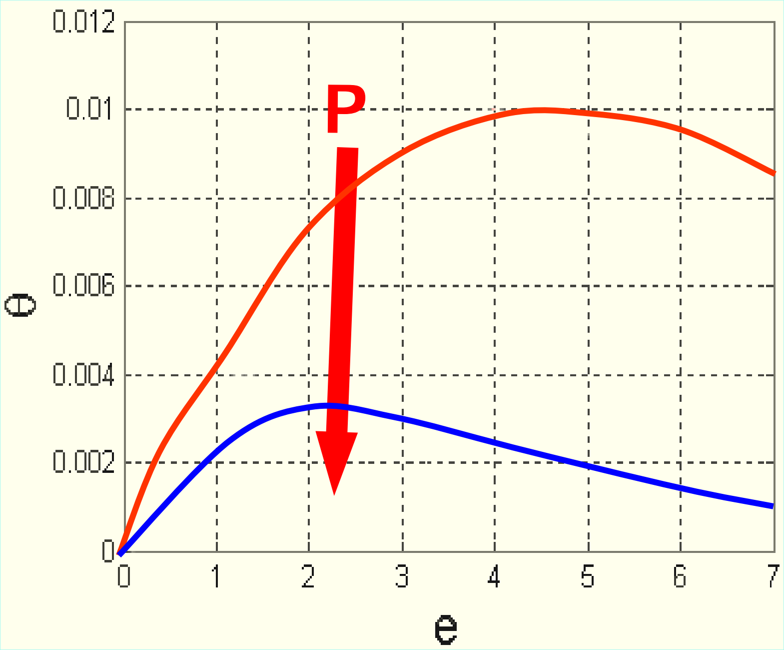
Model-based prediction for Twist Extrusion





- $P_b \approx$ *0.1 MPa*

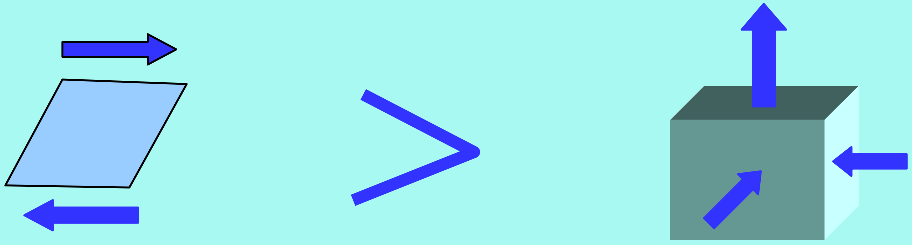
- $P_b =$ *1000 MPa*



Prediction (iv)

To get intense grain refinement, one needs to choose deformation schemes with small value of ductility and to perform deformation under pressure.

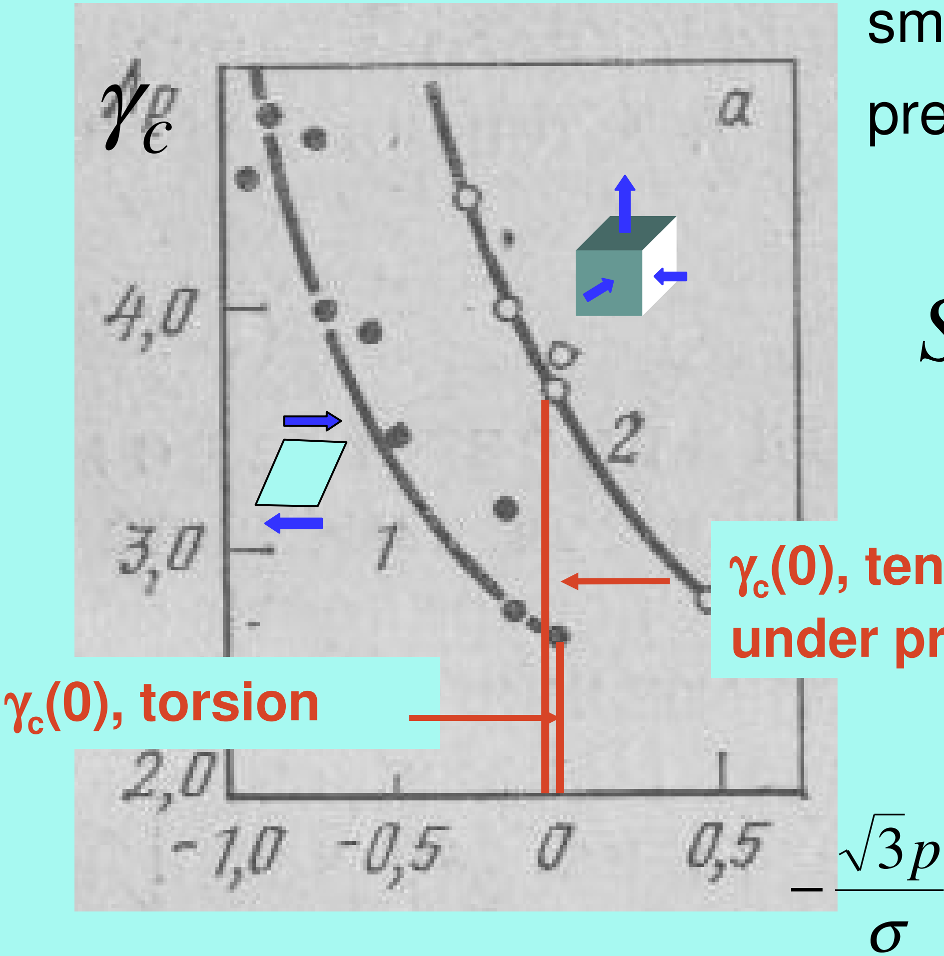
Grain refinement intensity is typically higher for simple shear than for uniaxial elongation



The reason is simple shear has smaller ductility (under the same pressure).

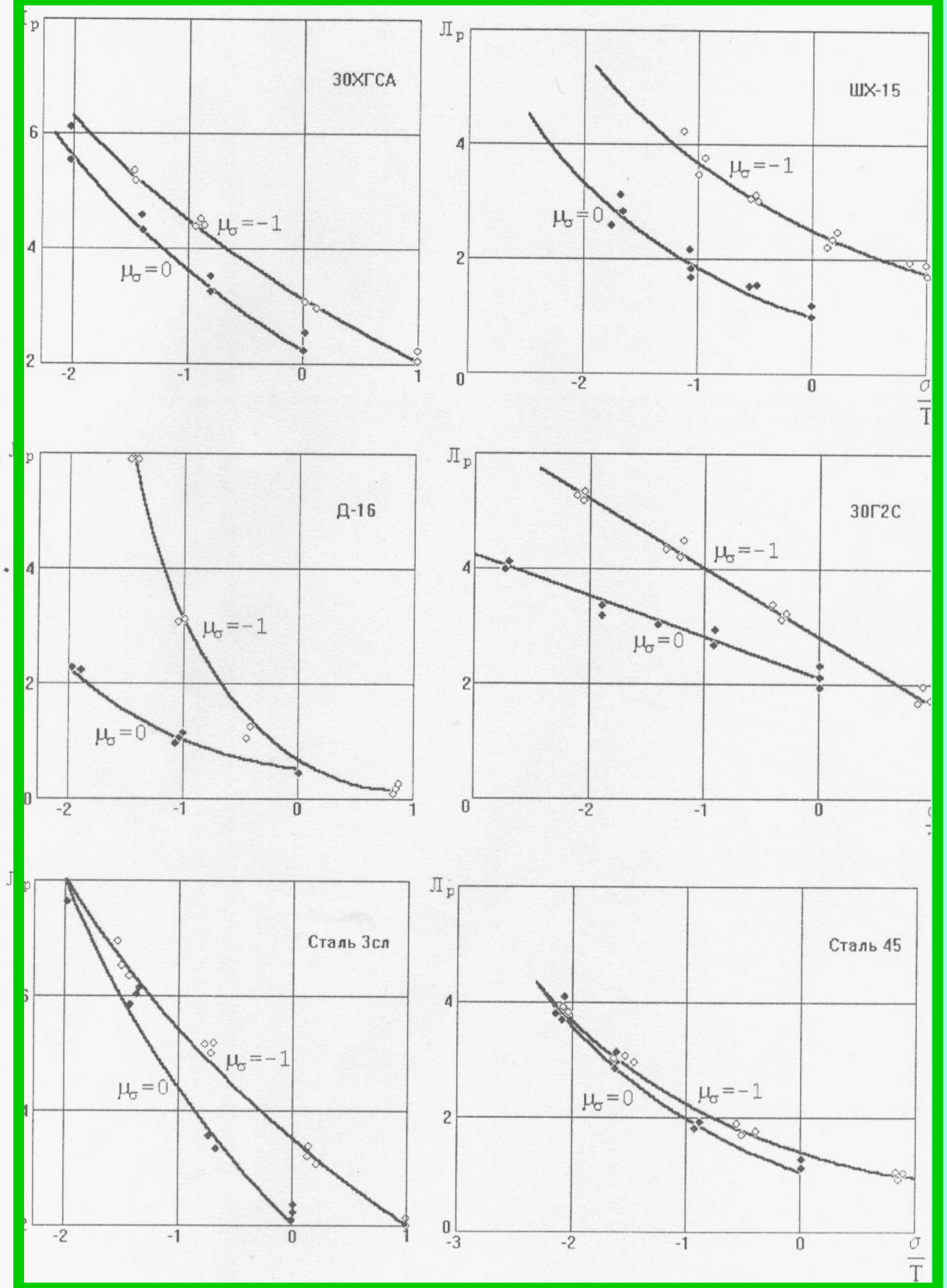
$$S \sim \left(\frac{N_c \cdot \gamma_p(p)}{D \cdot \gamma_c(0)} \right)^{\frac{1}{3}} \sqrt{\gamma}$$

$\gamma_c(0)$ is the metal ductility at p=0



$\gamma_c(0) \Rightarrow$ **S**

Ductility diagram, steel 08X18H10T
(Experiment data V.Kolmogorov, et al., 1986)

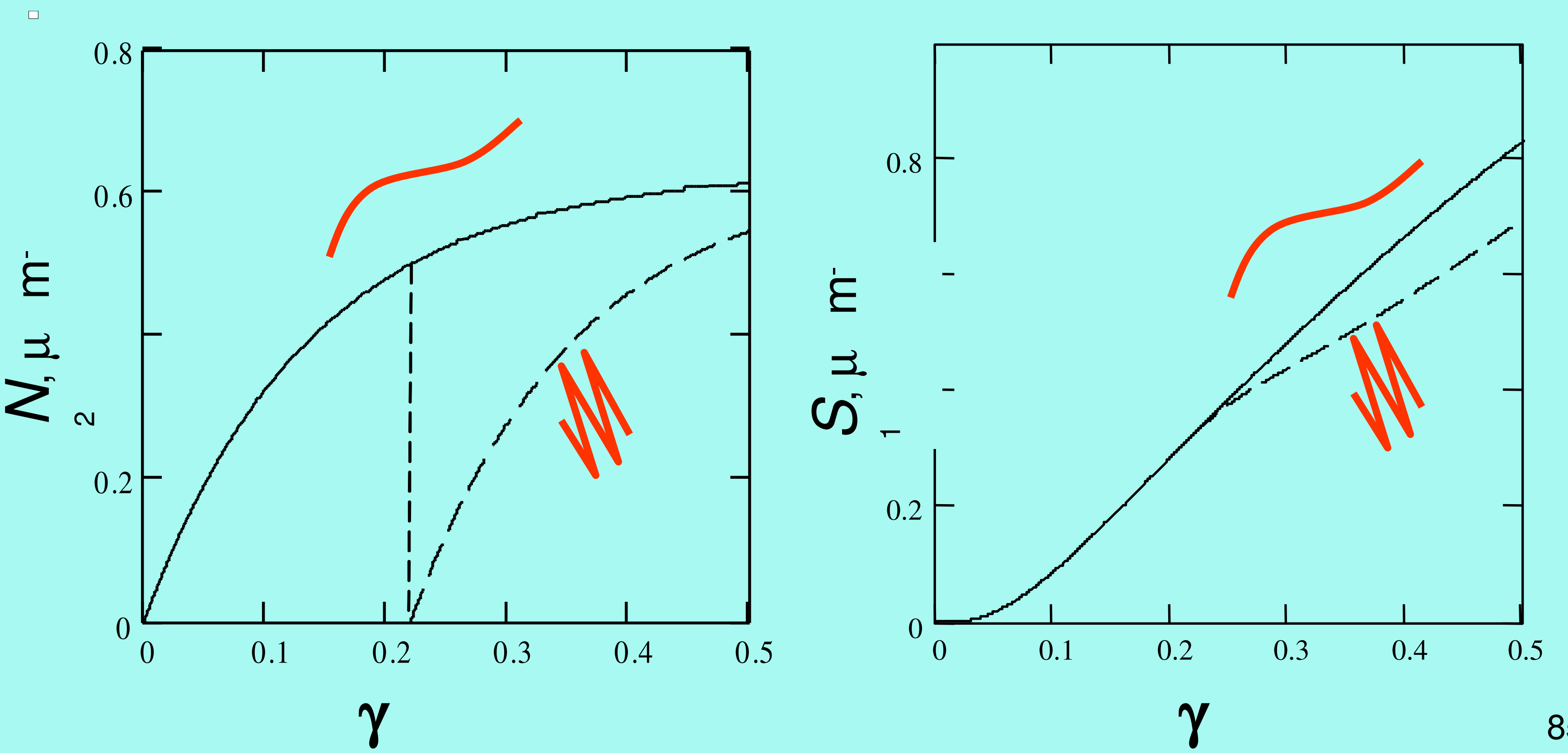


Ductility diagrams for various metals show that, as a rule, ductility $\gamma_c(0)$ of tension greater than that of torsion.

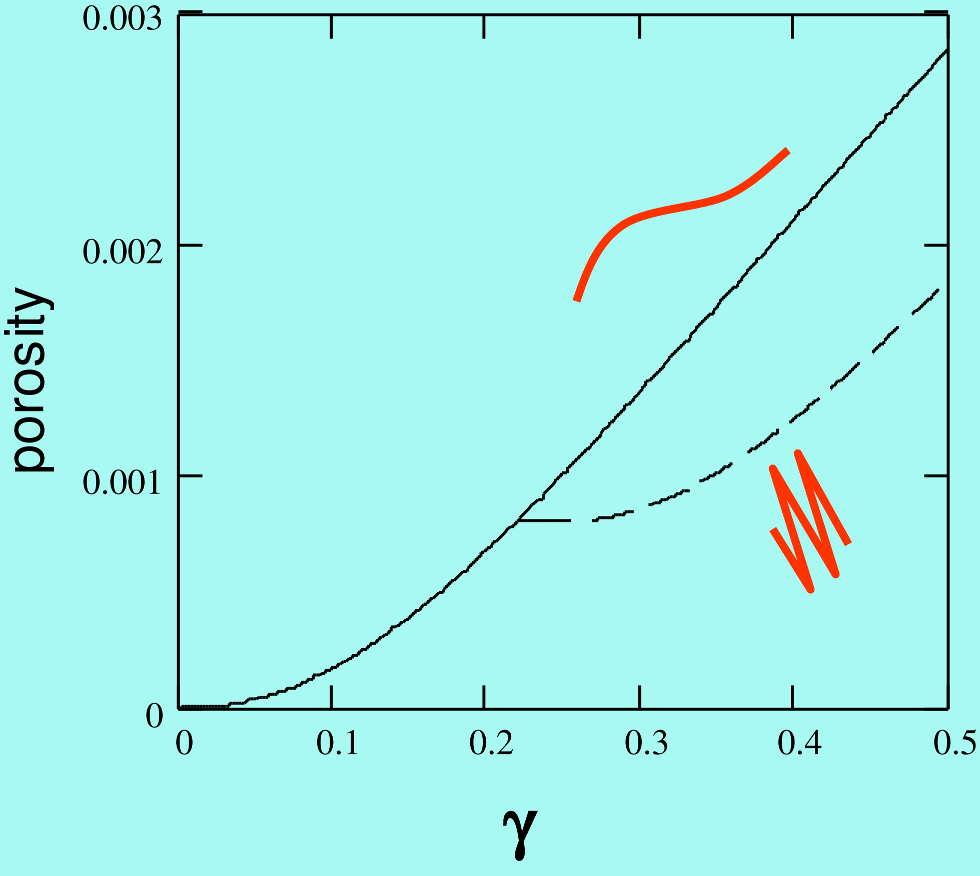
(Experiment data V.Ogorodnikov and I.Sivak, 1999)

Prediction (v)

Quasi-monotone deformations provide higher grain refinement intensity than cyclic deformations.

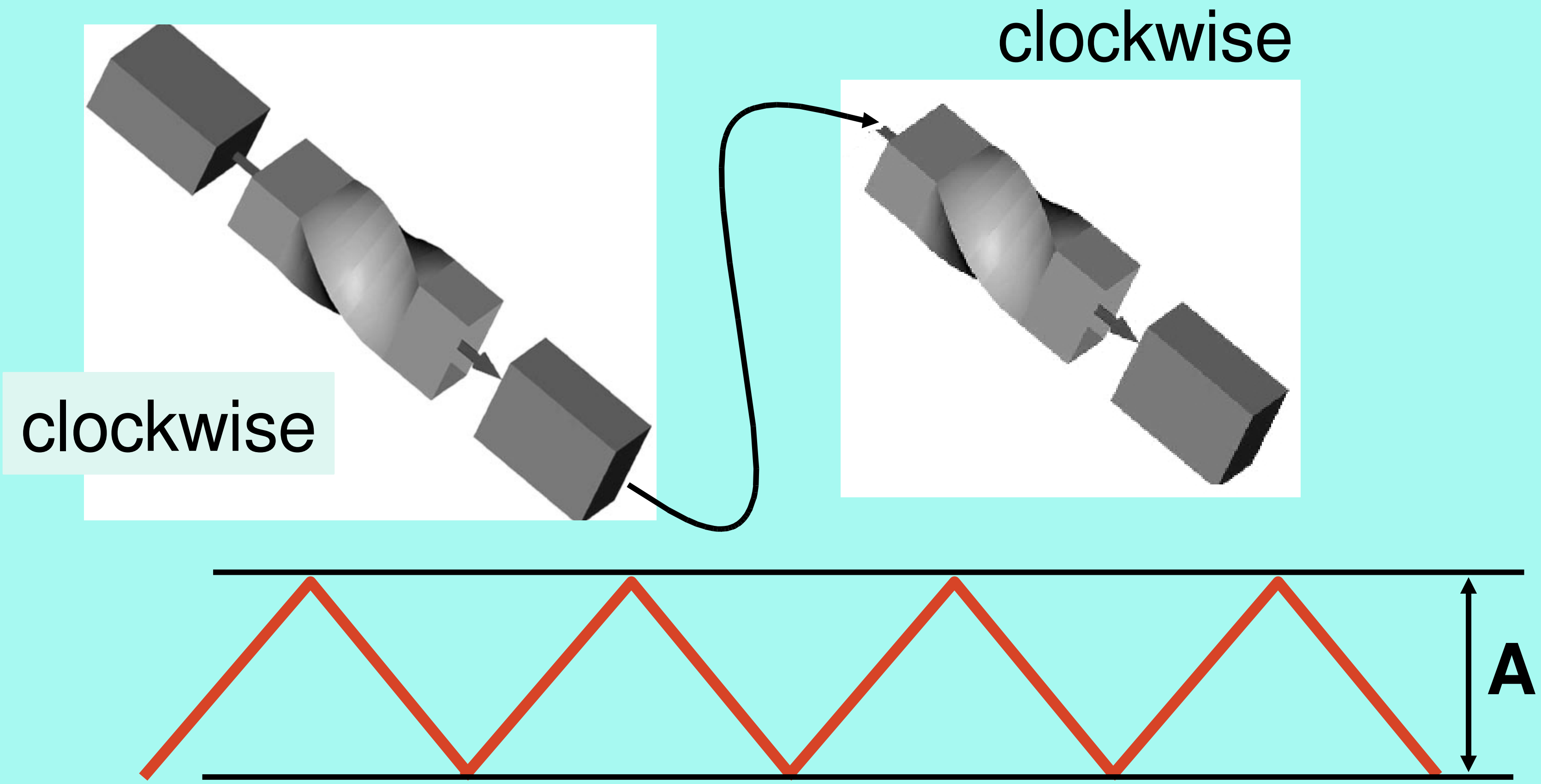


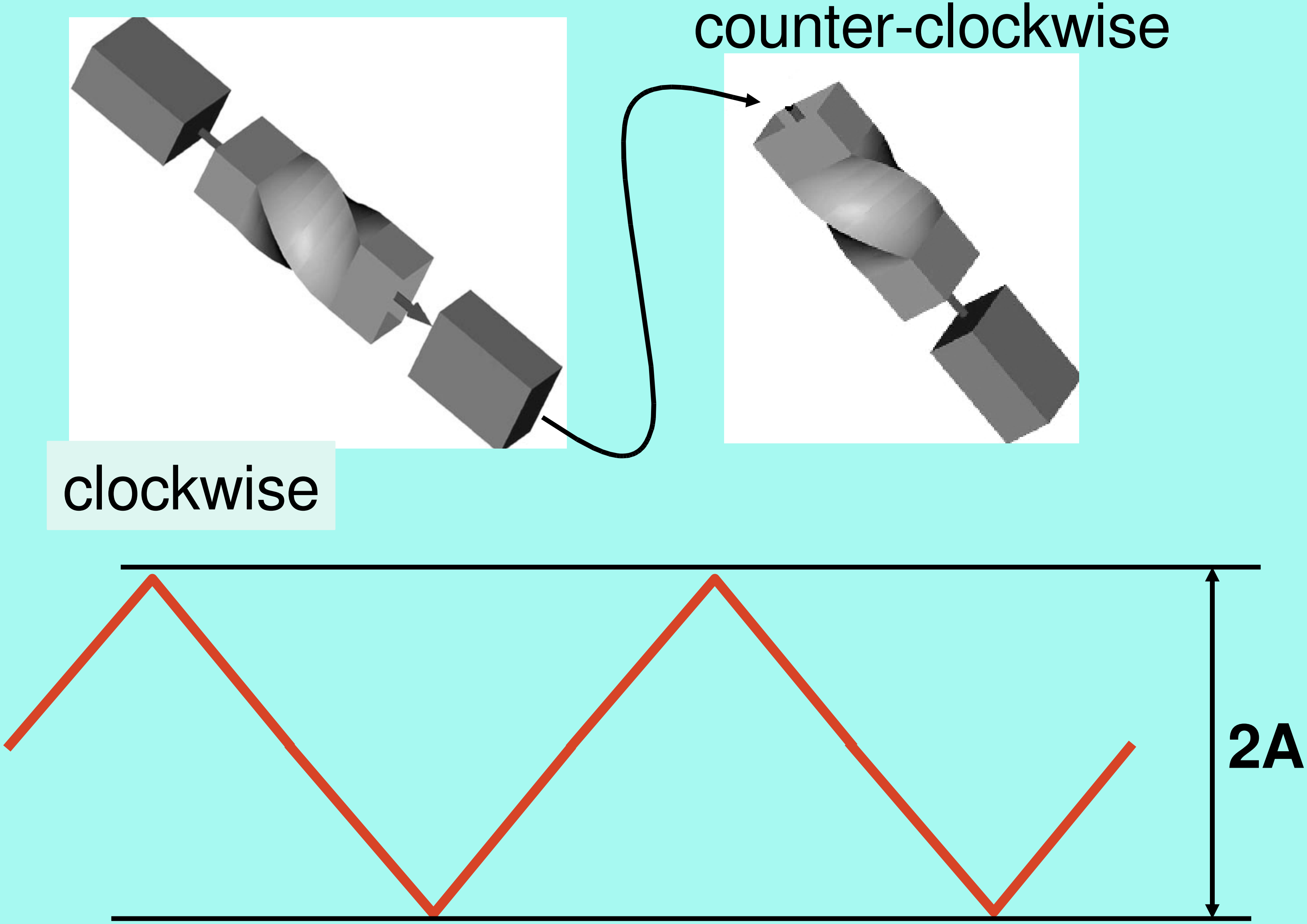
Cyclic deformations provide higher ductility than quasi-monotone deformations



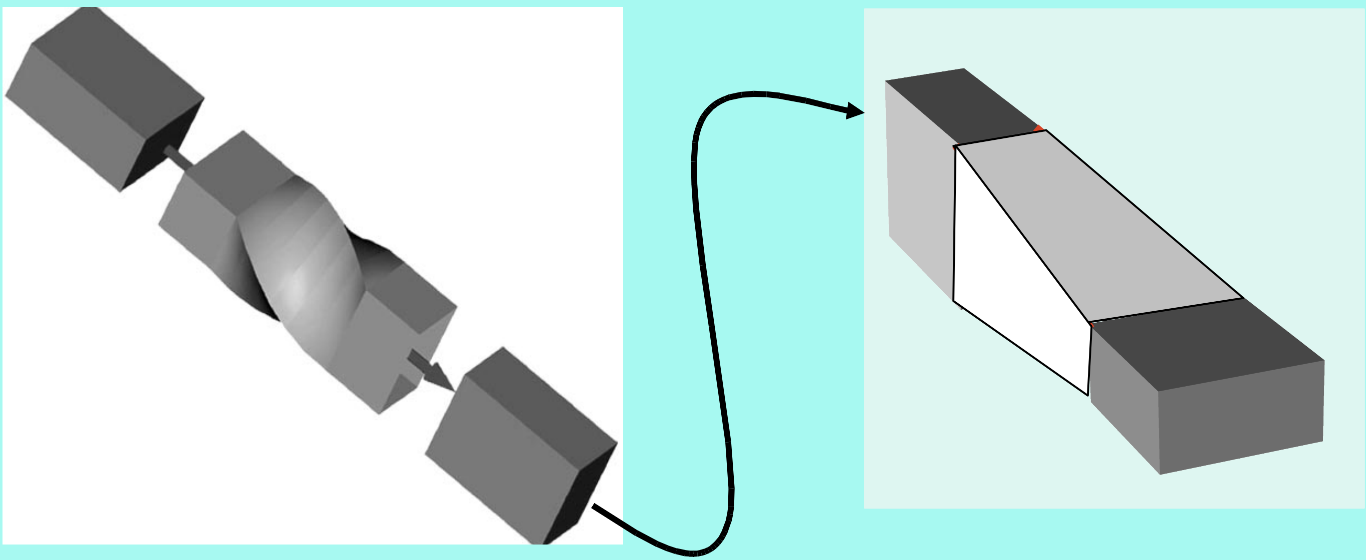
In order to increase the intensity of grain refinement under cyclic deformation, one has to increase the amplitude of deformation.

For example, in Twist Extrusion we combine clockwise and counter-clockwise dies.


clockwise
clockwise
A


counter-clockwise
clockwise
2A

To avoid cyclic deformation we combine Twist Extrusion with Spread Extrusion

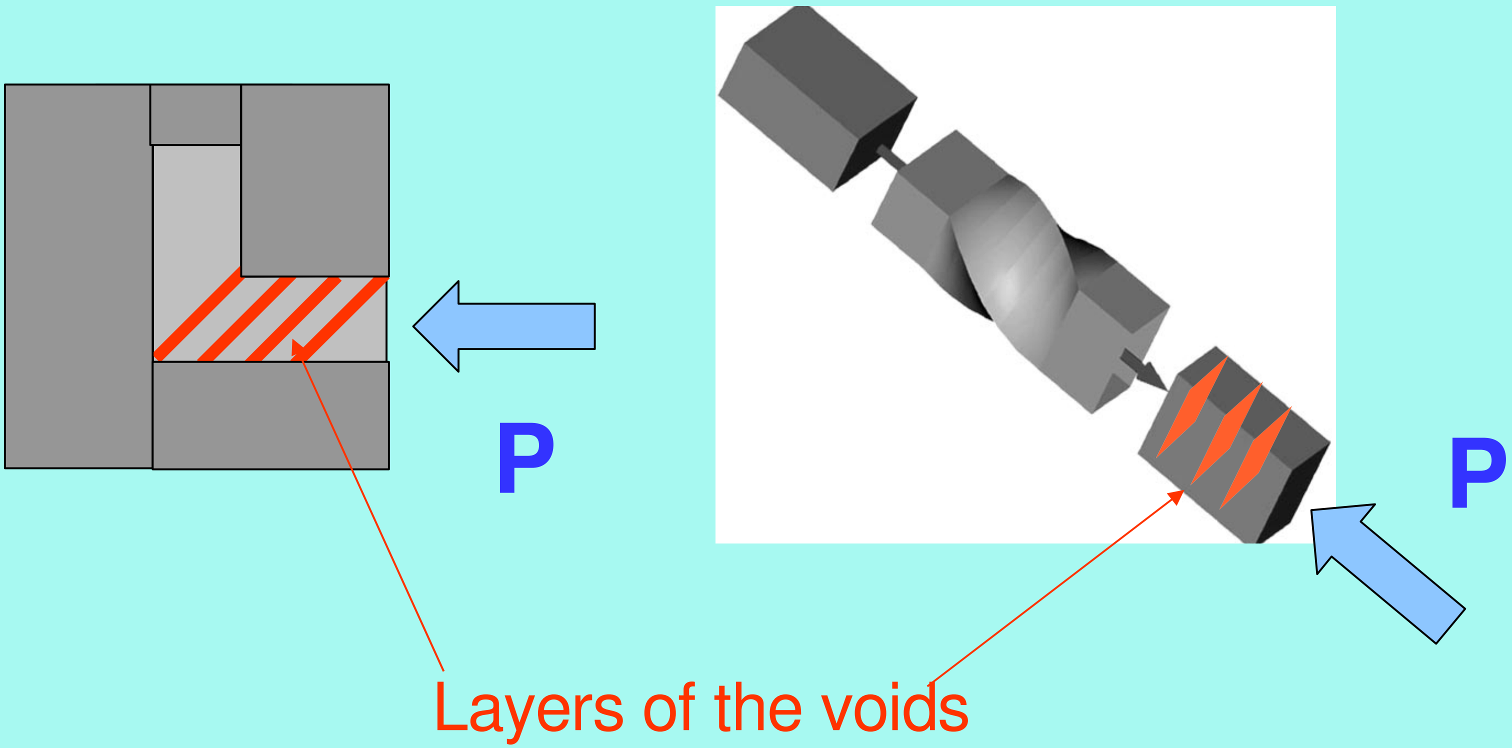


Twist Extrusion

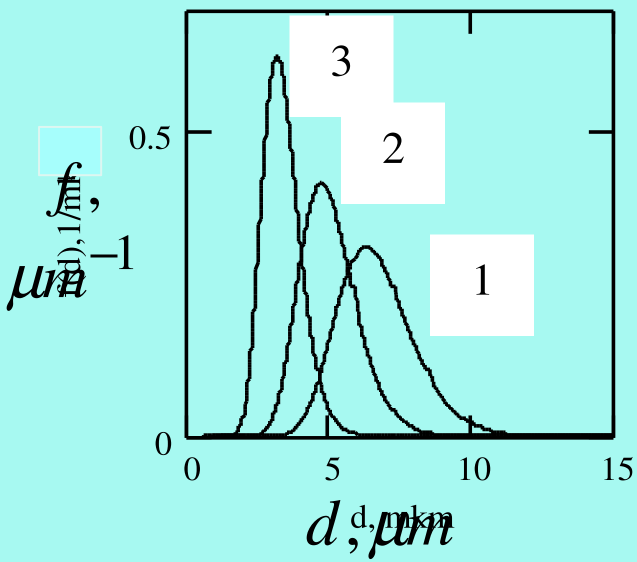
Spread Extrusion

Prediction (vi)

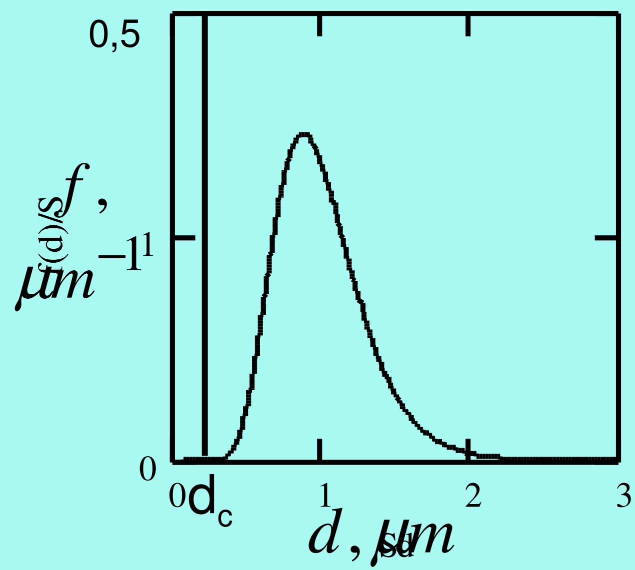
Sufficiently high pressure in the center of deformation prevents strain localization



Prediction (vii)
Grain size distribution

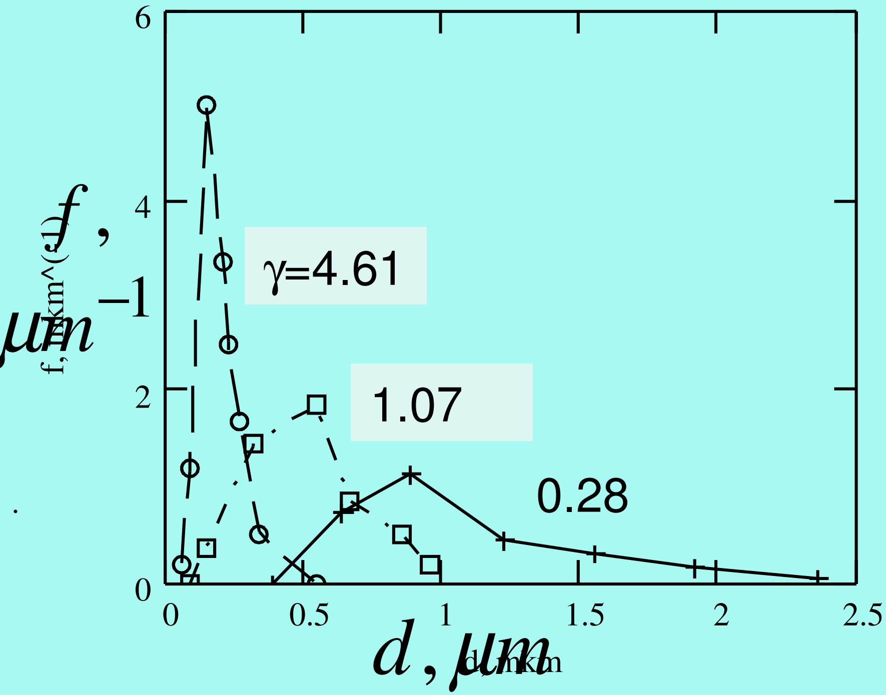


Self-similar stage

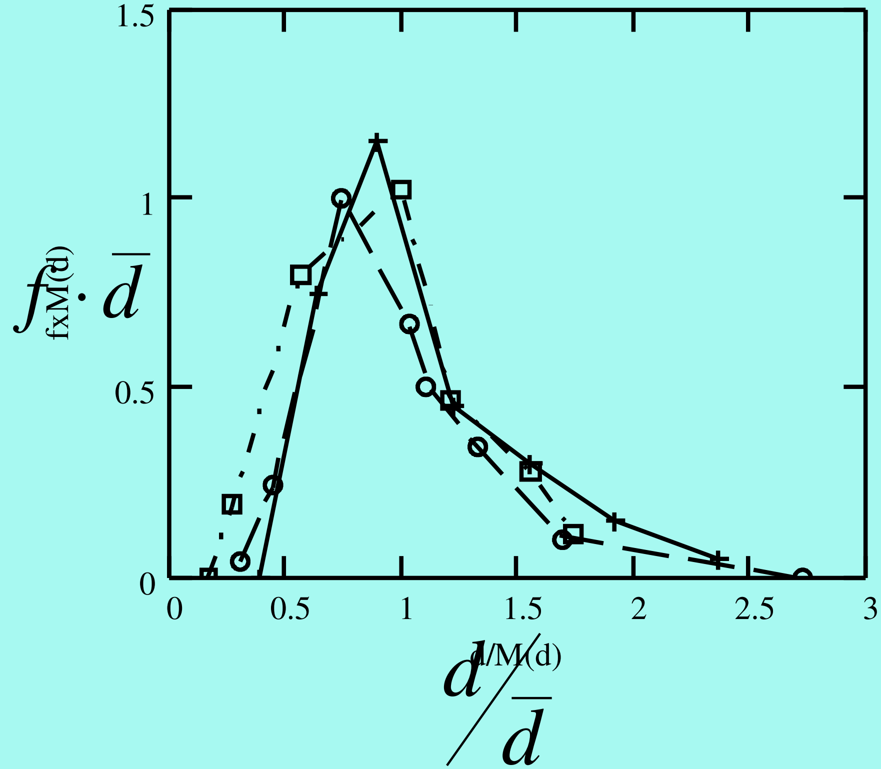


When there are fragments with size d_c

Self-similarity of Experimentally Obtained Distributions



Cu, torsion
(V.Panin et al., 1985)



Prediction (iv)

During the self-similar stage of grain refinement, the fragment boundary mesh in the cross-section of the specimen represents a fractal set with dimension η, $1<\eta<2$.

$$S \sim \frac{1}{\bar{d}^{\eta-1}}$$

.

$1<\eta<2$ - fractal dimension.
During the self-similar stage η is constant

$$\sigma_s \sim S$$

$$\sigma_s \sim \frac{1}{\bar{d}^{\nu}}$$ Hall-Petch

were $\nu = \eta - 1, \qquad 0 < \nu < 1$

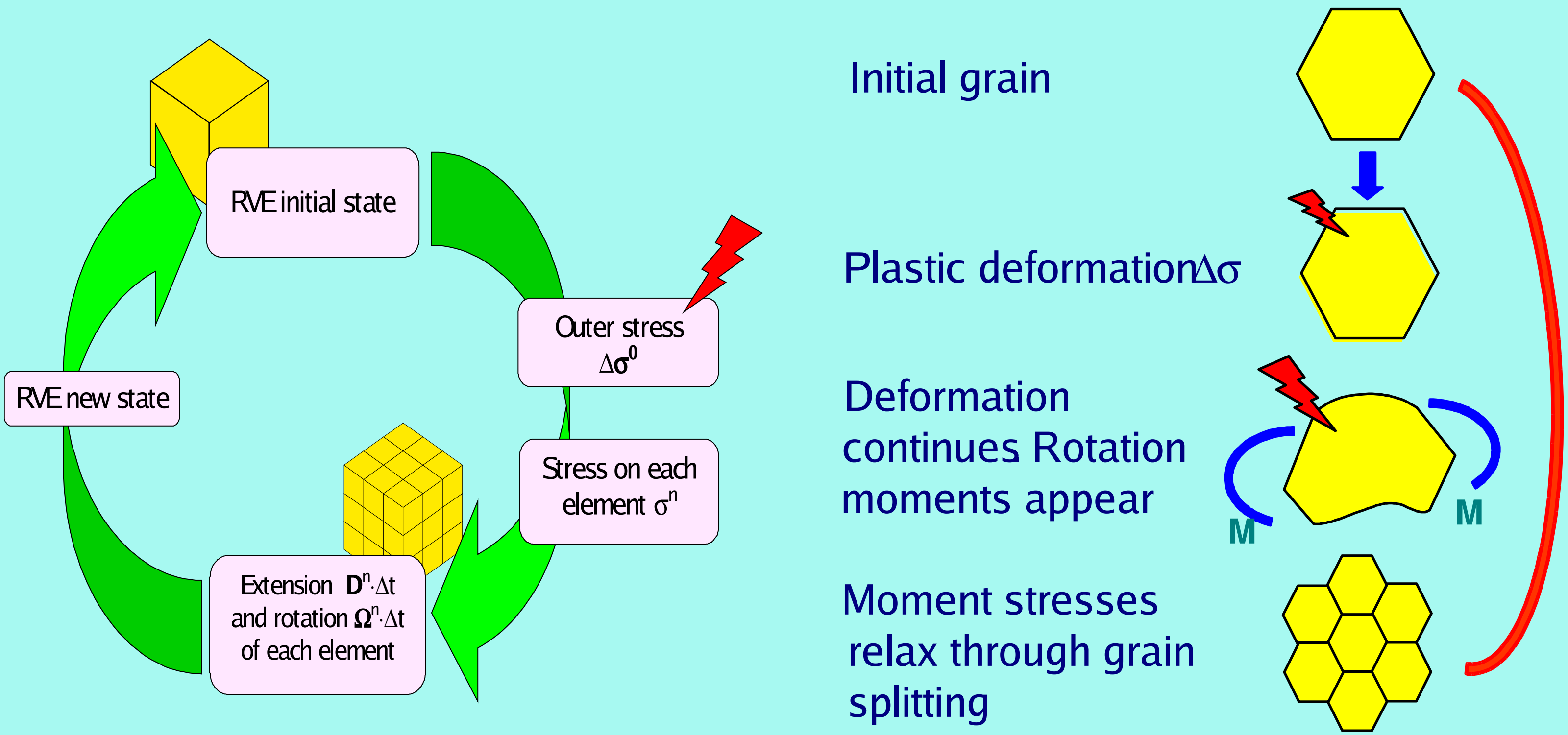
During the self-similar stage ν is constant

When sufficiently many indivisible fragments of size d_c appear, the self-similarity of the boundary mesh gets violated. In this case

$$S \sim \frac{1}{\bar{d}}$$

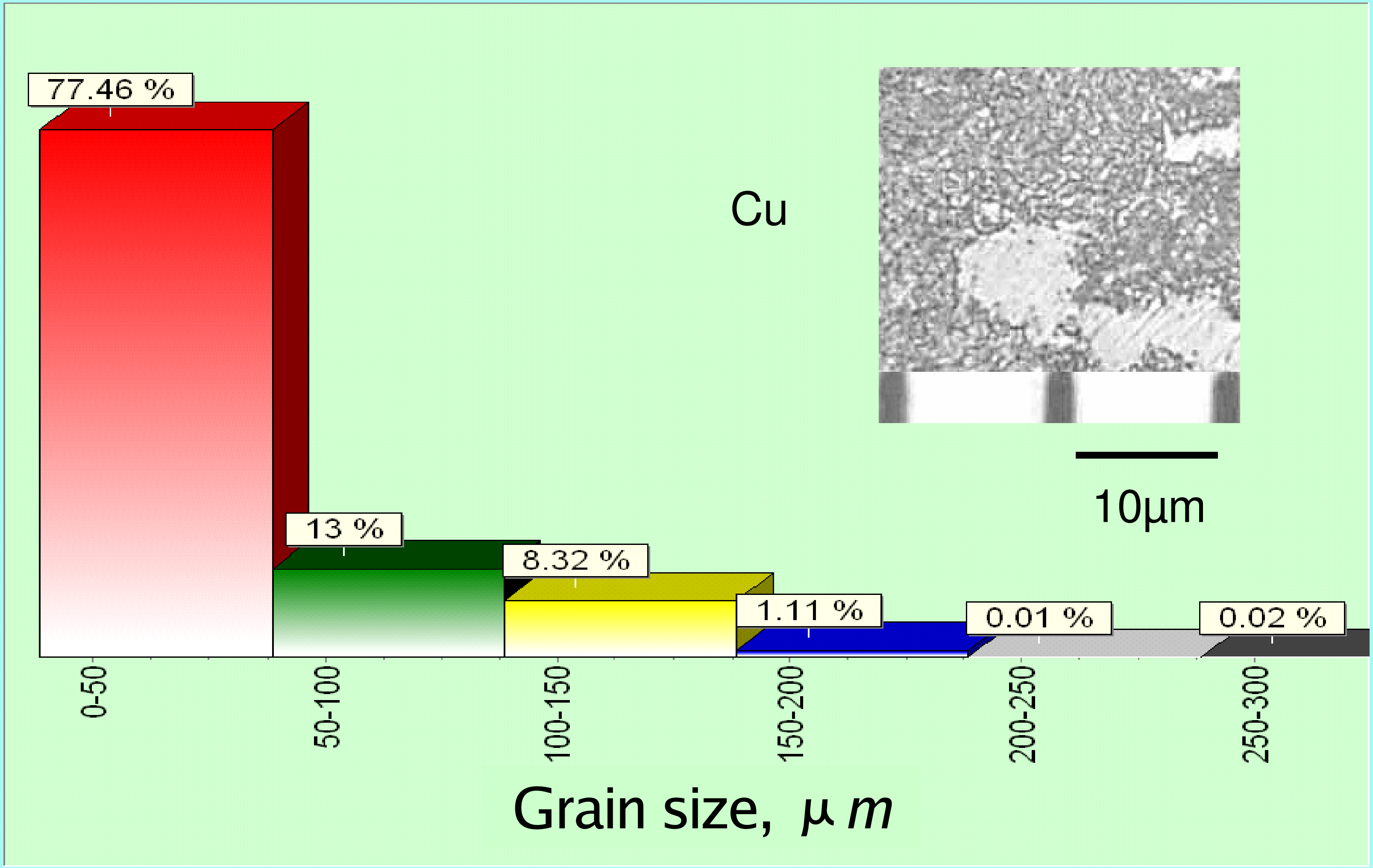
$$\sigma_s \sim \frac{1}{\bar{d}}$$

Simulation of the grain refinement processes by Cellular Model



Beygelzimer Y., et al., *Philosophical Magazine* A, **79**, N10, (1999)

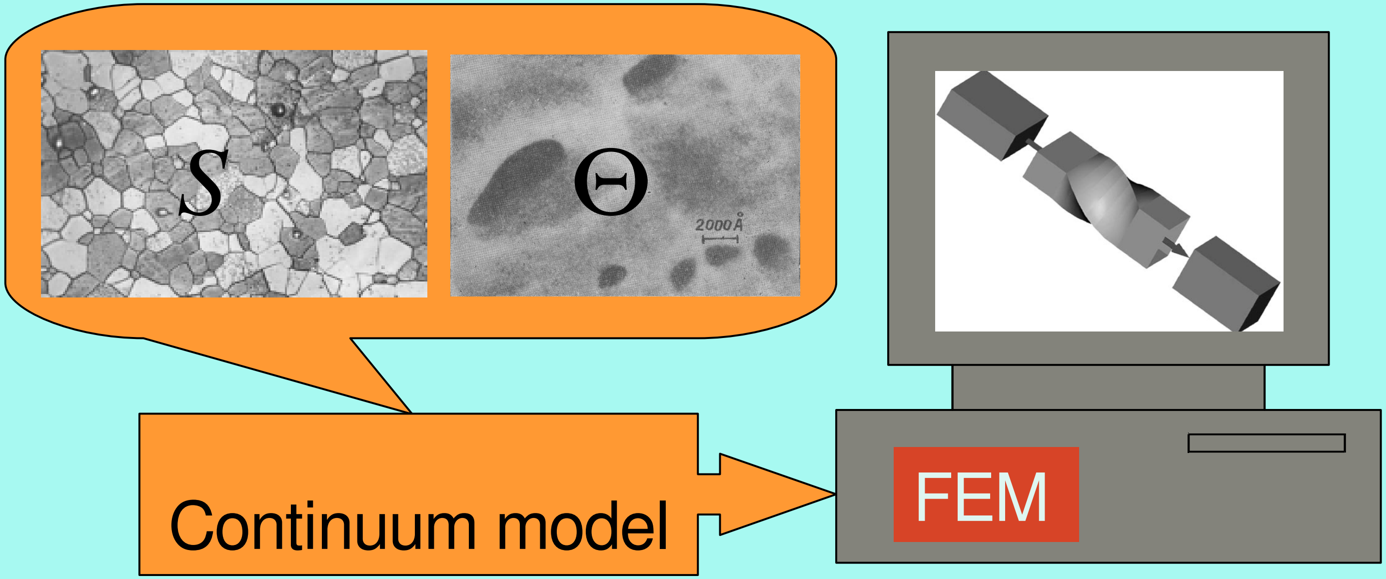
Limiting Grain size distribution (Cellular Model)



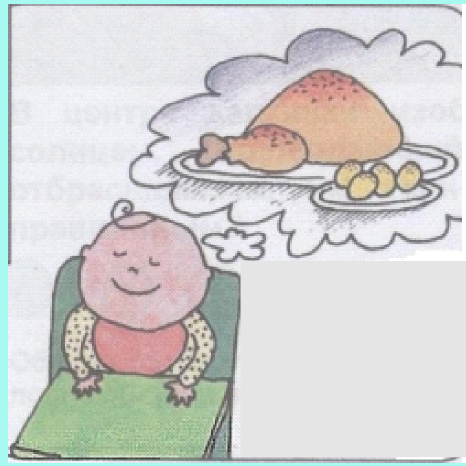
Final Thoughts

What do we hope for?

One can substitute the classical plasticity model by the above model in any FEM package to directly compute the stress-strained state of a metal and its interdependence with the structure



What do we hope for?



What do we have?

- The model is relatively new
- The limits are not entirely explored
- A long way toward good parameter estimation

… but there are grounds for hope