The advanced investigation method for

Statistical analysis of intermittent deformation behavior of metallic materials

Advanced Research of Structural Materials

2nd seminar

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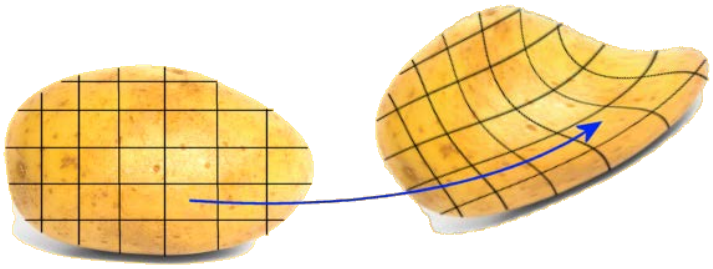
Plastic deformation

: “change of geometric features of solids” under internal or external force
: complex process consisting in “organization of elementary acts of slips”

continuous and intermittent deformation mode of metallic materials

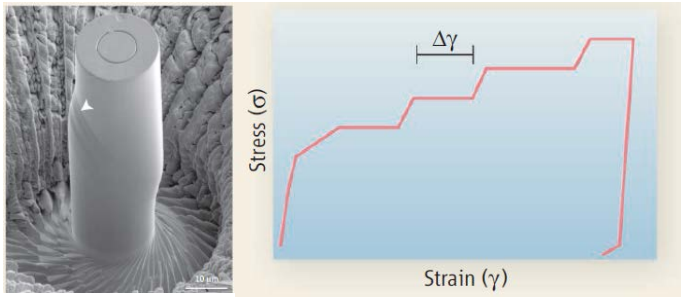
Continuum deformation
- viscous fluid flow

: Electric and plastic deformation with work hardening



Intermittent deformation
- stick & slip and “bursting”

: Portevin-Le Chatelier effect ($\delta\sigma/\delta\varepsilon < 0$)

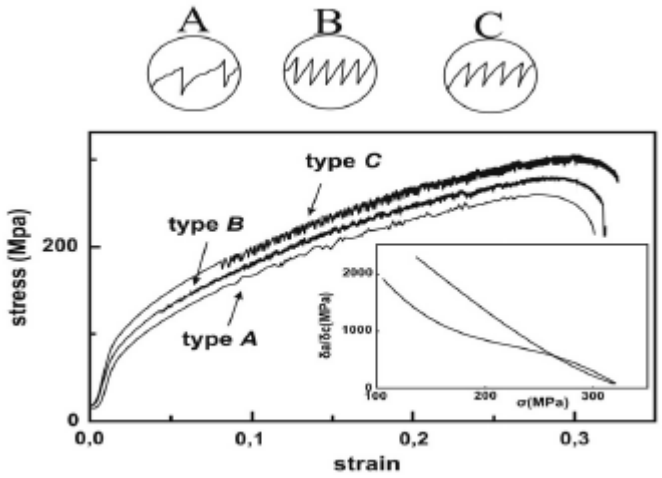


Heterogeneous plastic deformation of S-S curve

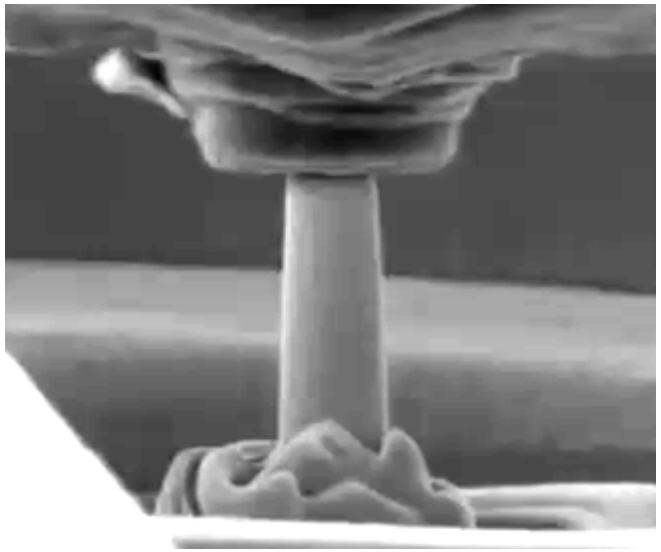
Portevin-Le Chatelier effect

: A serrated stress-strain curve undergoing “inhomogeneous” plastic deformation

→ serration occur at critical strain effected by temperature, strain rate.



1. Dynamic file-up of ⊥
2. Cross-slip of ⊥
3. Precipitation shearing by ⊥



Compression of Nb nano-pillar at 167K

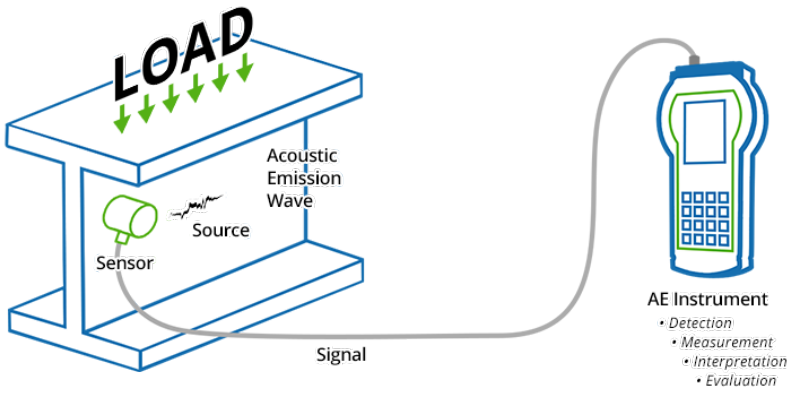
Ref : Journal of achievements in materials and manufacturing engineering, 60 (2013), 7

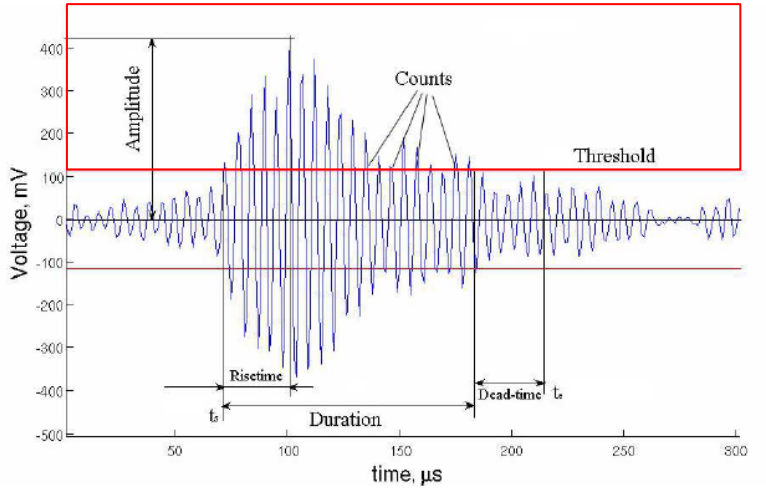
Acoustic emission technique for critical strain bursting

Acoustic emission

: elastic energy change during local, dynamic & irreversible changes of structure.

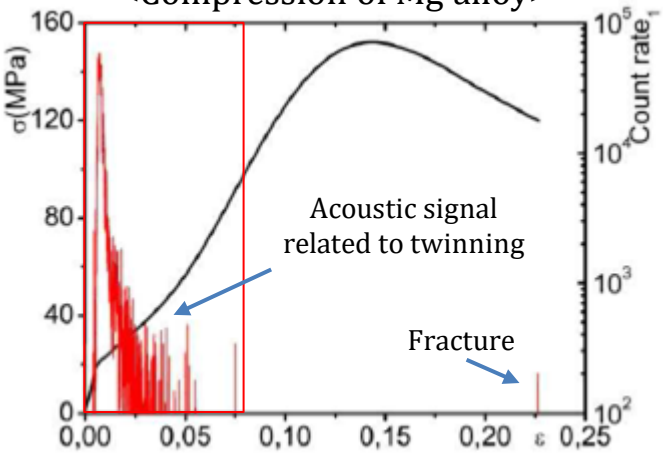
→ serration occur at critical strain





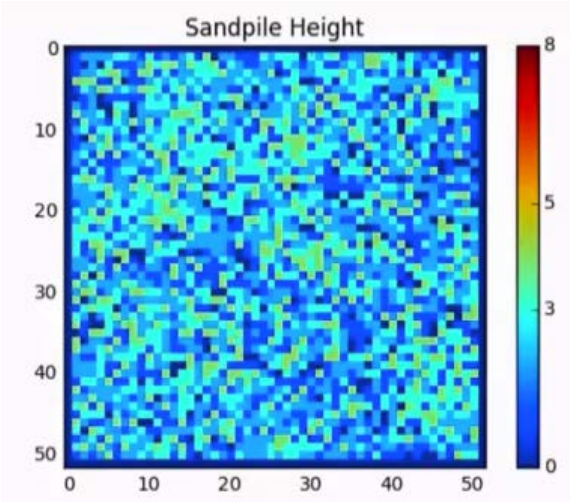
Mechanism of plastic deformation	Strength of AE signal
Frank-Read source	strong
Twin nucleation	strong
Yield phenomenon	strong
Cutting of coherent precipitates by dislocations	strong
Orowan bowing	weak
Twin growth and thickening	negligible
Grain boundary sliding without cracking	negligible

<Compression of Mg alloy>

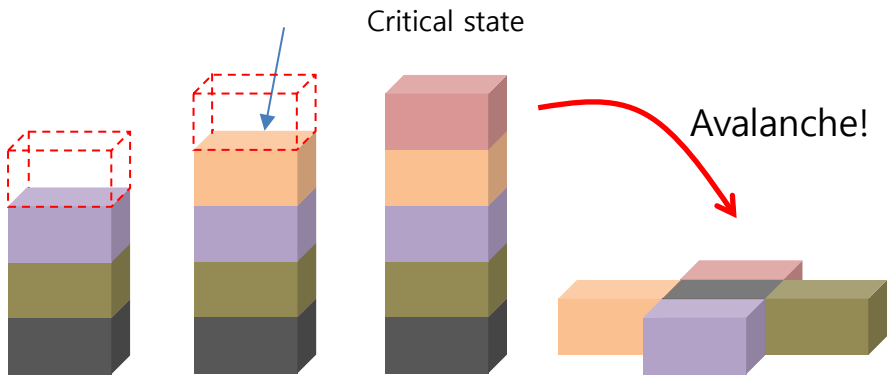


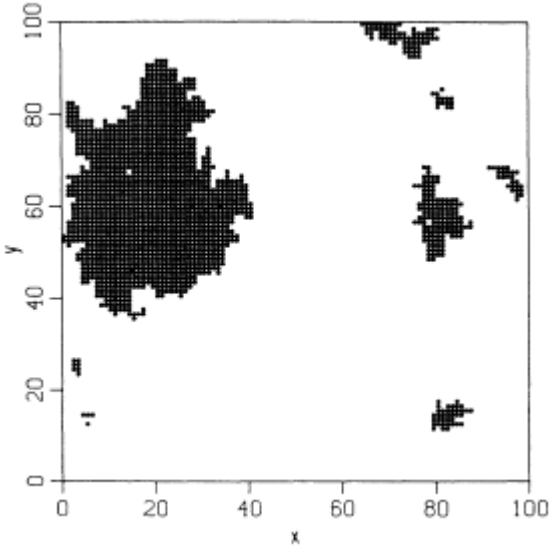
Ref : K. Mathis et, al. exploring plastic deformation of metallic materials by acoustic emission technique.

▶self organization to critical state



Critical state : small stimulation can change the whole state of system

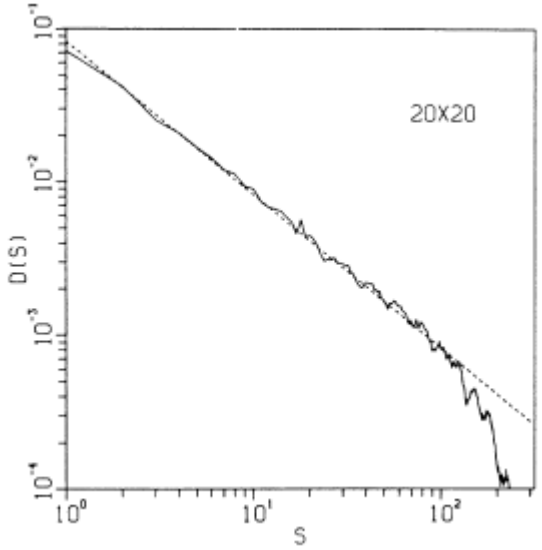




Statistical analysis :
Lifetime of cluster

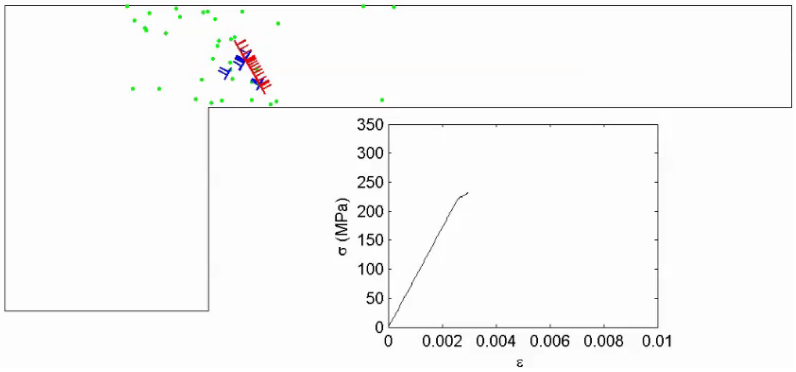
$$D(t) \approx S^{-\tau}$$

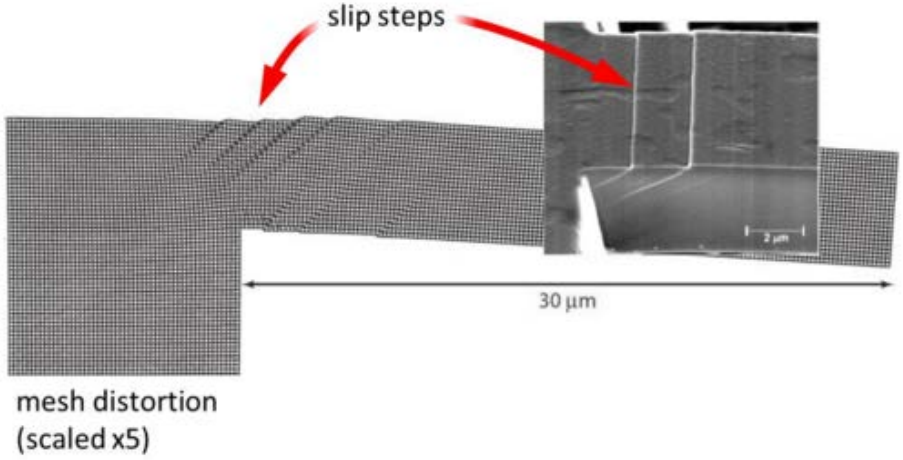
Gutenberg – Richter law

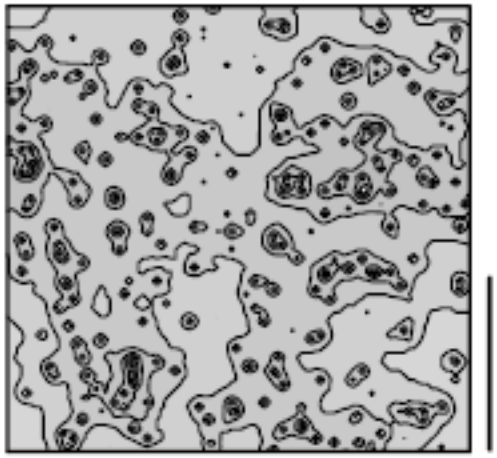


The critical slip state by dislocation movement

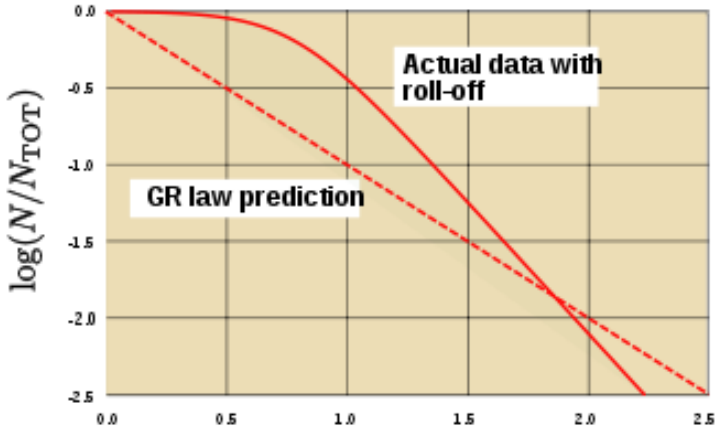
▶ Slip deformation by critical movement of dislocation







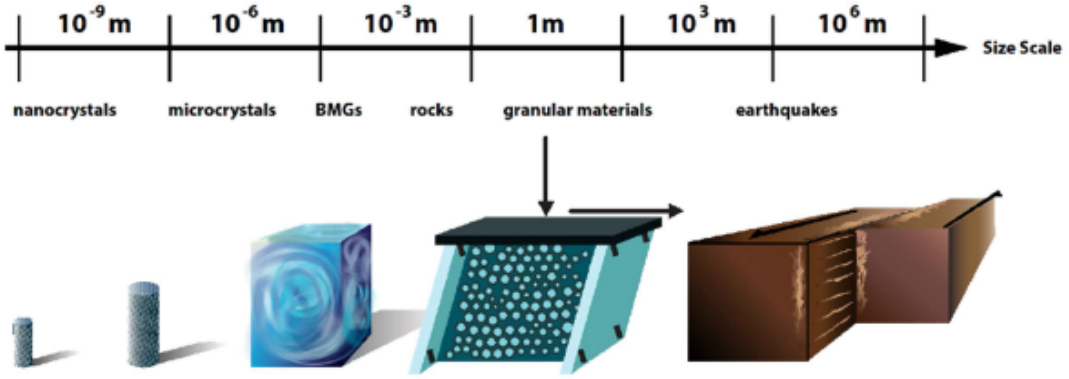
$$P(>S) = AS^{-\beta}\exp(\frac{-S}{S_c})$$



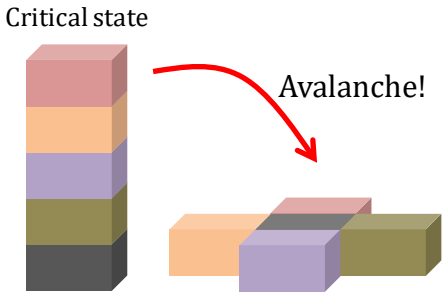
Size of dislocation slip

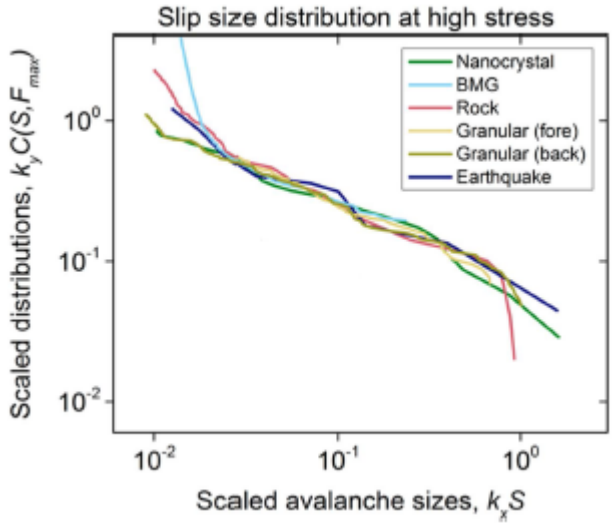
Higher # of events close to Sc → Small stimulation can generate
: high value of β

- **Nature : Self organizing to critical state**



Critical value of system



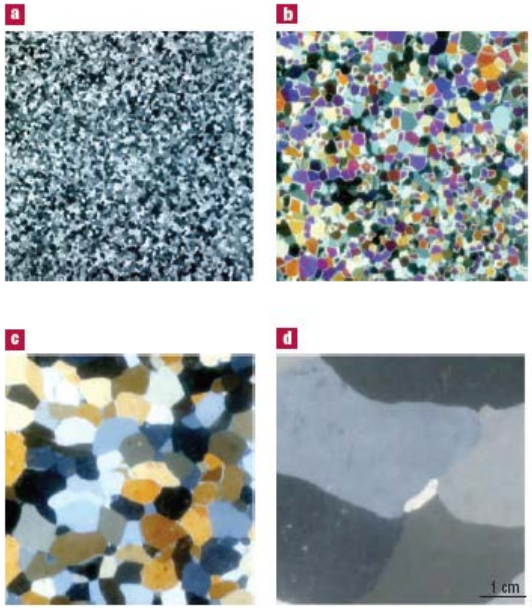


$$P(>S) = AS^{-\beta}\exp(\frac{-S}{S_c})$$ β : steepness of distribution curves

Steeper distribution curve
: Each events are strongly controlled by inner state of matrix
: lots of small events & a few big events

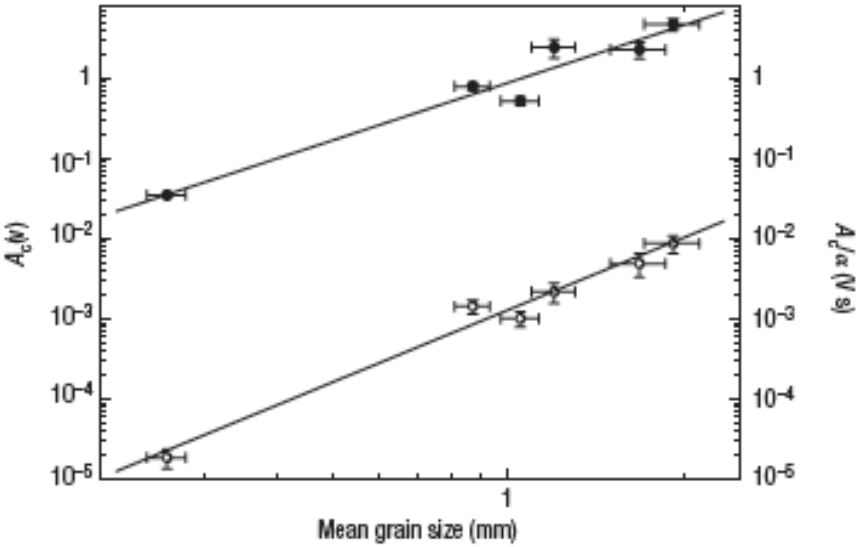
Low slop of distribution curve
: Relations between events and the events are not controlled by matrix.

Critical value for dislocation avalanche size



Materials : -10℃ ICE

G.B slip → negligible
Dislocation → Strong



$$P(>S) = AS^{-\beta}\exp(\frac{-S}{S_c})$$

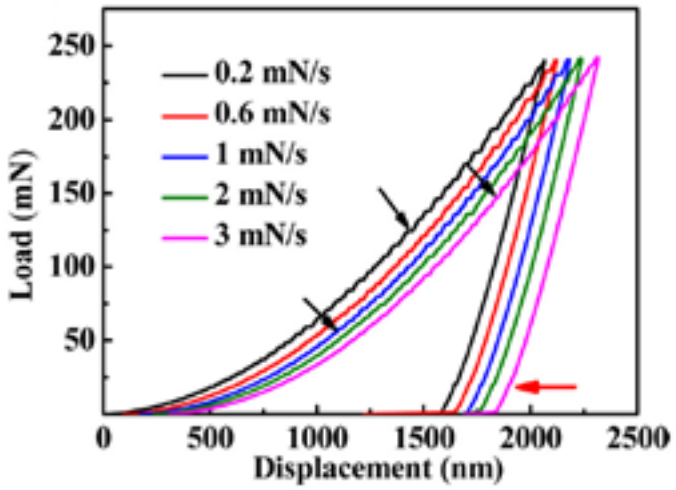
Sc increase with the size of crystal
→ G.B : barrier of ⊥ propagation

Beta : scaling exponent
Sc : cut off of strain

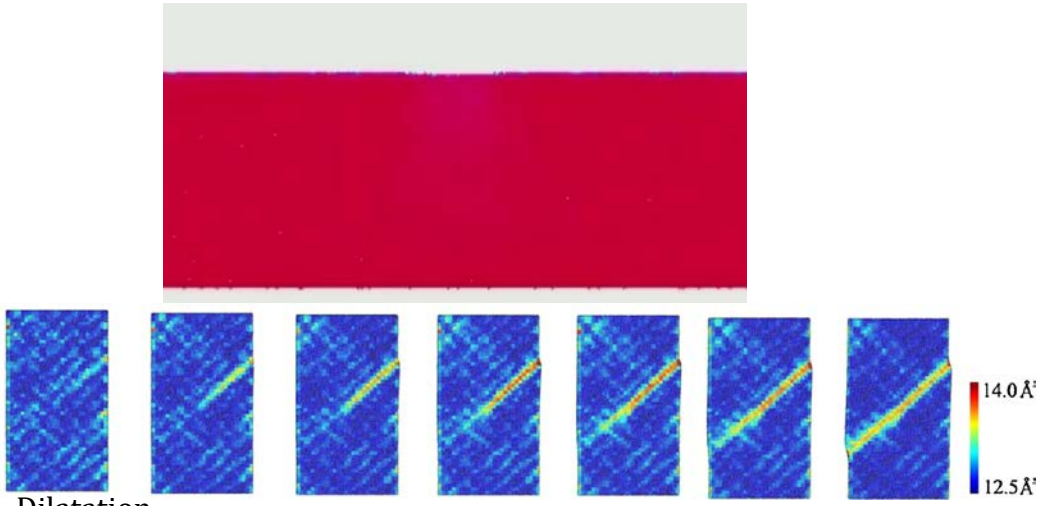
Ref : Nature, 4 (2005) 465

Pop-ins of nano-indentation

P-h curves of Mg based BMG

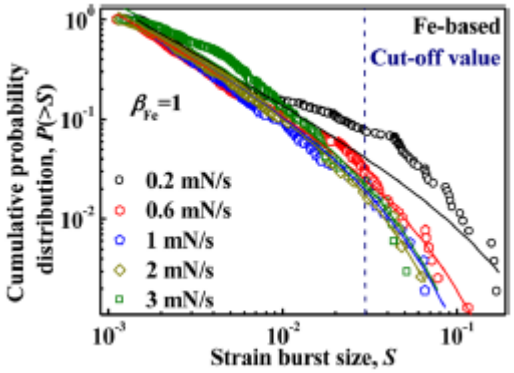


P-h curves of Zr based BMG

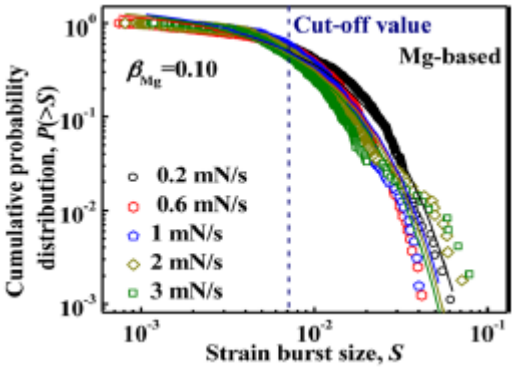


Dilatation

Hard Fe-based MG



Soft Mg-based MG



$$P(>S) = AS^{-\beta} \exp\left(\frac{-S}{S_c}\right)^2$$

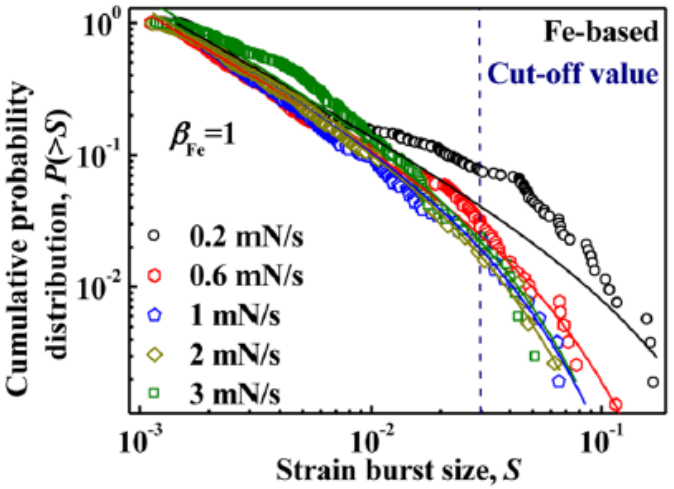
β : scale exponent

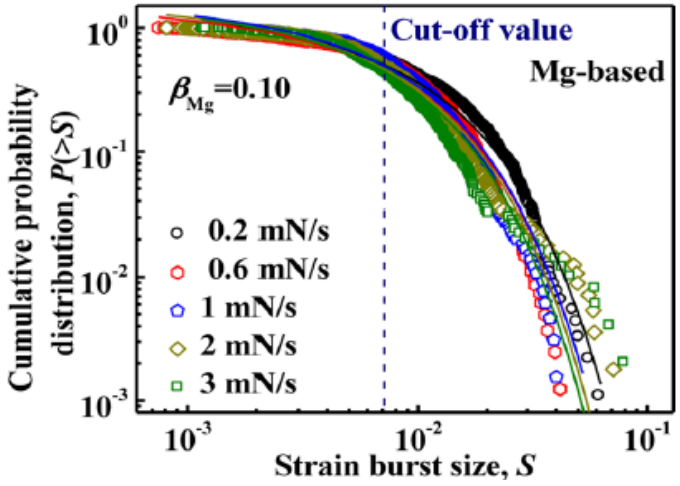
→ high β value = SOC state
: Jamming state

→ low β value = Chaotic state
: Unjamming state

Evaluation of Self-organizated state in metallic glass

▶ Statistical evaluation of Shear band size with power law





Power law : $P(>S) = AS^{-\beta}\exp(\frac{-S}{S_c})$

β : 균일한 shear band size 분포
: shear bursting size가 균일하게 분포

High β (SOC)	Low β (Chaotic)
Strong glass Hard / Brittle glass Solid Solution hardening	Fragile glass Soft / Ductile glass Composite

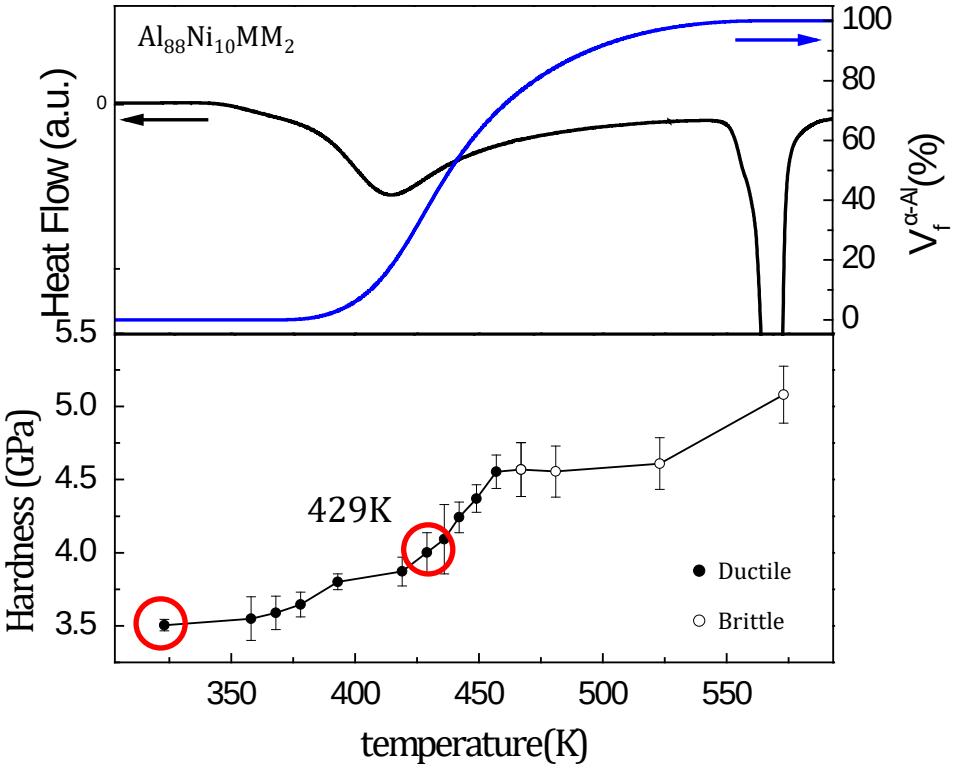
Sc : 절단값 (경향성에서 벗어나는 임계값)
= S > Sc SOC state에서 벗어나 불규칙한 성장

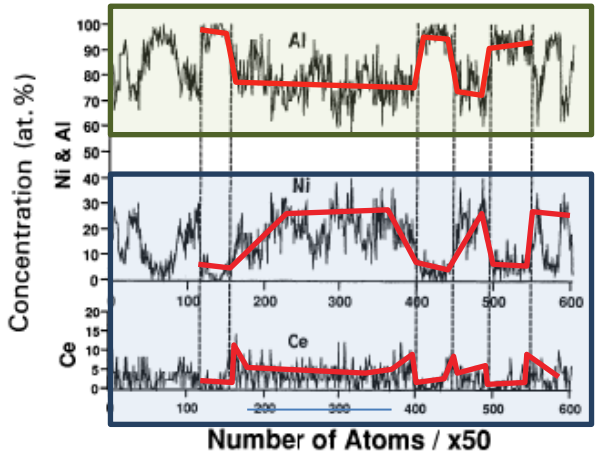
High S_c	Low S_c
High strength Fully amorphous	Heterogeneous Nano - Composite Phase separation

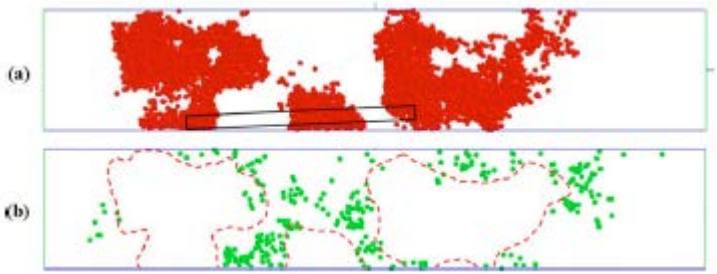
Ref : PRL, 105 (2010) 035501 / APL, 103 (2013) 101907
Int. J. Plas, 77 (2016) 141 / Metals, 5 (2015) 1188

Hardening mechanism of partial crystallization of $Al_{88}Ni_{10}MM_2$

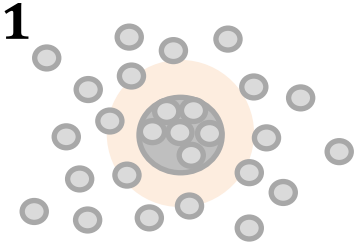
▶ nano-indentation results of annealed $Al_{90-x}Ni_{10}MM_x$ amorphous ribbon





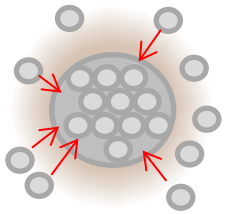


1



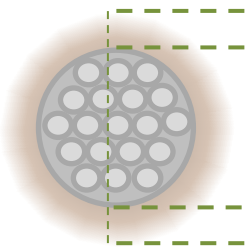
In-situ Al nanocrystals
→ Softening effect

2



Growth of α-Al
→ Diffusion growth

3

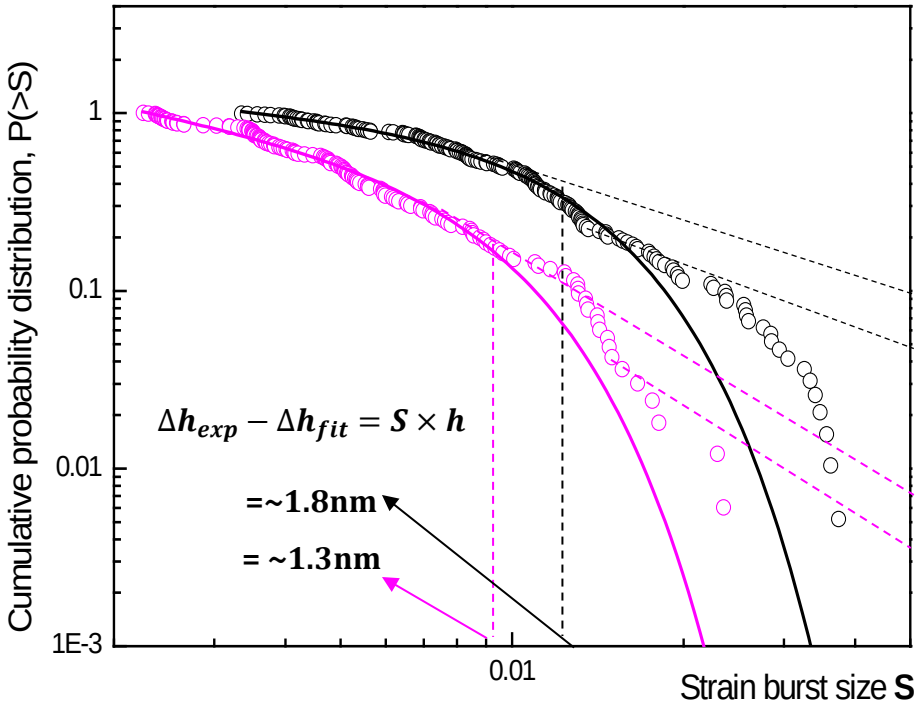


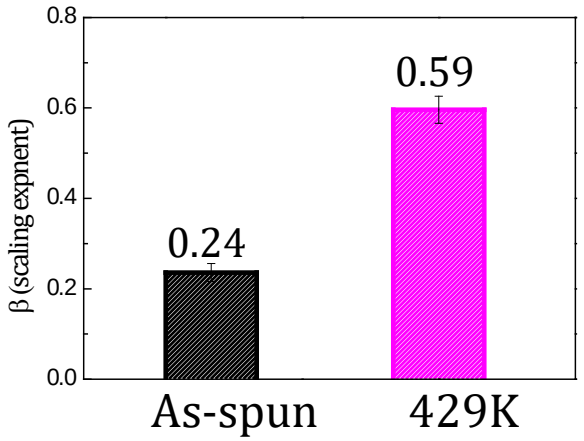
2nd phase arrounded by hard matrix

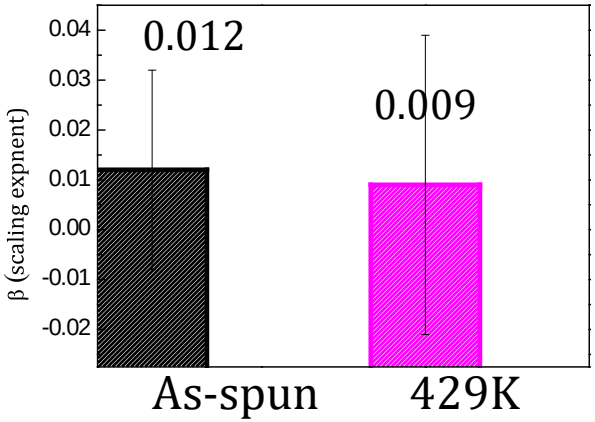
Mean size 9.2nm
(from SAXS modeling)

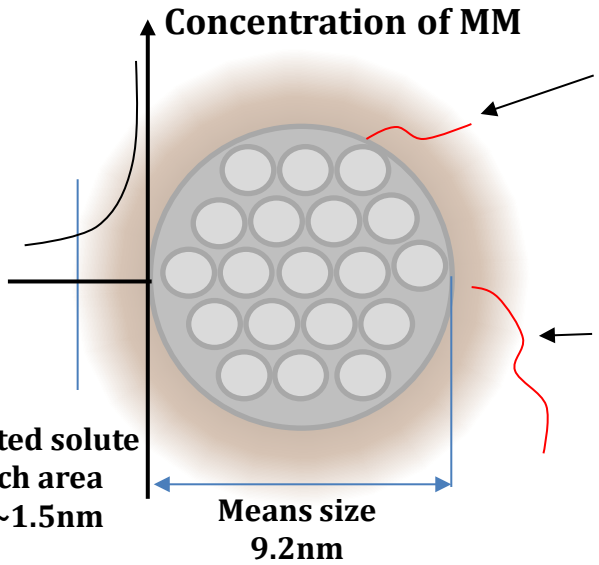
Expected solute rich area : ~1.5nm

Shear band formation of hardened matrix









Shear bands (S < 1.3nm)
: Inside of solute rich area
→ SOC state, (β ↑)

Shear bands (larger than 1.3nm)
: Compositional fluctuation
→ Chaotic & Scale-less bursting

Summary

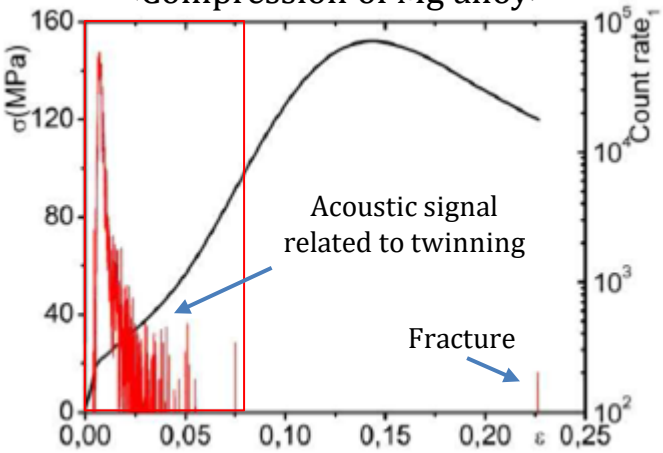
Heterogeneous deformation of metallic materials

(Portevin-Le Chatelier effect)

→ Unique method for dislocation & slip movement.

→ Signal is differ from mechanism of deformation.

<Compression of Mg alloy>

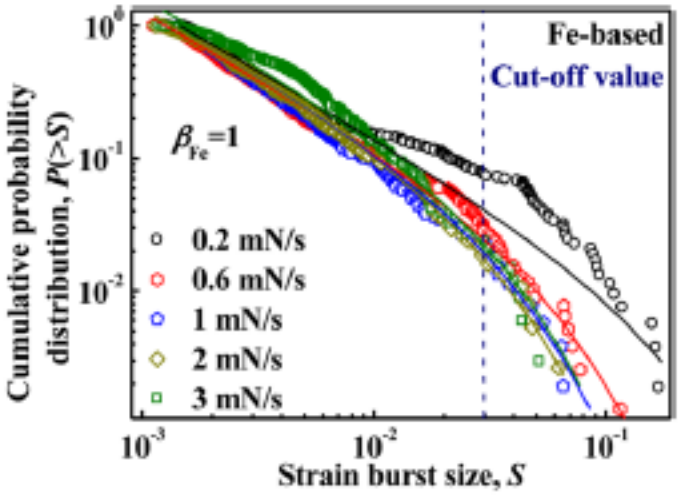


Self-organization of heterogeneous deformation

→ Statistical collecting of size of event can evaluate the effect of matrix on the events.

→ Linear distribution of power function
= SOC state : outbreak of events is strongly related to condition of matrix

= Calculation of β value give us the information about shear band deformation trend of metallic materials



Thanks for your kind attention