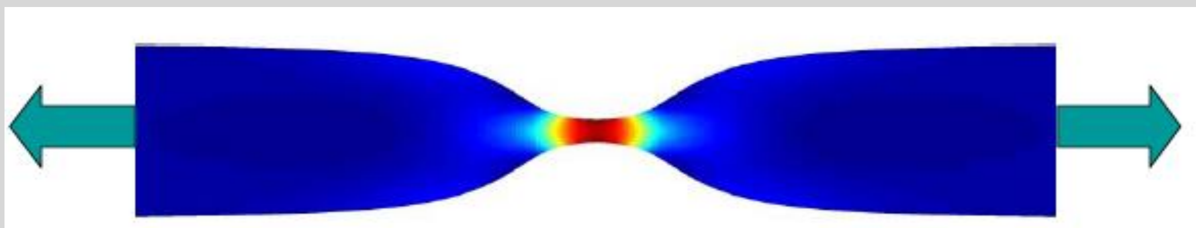
Discontinuous behavior in metallic glasses



Gang WANG
Institute of Materials, Shanghai University

August, 7 – 18, 2017

Beijing, China

Acknowledgements

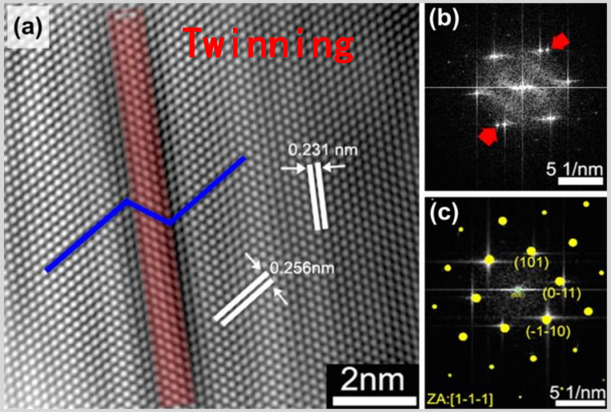
Prof. Jingli Ren (Zhengzhou University)
Prof. P.K. Liaw (The University of Tennessee)
Prof. K.A. Dahmen (University of Illinois at Urbana Champaign)
Prof. J. Eckert (IFW-dresden)
Dr. N. Mattern (IFW-dresden)

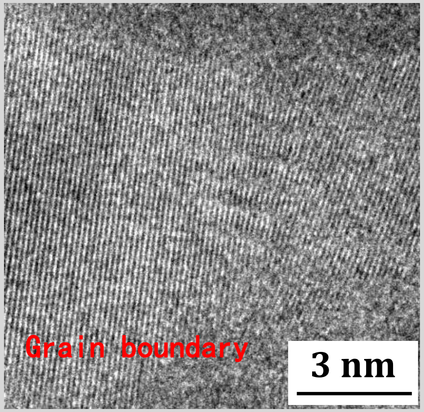
Supported by NSF of China, MOST of China.

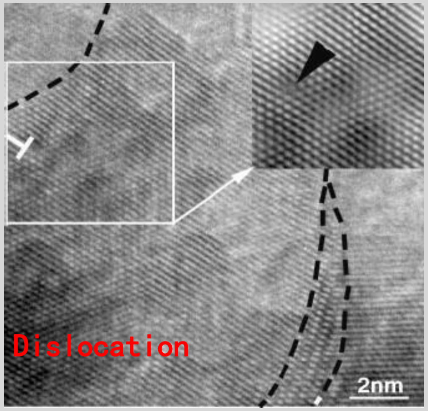
Dr. Xilei Bian (Shanghai University)
Ms. Dongxue Han (Shanghai University)
Mr. Xing Tong (Shanghai University)

Background

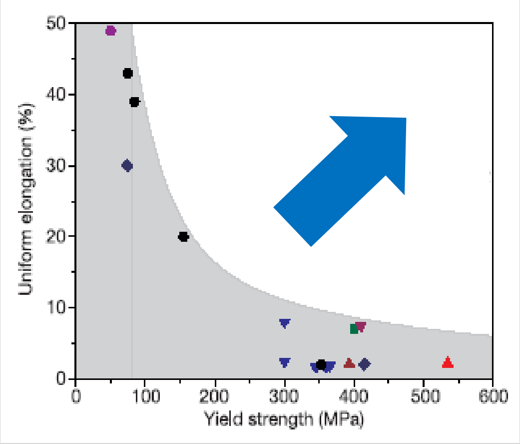
Crystallographic defects dominating the plastic deformation of crystalline materials.







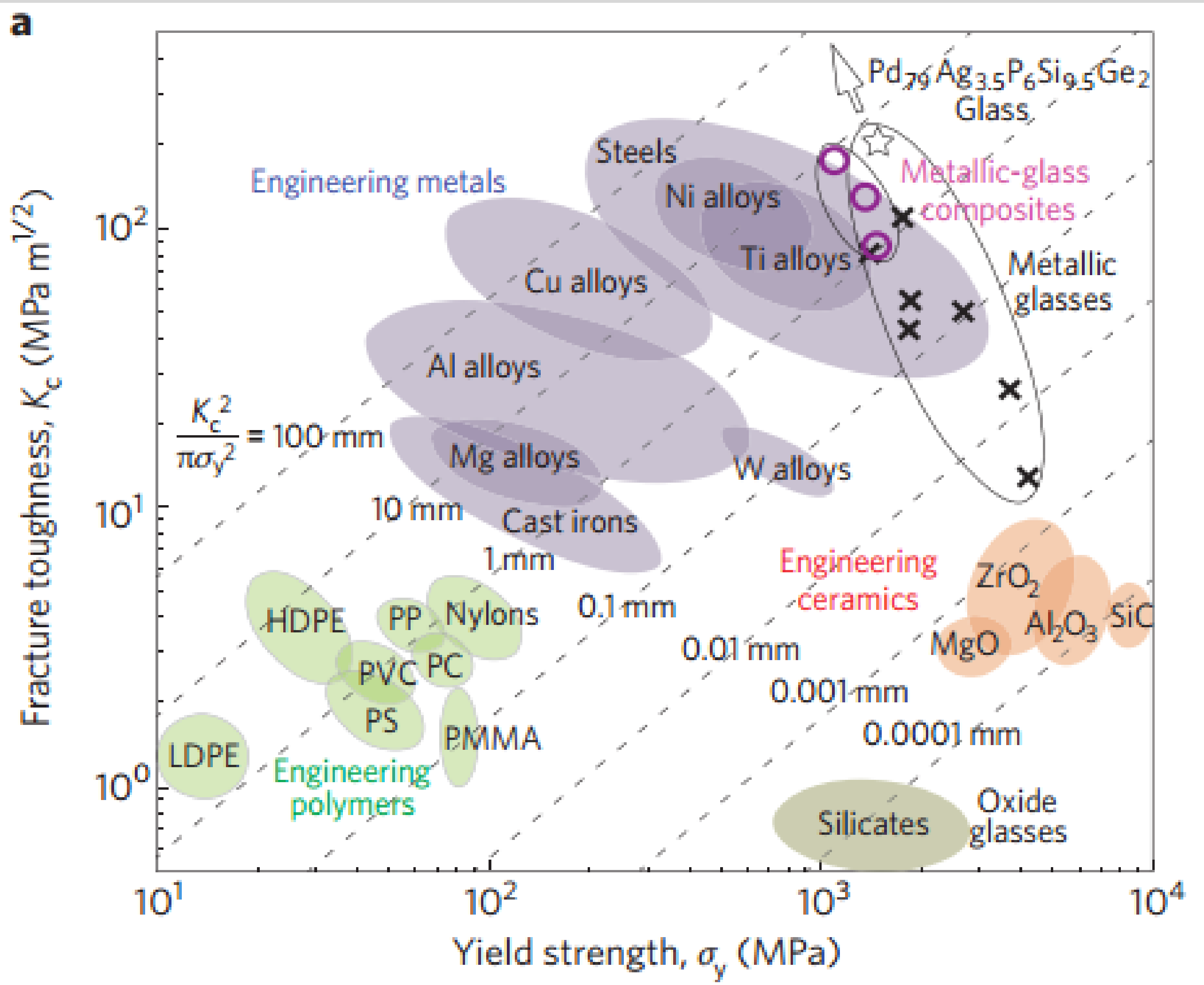
Strength and plasticity - the most important properties, which can be modified by the modification of the defects.



$$\sigma_y = \sigma_o + \frac{k_y}{\sqrt{d}}$$

Hall-petch relationship

Background



Nature Mater. **10,** 123 (2011)

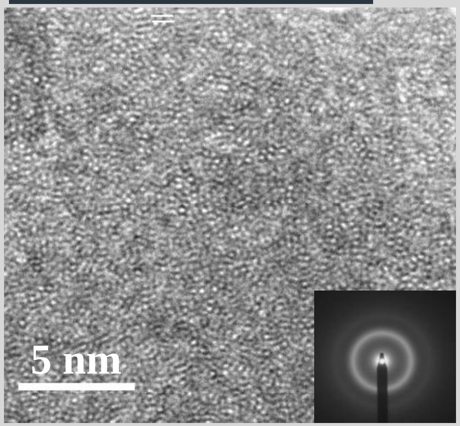
- High fracture toughness
- High yield strength
- High hardness
- High corrosion resistant
- ....

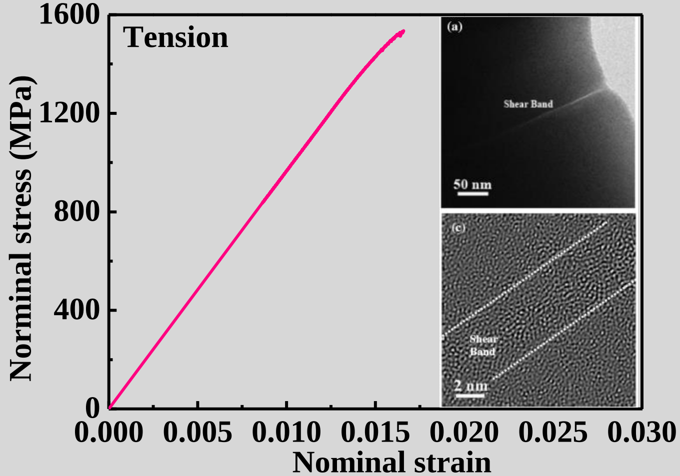
Application?

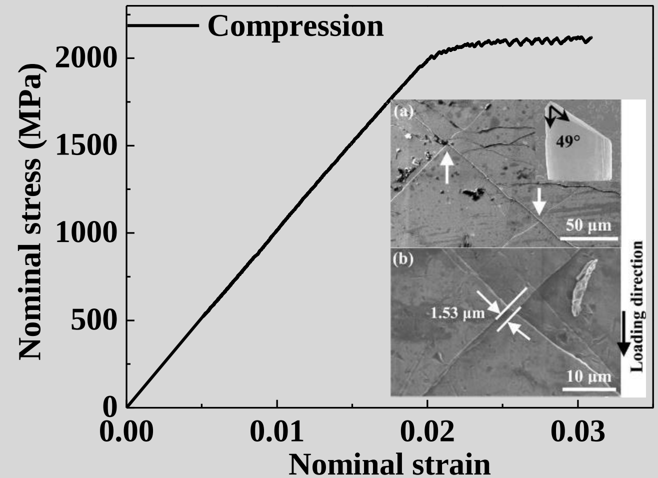
Some problems

High toughness
High strength

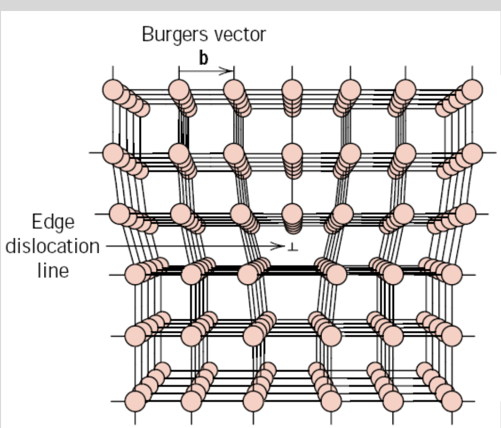
≠ Good plasticity   Work-hardening mechanism?

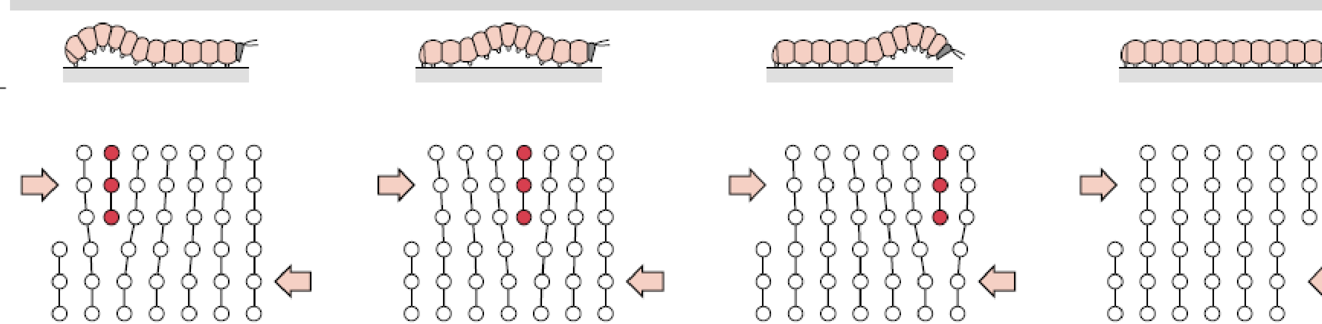






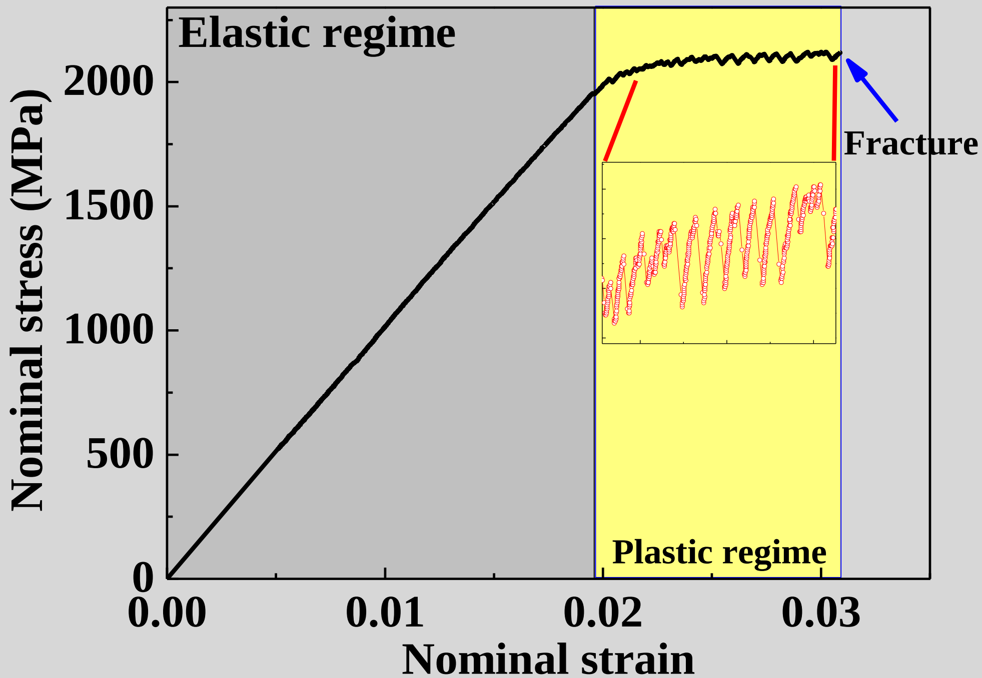
Plastic deformation micromechanism in crystalline materials



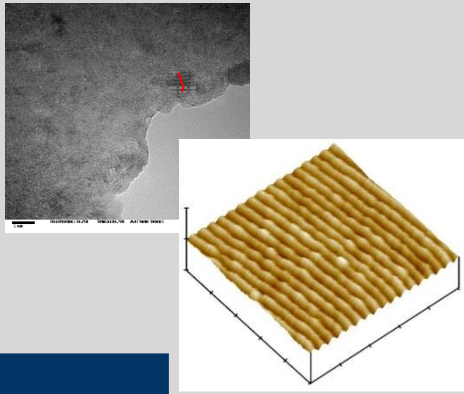


PRL **96,** 245502 (2006); APL **89,** 251909 (2006); JMR **22,** 869 (2007)]

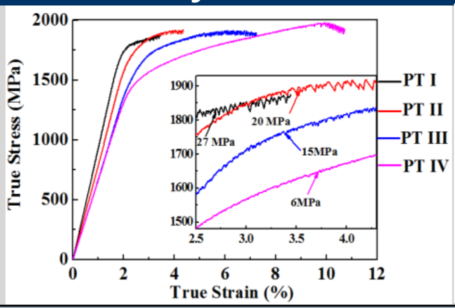
Research scope （Outline）

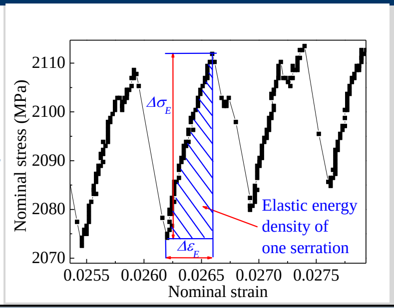


(b)
Fracture : Crack propagation ; Release of fracture energy; Fracture toughness



(a)
Plastic deformation : Intermittent shear bands formation and propagation ; The plastic deformation ability.





Part I Intermittent plastic deformation

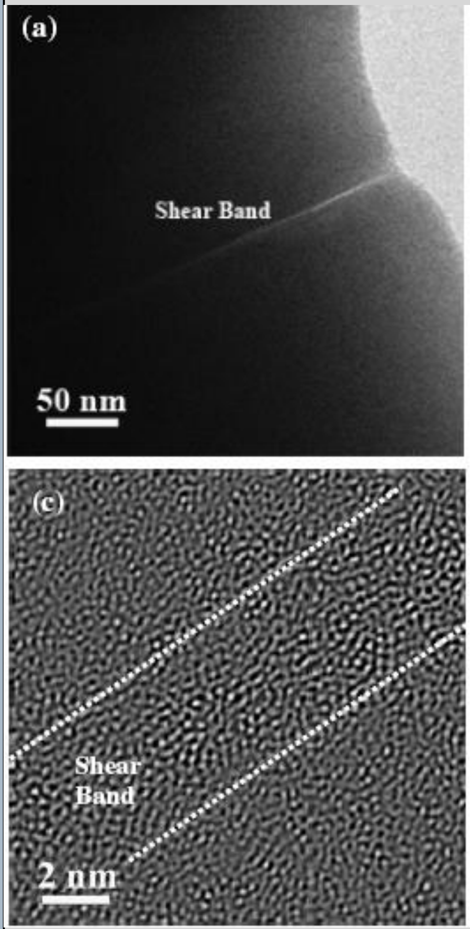
Part II Influences of structures on on intermittent plastic deformation

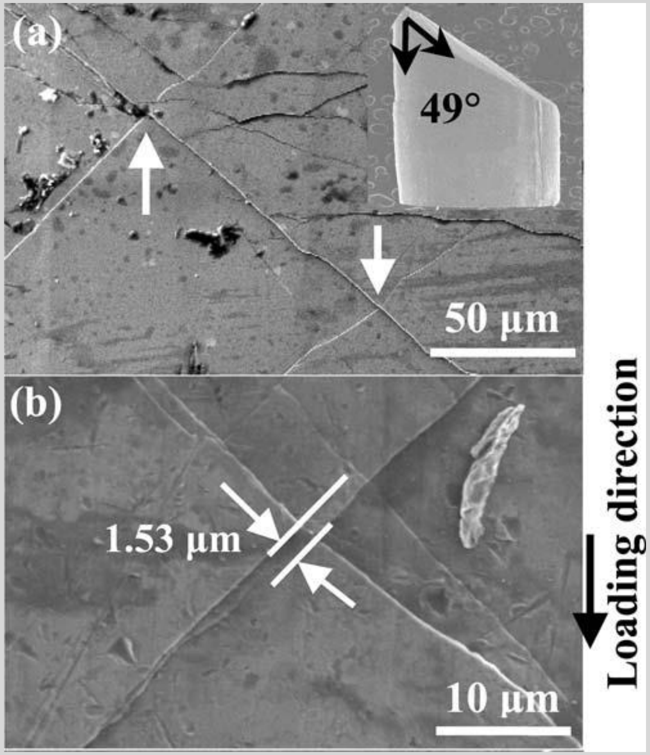
Part III Stick-slip behavior in nanoscratch

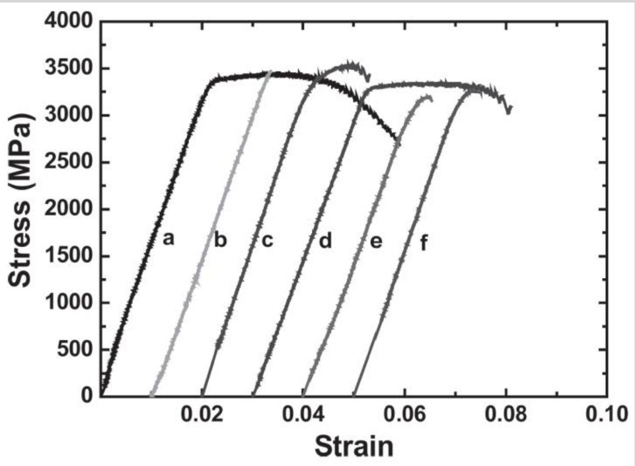
Part IV Discontinuous crack propagation

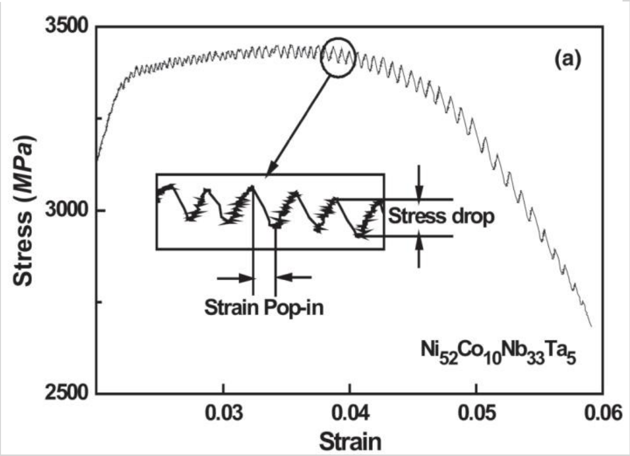
Part I Intermittent plastic deformation

Stress ⇨ STZs ⇨ Shear localization ⇨ Shear banding ⇨ Catastrophic fracture









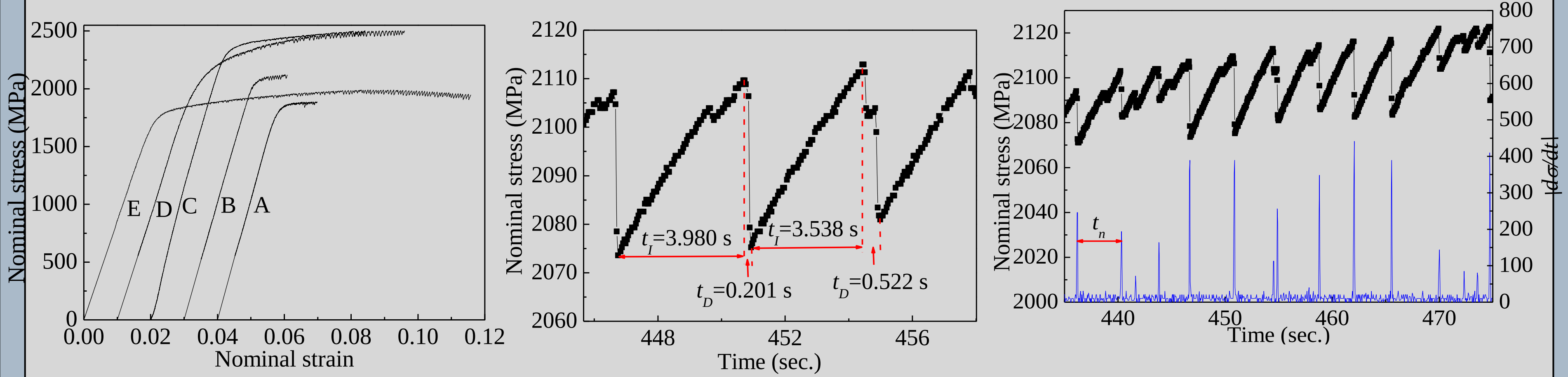
[M.W. Chen et al, PRL **96,** 245502 (2006); G. Wang et al. APL **89,** 251909 (2006)]

Part I Intermittent plastic deformation

Serration events *(Typical characteristics)*

Plastic deformation of BMGs generally exhibits serrated flow, i.e. repeated cycles of a sudden stress drop followed by reloading elastically

Serrations correspond to the shear bands formation and propagation



A: $Zr_{55}Ni_5Cu_{30}Al_{10}$

B: $Zr_{41.25}Ti_{13.75}Ni_{10}Cu_{12.5}Be_{22.5}$

C: $Cu_{42.5}Ti_{42.5}Zr_{2.5}Hf_5Ni_{7.5}$

D: $Zr_{51}Cu_{23.25}Ni_{13.5}Al_{12.25}$.

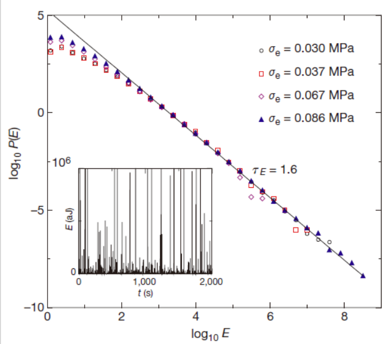
E: $Cu_{47.5}Zr_{47.5}Al_5$

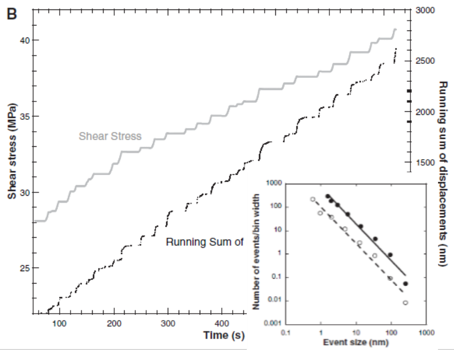
Characteristics:

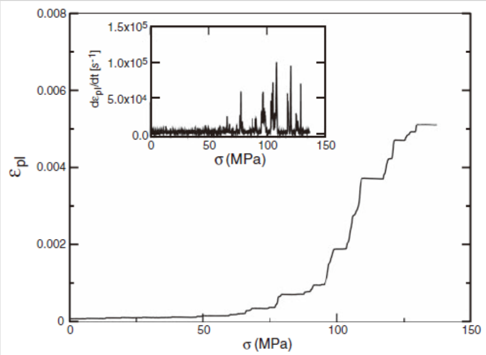
- **Serration events lack any typical time scale ($t_0 \neq t_1 \neq \ldots\ldots \neq t_{n+1}$)**
- **Process under external stress (stress increase) is much slower than the internal relaxation process (stress drop). ($t_I > t_D$)**
- **A large number of interacting entities. (The number of serration events is about 30)**

Part I Intermittent plastic deformation

The continuum approach fails to account for microscopic plastic deformation because of discontinuous defect motions in crystalline materials.





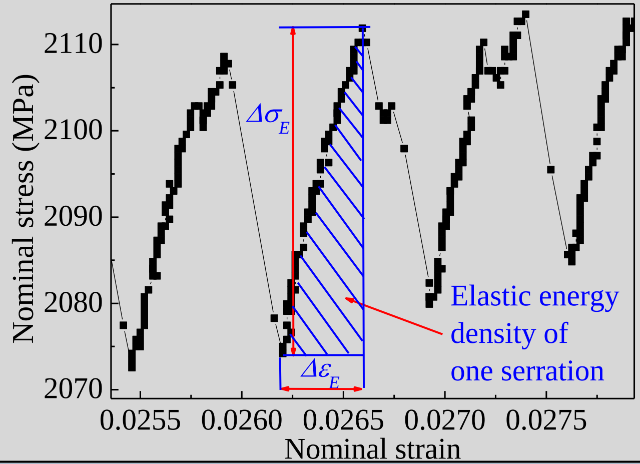


Single crystal (ice) **Polycrystal** **Microcrystal**

Science 2006, 312: 1188;
Science 2007, 318: 251;
Nature 2001, 410: 667.

Power law: $P(E) \sim E^{-\tau}$

$P(E)$: propability

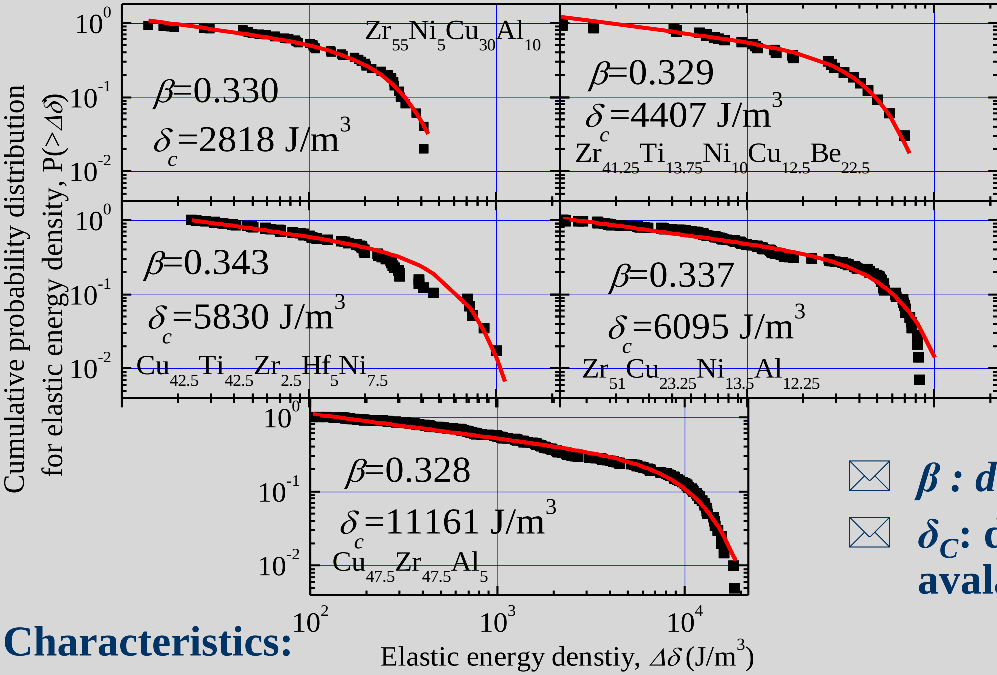


$$\Delta\delta = \frac{1}{2}\Delta\sigma_E \Delta\varepsilon_E$$

The elastic energy density of one serration event ($\Delta\delta$)

Part I Intermittent plastic deformation

Ergodic process of the elastic energy density in five BMGs



$$P(\geq \Delta\delta) = A\Delta\delta^{-\beta}\exp\left[-\left(\Delta\delta/\delta_C\right)^2\right]$$

Scattering points: *Δδ* (measured from stress-strain curves)

Red solid lines: fitted by Power-law function

$\beta = 0.335 \pm 0.008$

- ***β* : depending on the deformation mechanism**
- **δ_C: depending on the characteristic length of avalanche**

Characteristics:

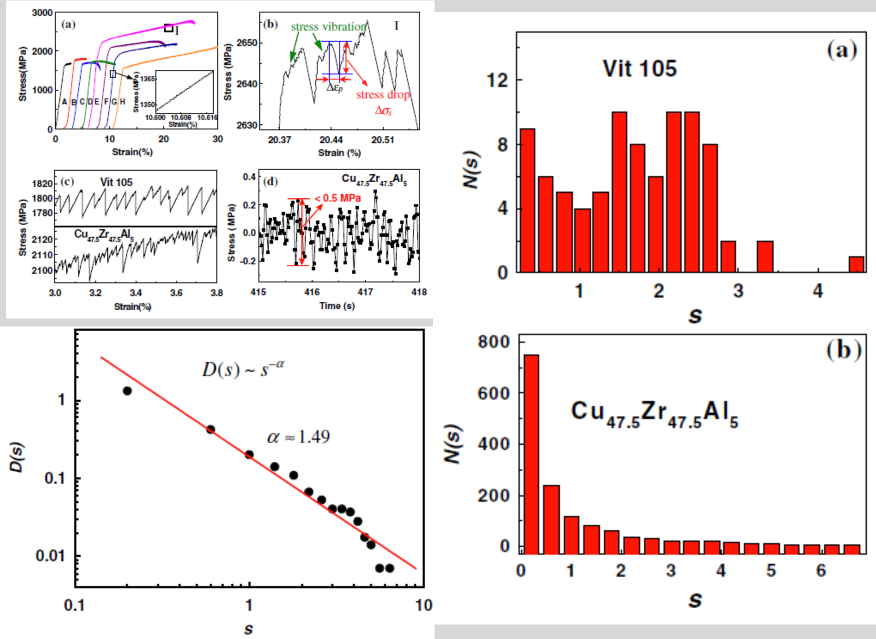
- **Serration events lack any typical time scale ($t_0 \neq t_1 \neq \ldots\ldots \neq t_{n+1}$)**
- **Process under external stress (stress increase) is much slower than the internal relaxation process (stress drop). ($t_I > t_D$)**
- **A large number of interacting entities. (The number of serration events is about 30)**
- **Power-law distribution**

⇨ **Self-organized criticality (SOC)**

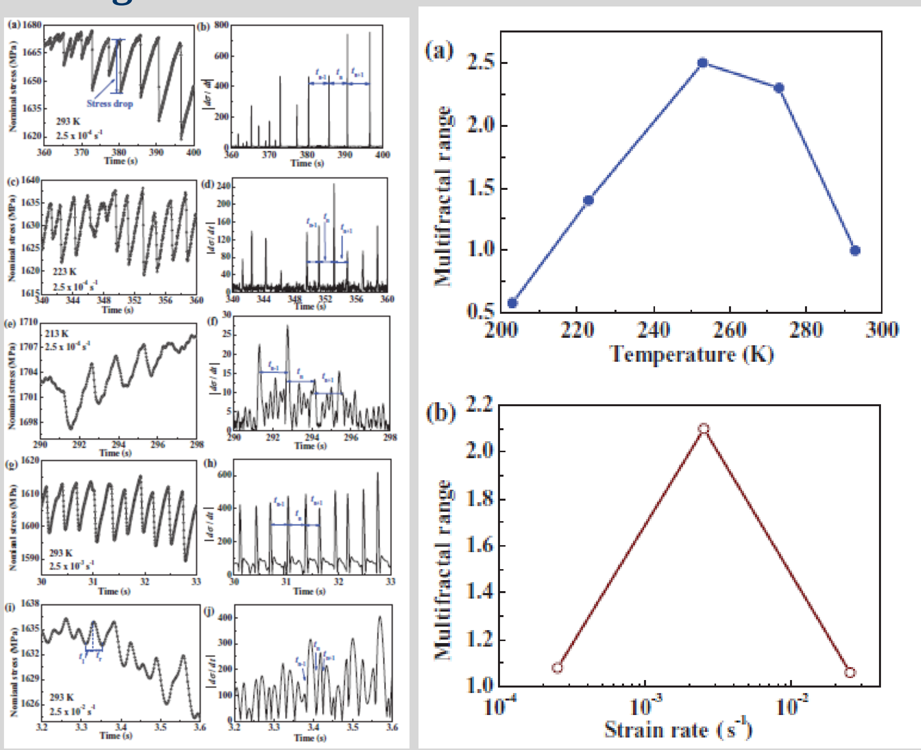
[Acta Materialia **57,** 6146 (2009)]

Part I Intermittent plastic deformation

- Ductile: Self-organized critical behavior
- Brittle: Chaotic behavior
- Low rate: Self-organized critical behavior
- High rate: Chaotic behavior



Chaos ----- Self organized critical (SOC) behavior



Chaos ----- Multifractal ----- SOC

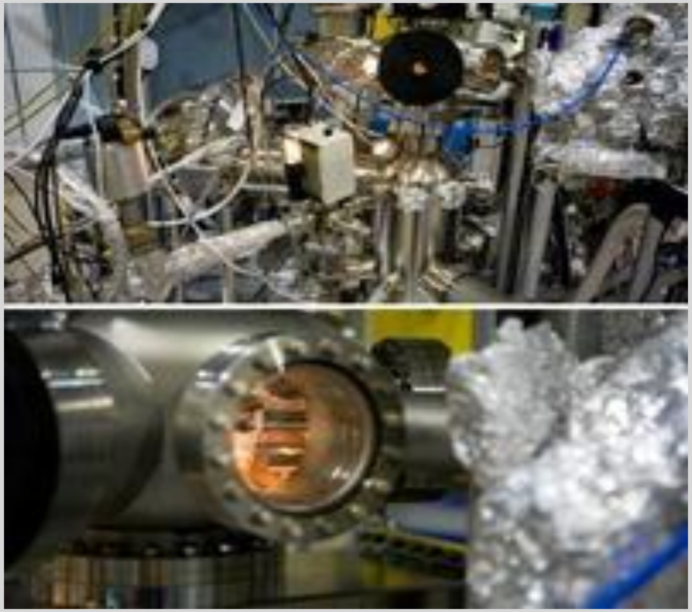
多重分形

Loading rate, temperature, chemical components

B.A. Sun et al. PRL **105,** 035501 (2010);
R. Sarmah et al. Acta Mater. **59,** 4482 (2011)

J.L. Ren, et al. Phys. Rev. B 86, 134303 (2012);
J.L. Ren, et al. J. Appl. Phys. 116, 033520 (2014);
J.L. Ren, et al. Phys. Rev. E 92, 012113 (2015)

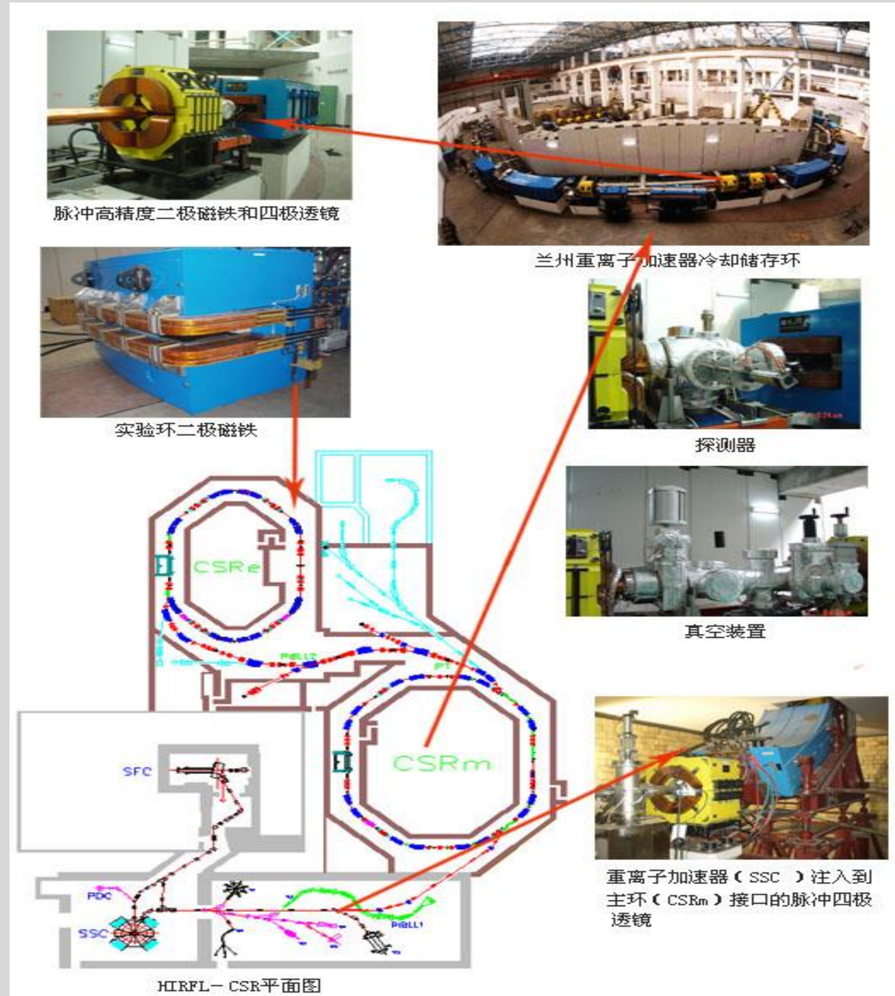
Part II Influences of structures on on intermittent plastic deformation



A terminal of 320 kV High-Voltage Experimental platform equipped with an electron cyclotron resonance ion source in Institute of Modern Physics, Lanzhou, China, providing a **7 MeV Xe^{26+} beam** for irradiation.

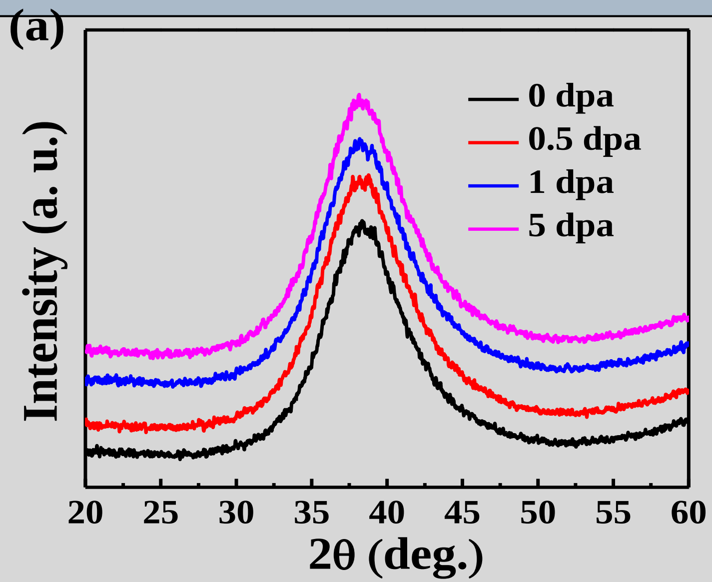
The incident flux was about 3.43×10^{14} ions/cm^{-2}s^{-1}.

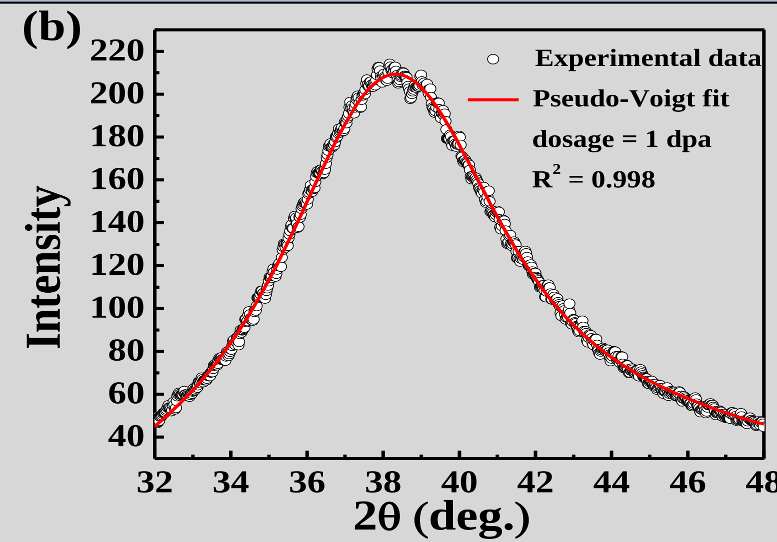
Base pressure lower than 5×10^{-5} Pa.



Heavy Ion Research Facility In Lanzhou (HIRFL)

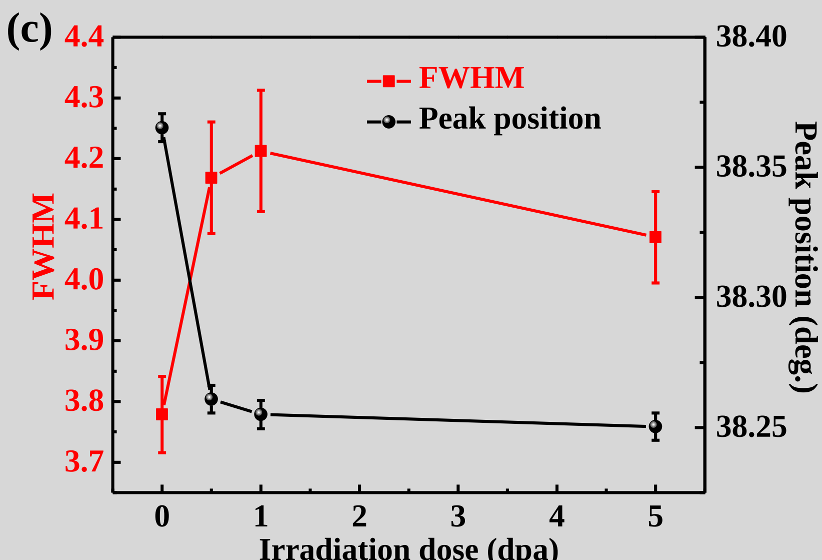
Part II Influences of structures on on intermittent plastic deformation





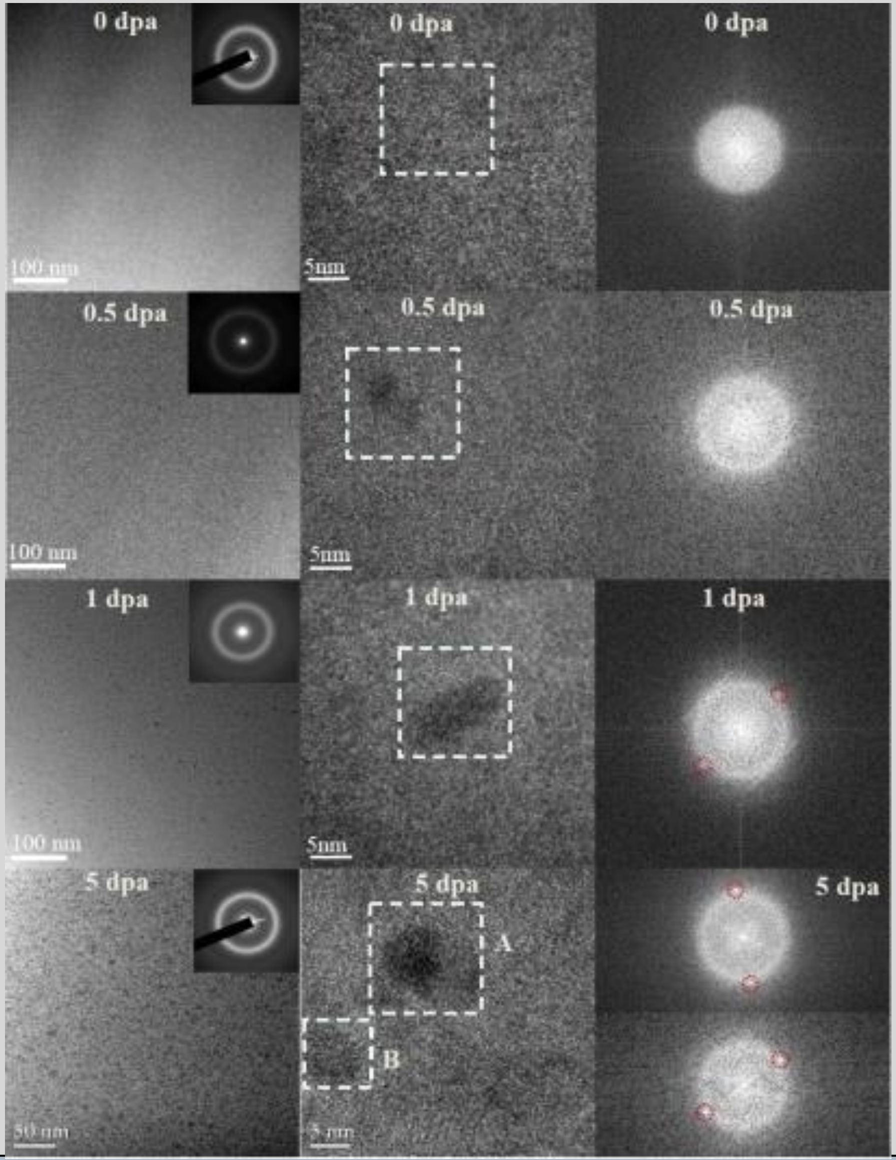
- Degree of ordering decreases
- Expansion in the interatomic distance

$Zr_{50.7}Cu_{28}Ni_9Al_{12.3}$



dpa (displacement per atom) is defined as the average number of displacements per atom per unit volume per unit time for a given irradiation dosage

Part II Influences of structures on on intermittent plastic deformation



Fully amorphous（0 dpa）

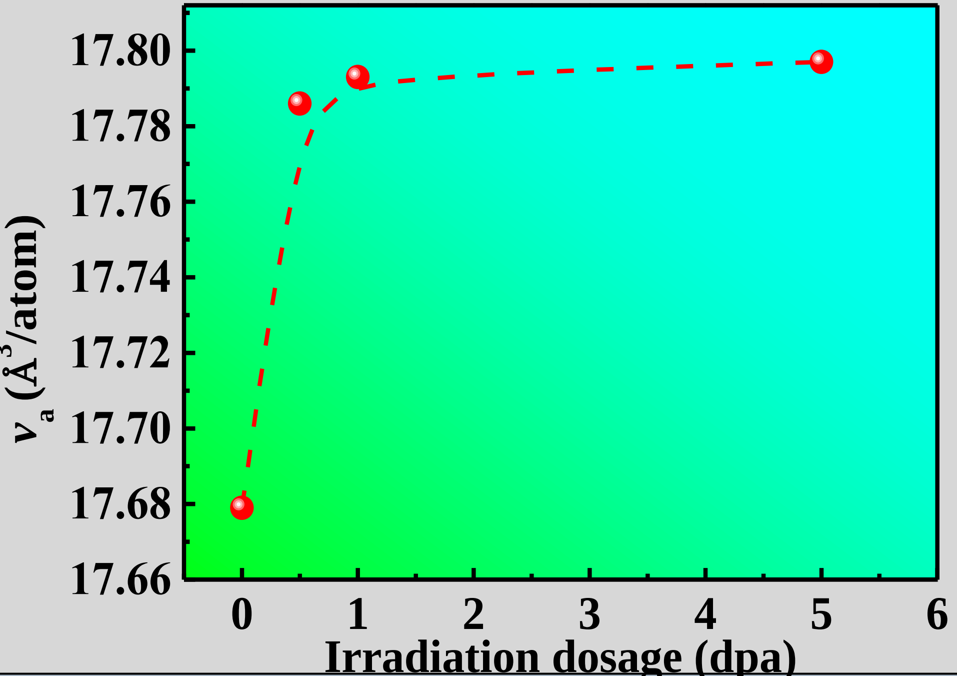
Some changes（0.5 dpa）

Nanocrystals（1 dpa）

Crystalline phase（5 dpa）

Part II Influences of structures on on intermittent plastic deformation

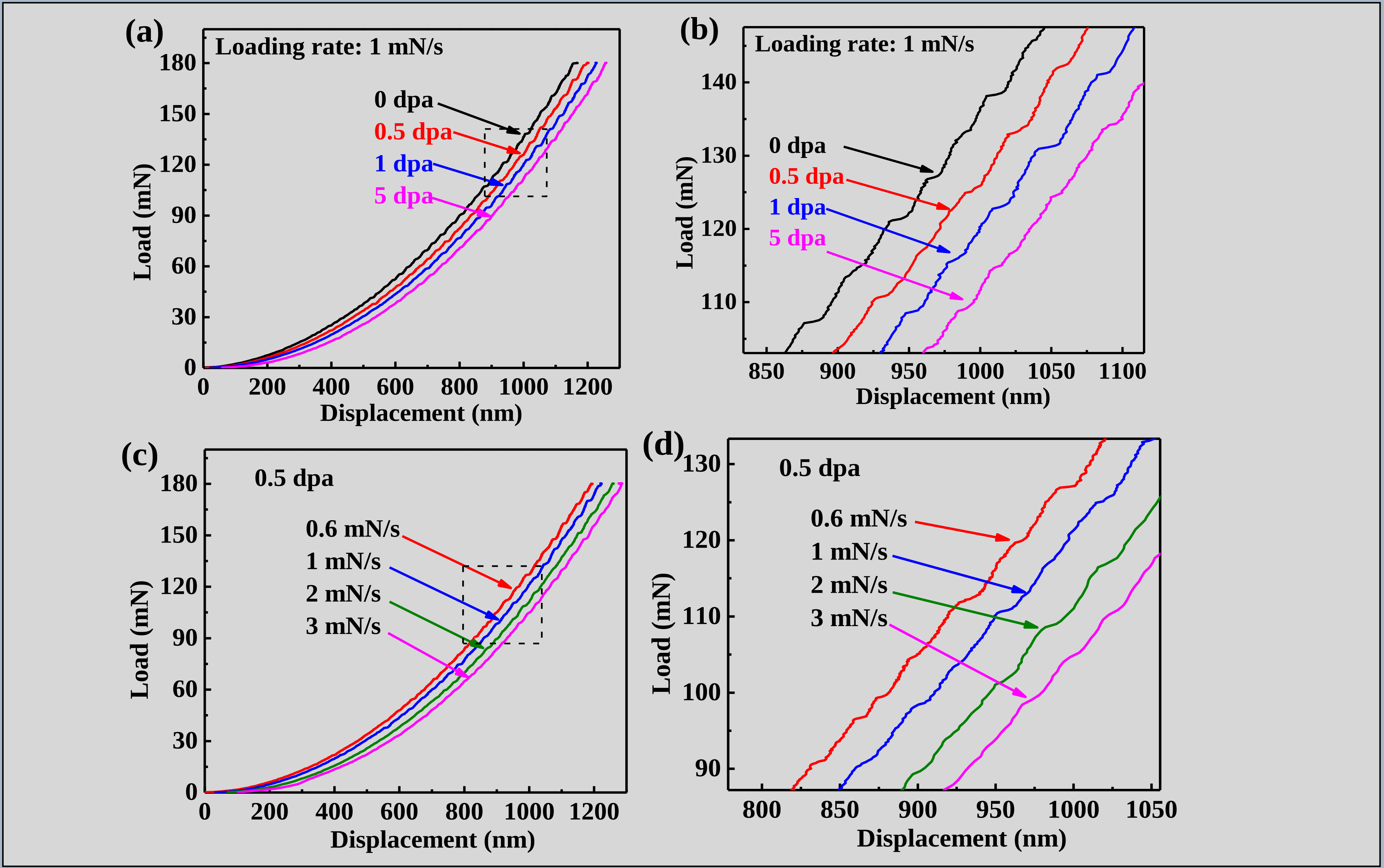
Dosage (dpa)	Peak position (°)	FWHM	H (GPa)
0	38.365 ± 0.005	3.779 ± 0.063	6.353
0.5	36.261 ± 0.005	4.168 ± 0.092	6.211
1	38.255 ± 0.005	4.213 ± 0.100	6.105
5	38.250 ± 0.005	4.070 ± 0.075	6.202



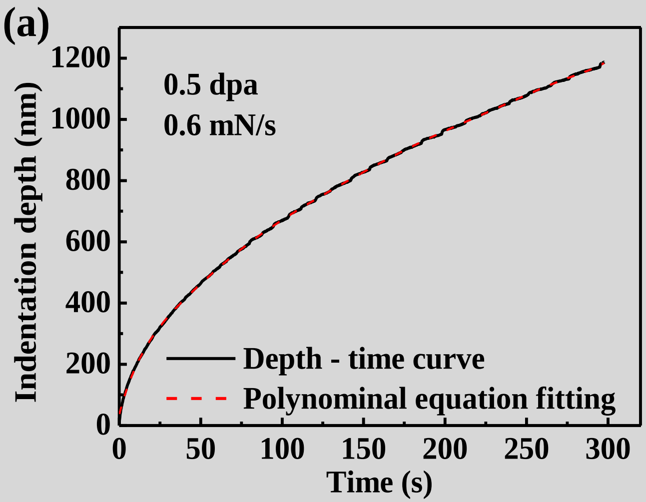
$$q \cdot v_a^{0.433} = 9.3$$

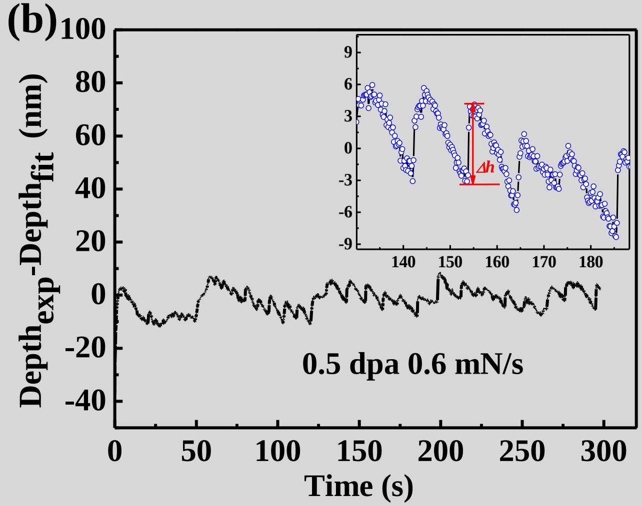
Irradiation causes Dilatation

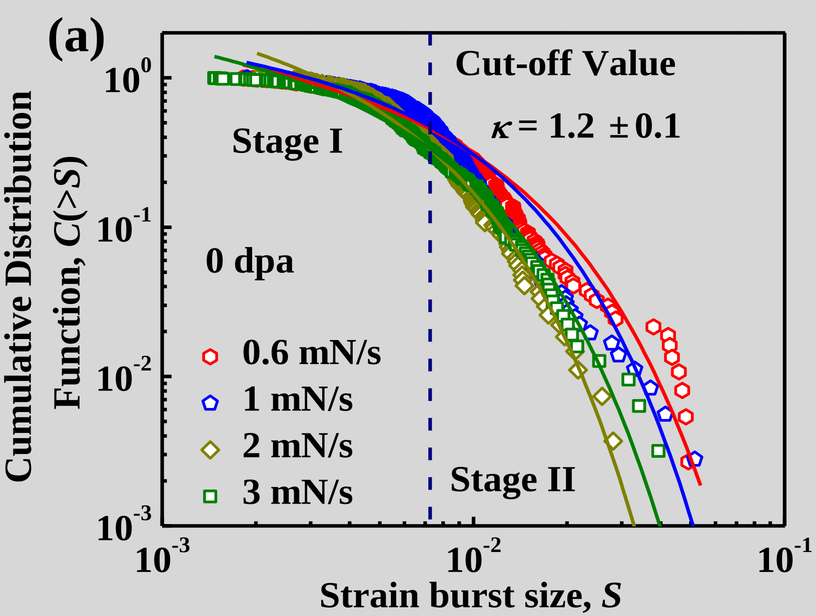
Part II Influences of structures on on intermittent plastic deformation

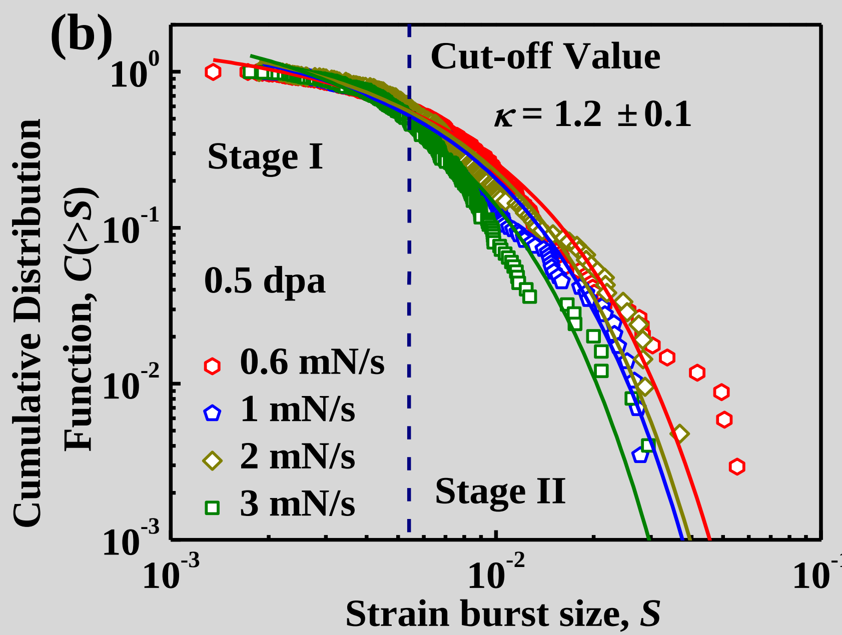


Part II Influences of structures on on intermittent plastic deformation

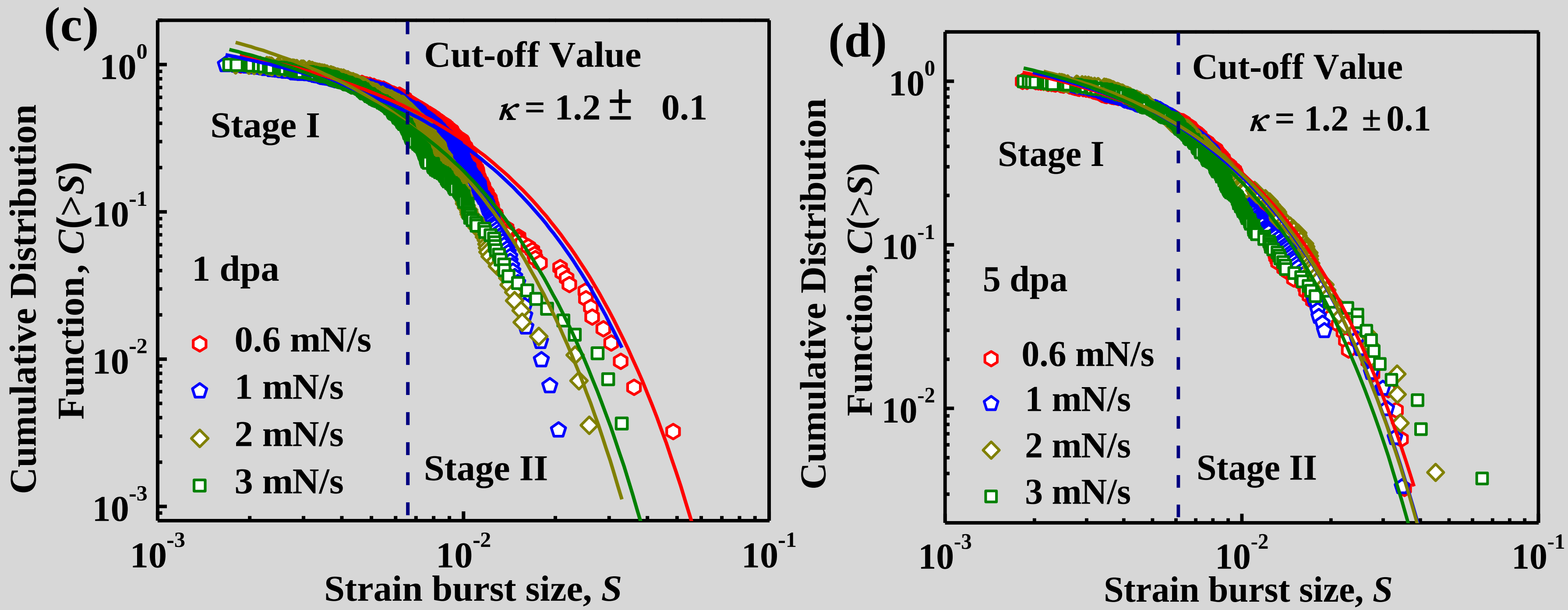








Part II Influences of structures on on intermittent plastic deformation



$$C(S) \sim S^{-(\kappa-1)} F(S/S_C)$$

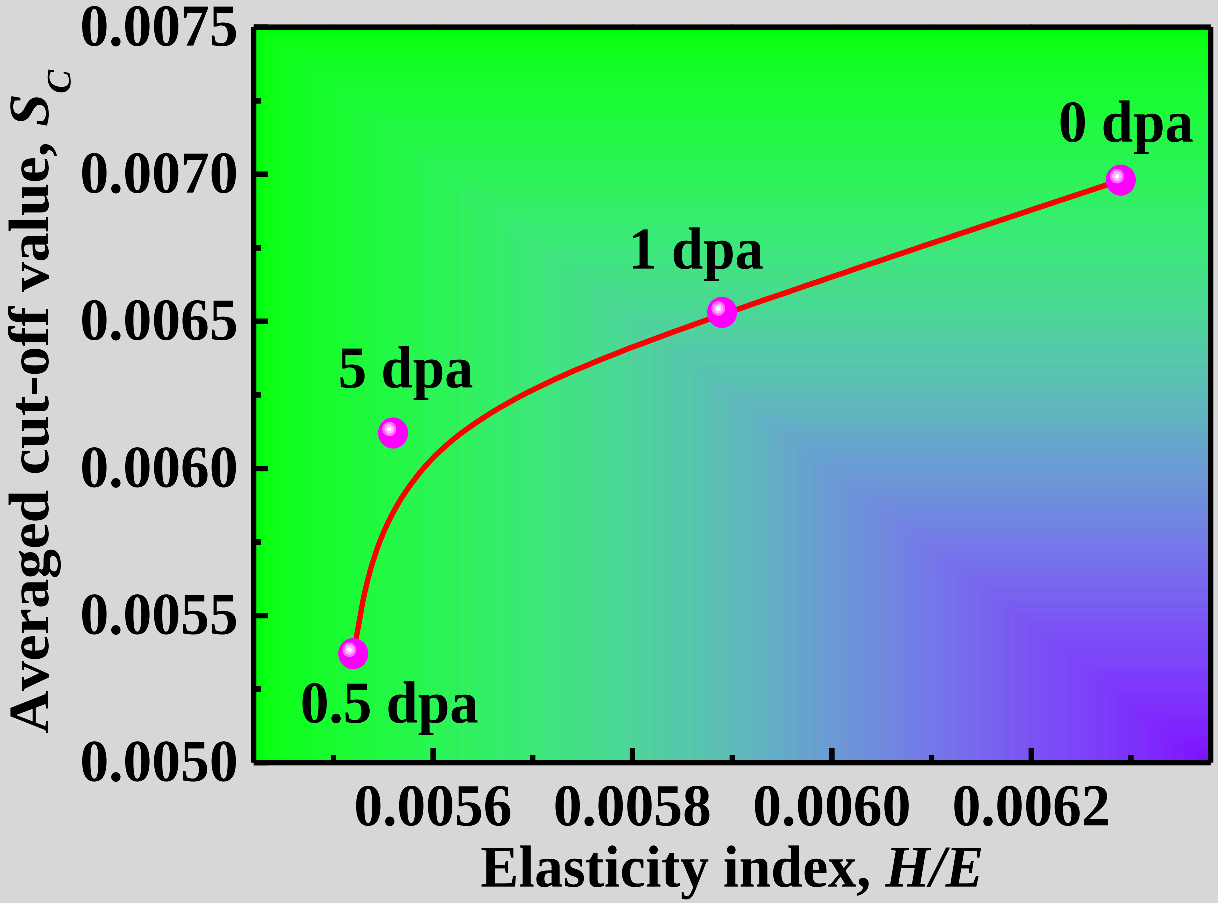
$F(S/S_C)$ [= exp(-(S/S_C))]: a quickly decaying scaling function

κ: a scaling exponent (κ = 1.5 in the mean field theory)

S_C: the size of the largest typical "critical" avalanche that acts as a cut-off in $F(S/S_C)$, and decays exponentially to leading order for large S/S_C >> 1.

Mean-field theory: 把一些单个的涨落现象，平均于周围环境中。

Part II Influences of structures on on intermittent plastic deformation



Elastic index: The energy for supporting the shear slip of flow units

Part II Influences of structures on on intermittent plastic deformation

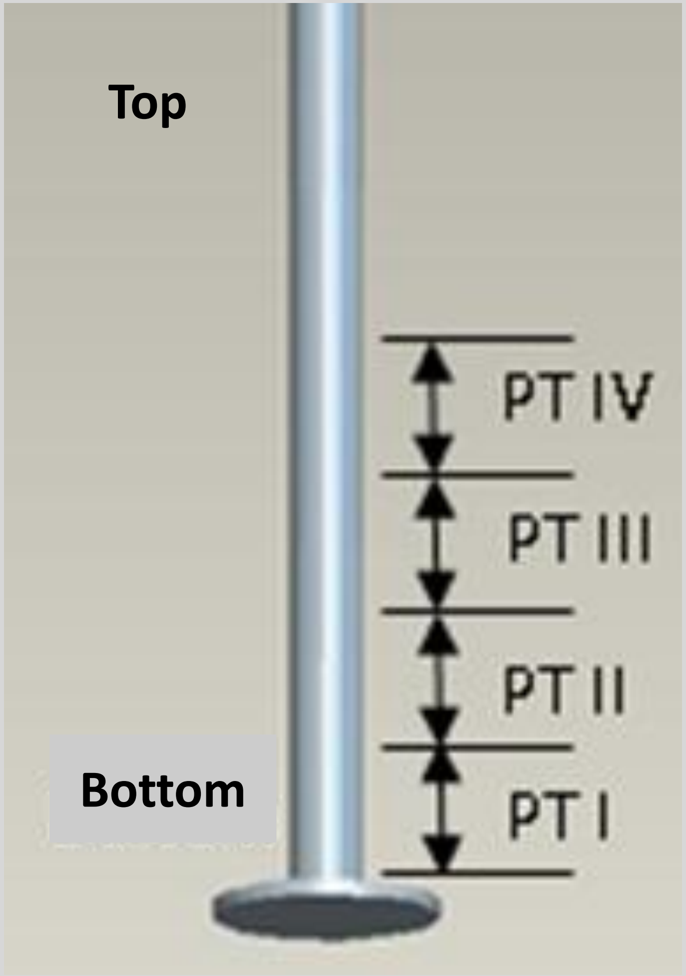
$Cu_{50}Zr_{45}Ti_5$

Low glass forming ability

Arc-melting

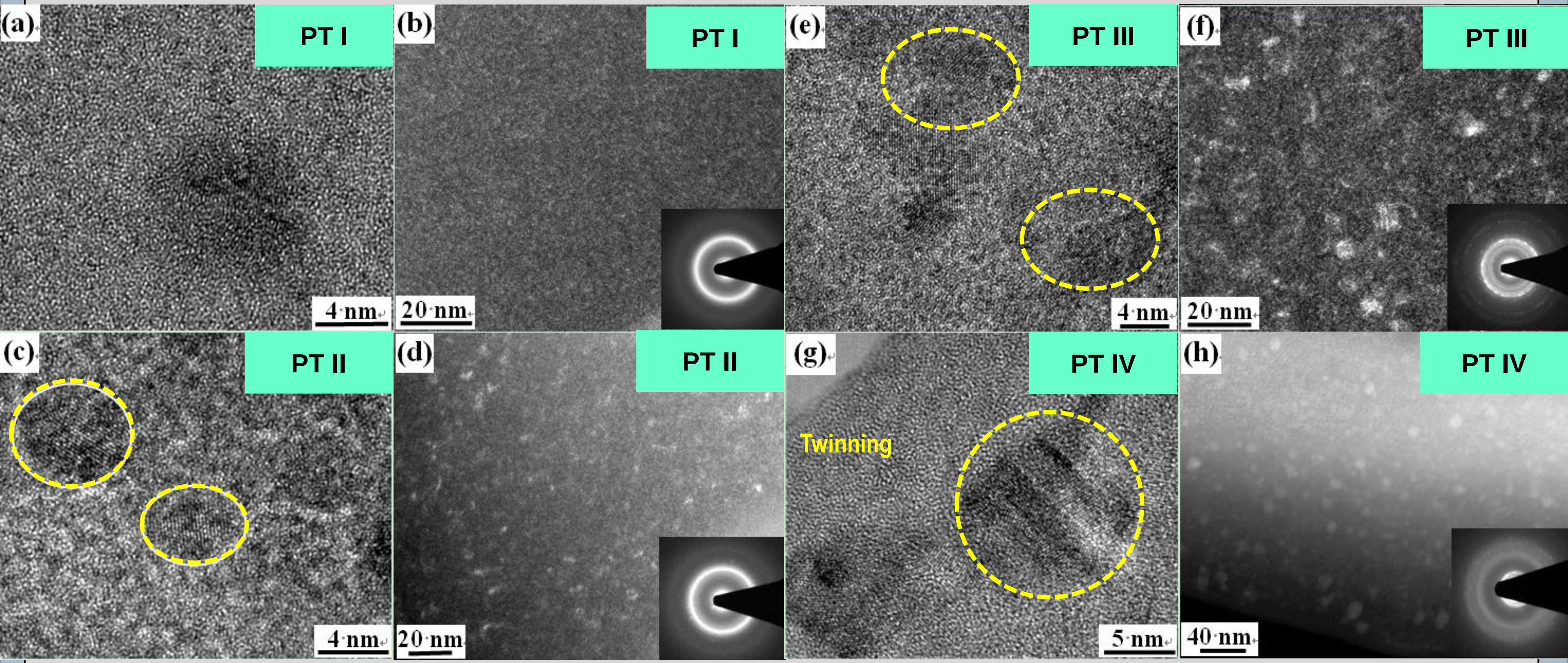
Titanium-gettered argon

Suction casting



A rod-like sample

Part II Influences of structures on on intermittent plastic deformation



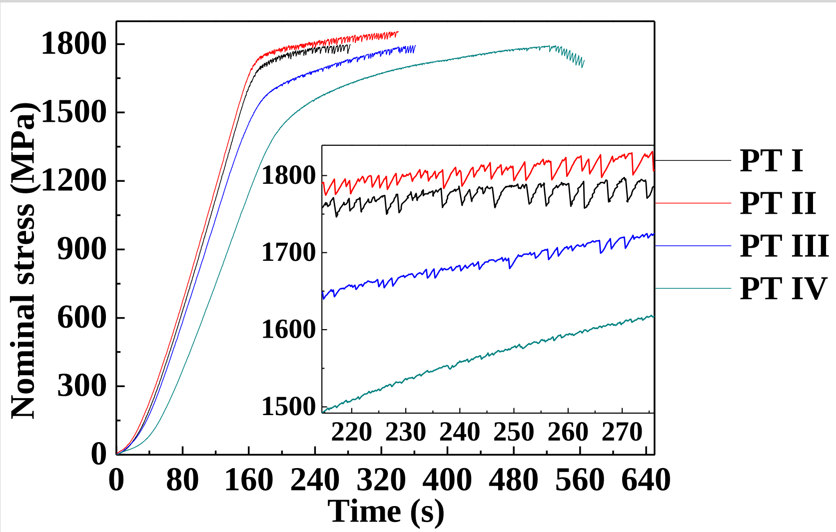
PT I: Homogeneous contrast; Monolithic amorphous; Two diffraction halos

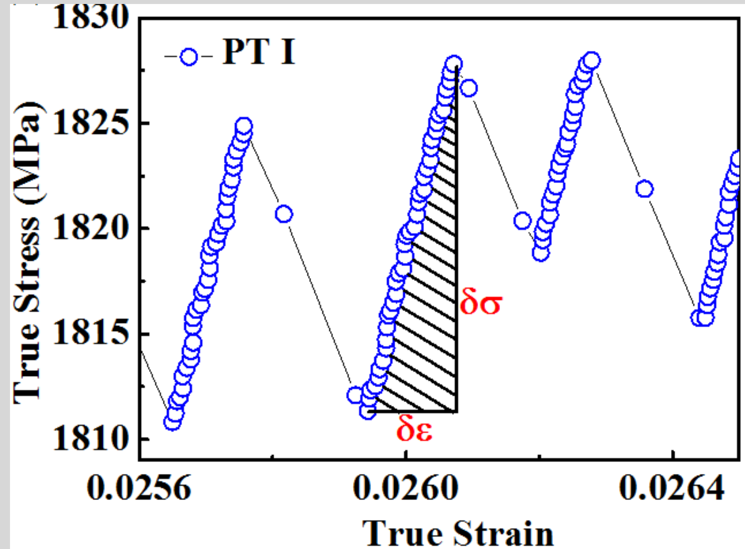
PT II: Small nanocrystals; White spots

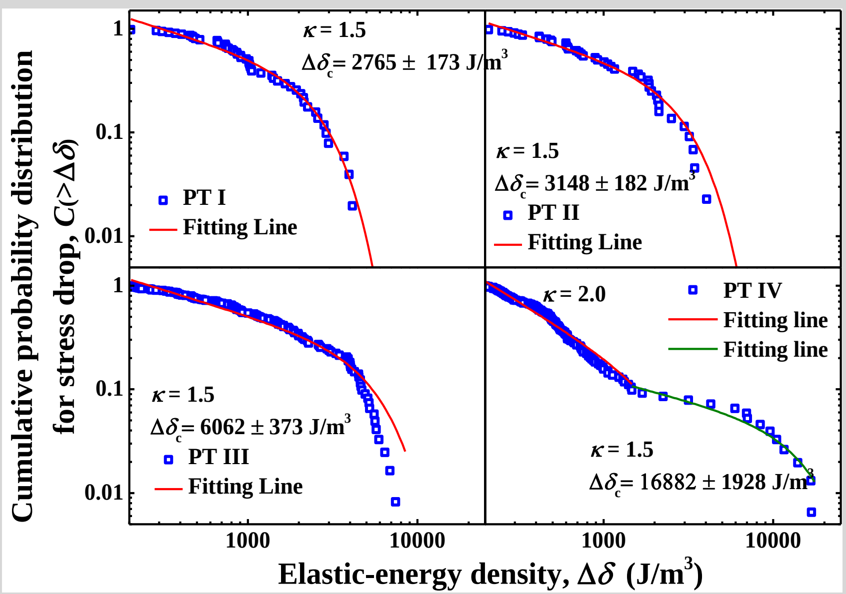
PT III: Large nanocrystals; A larger size and volume fraction than PT II

PT IV: Twinning nanocrystals

Part II Influences of structures on on intermittent plastic deformation



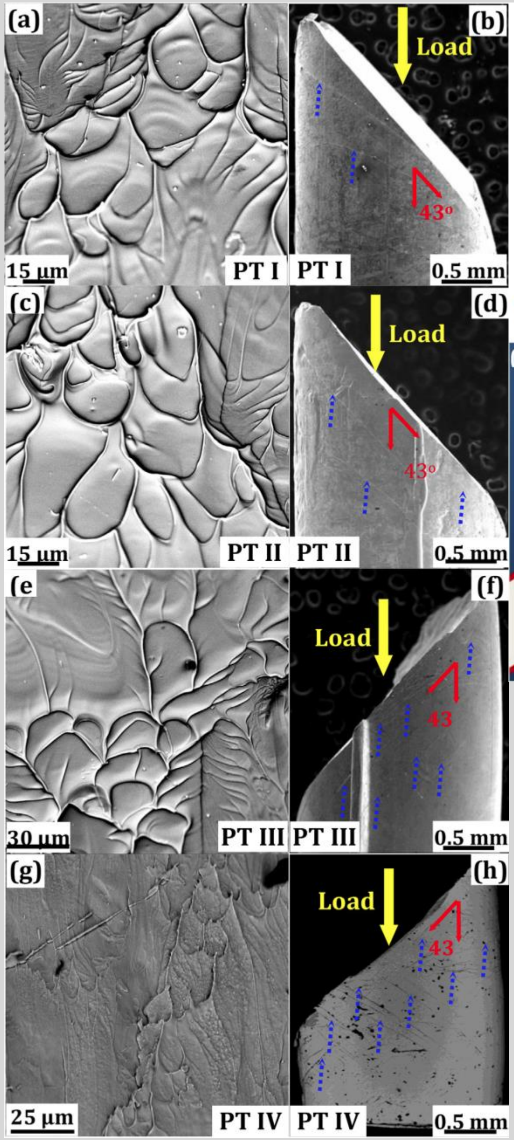


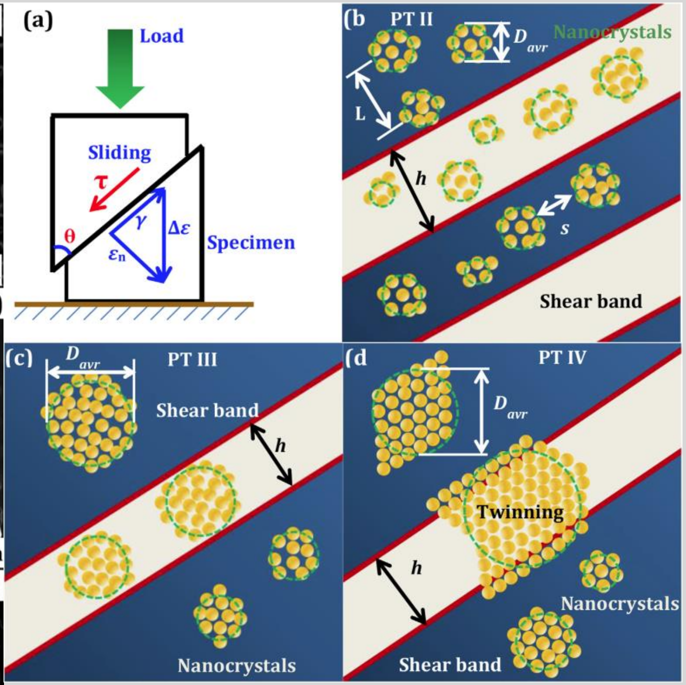


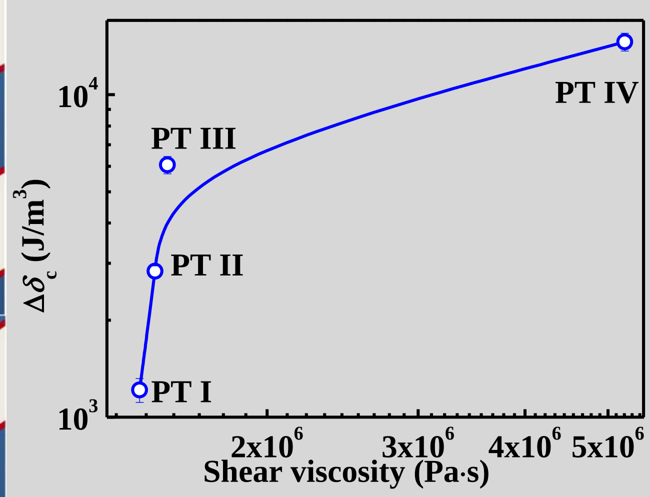
$$P(\geqslant \Delta\delta) = A\Delta\delta^{-\beta}\exp[-(\Delta\delta/\delta_C)^2]$$

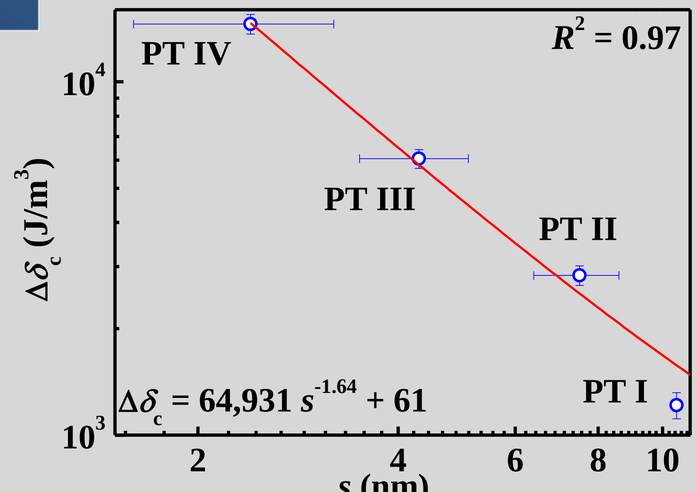
$\Delta\delta_C$: critical size for large shear avalanche

Part II Influences of structures on on intermittent plastic deformation

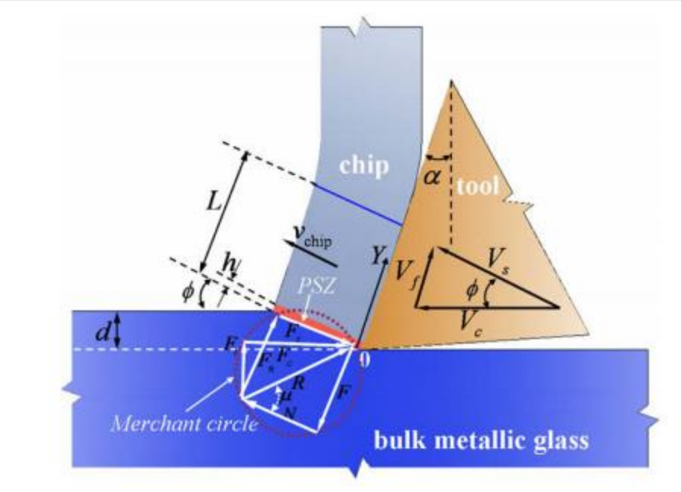


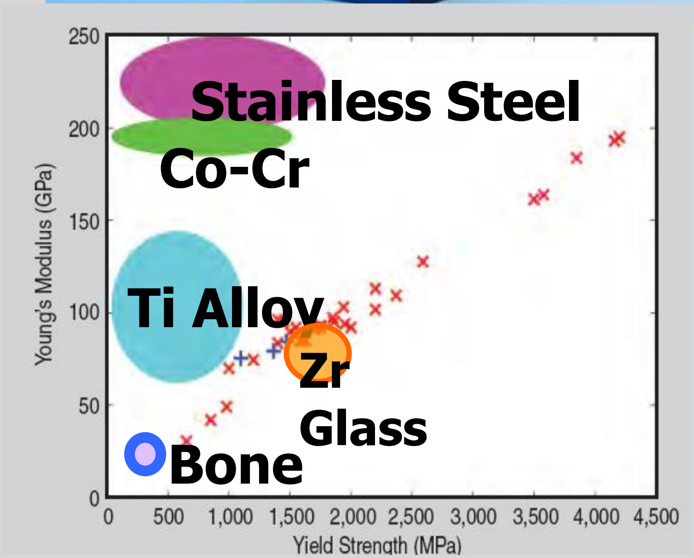






Part III Stick-slip behavior in nanoscratch



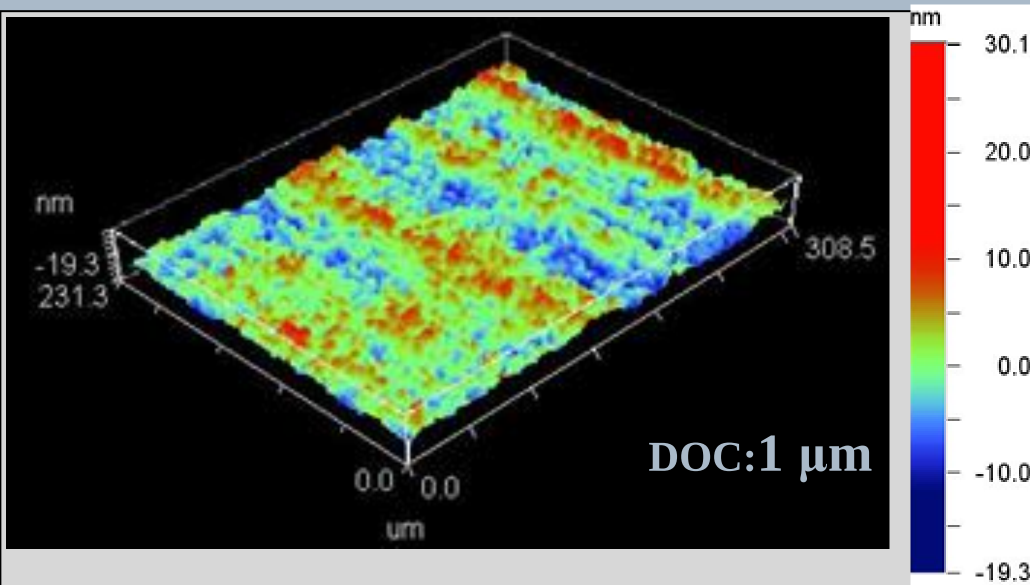


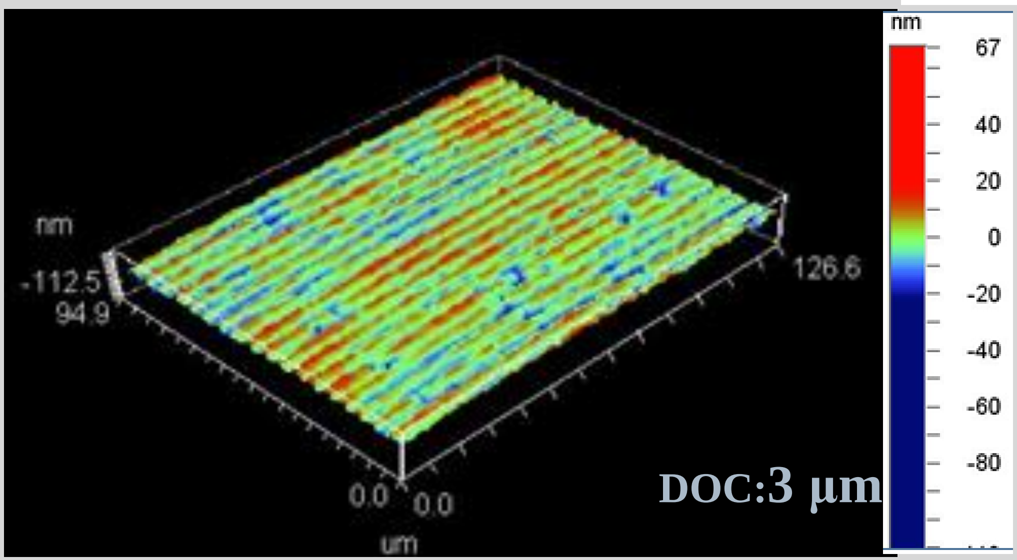
M.D. Demetriou. JOM 62(2) 83 (2012)

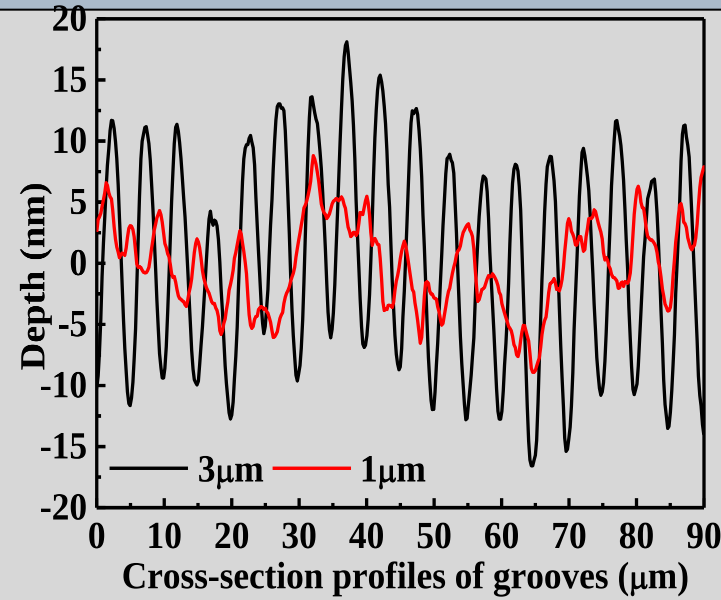
- Good glass forming ability
- High yielding strength [(1660±20) MPa]
- Low elastic modulus (80-90 GPa)
- High toughness (53 $MPa.m^{1/2}$)
- Small density (5.9 g/cm^3)
  - Most important
- Without Fe element

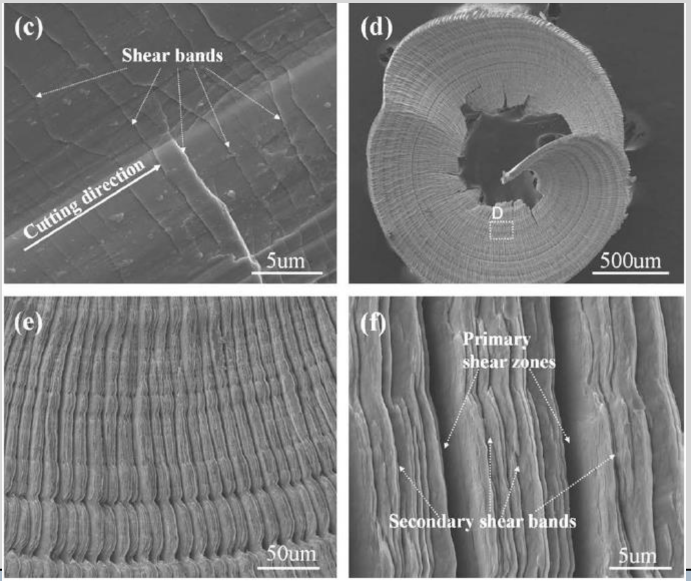
L.H. Dai, et al. Acta Mater. 2009

Part III Stick-slip behavior in nanoscratch



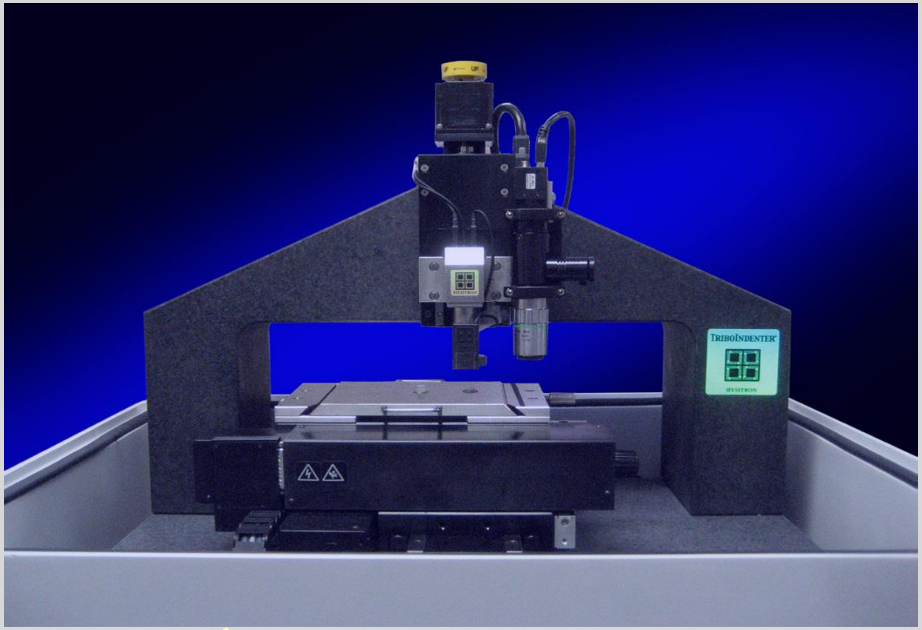






L.H. Dai, et al. Acta Mater. 2009

Part III Stick-slip behavior in nanoscratch



TI-900

Nanoindenion:

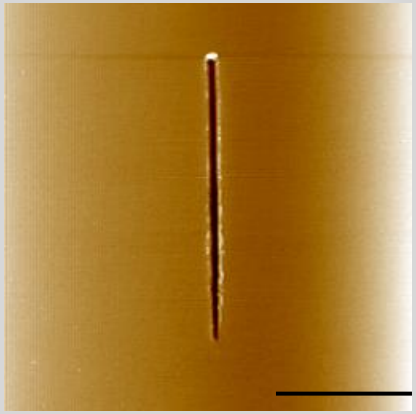
load resolution: 1nN

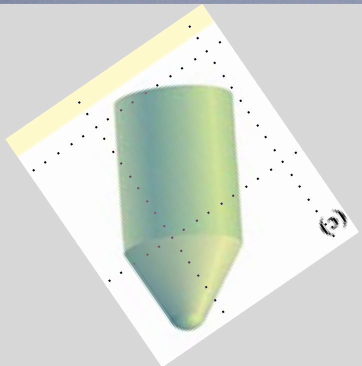
displacement resolution: 0.006 nm

Nanoscratch:

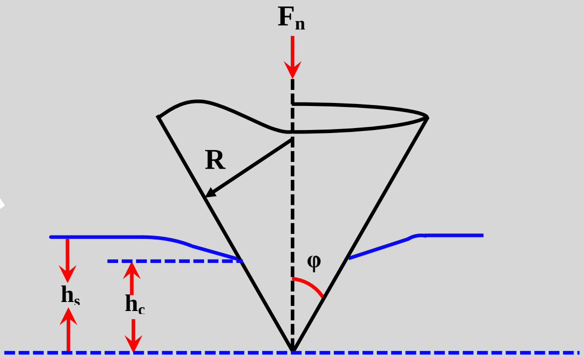
load t resolution: 50 nN

displacement resolution: 0.02nm



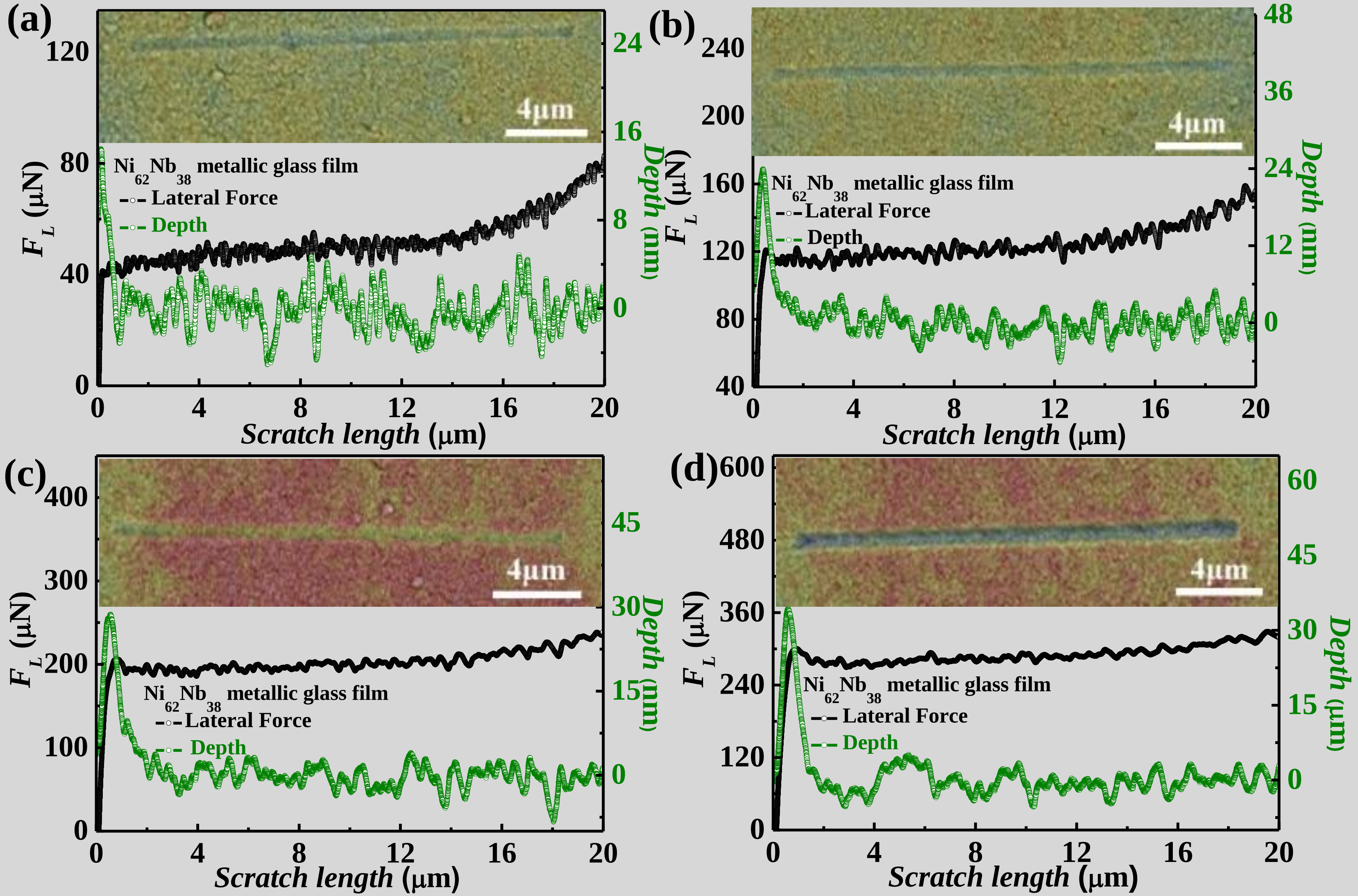


conical indentor

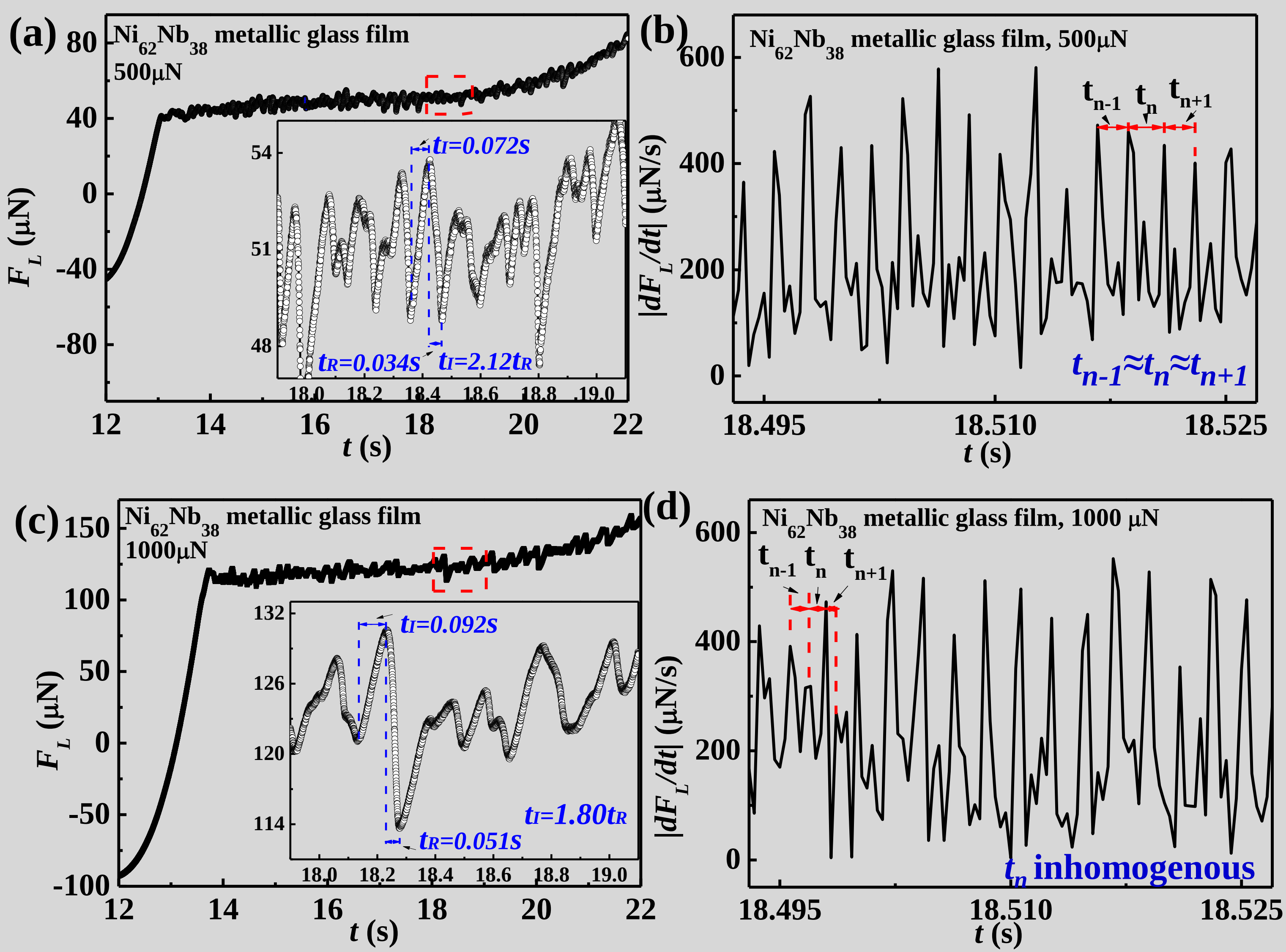


the scratch length was 20 μm,
the moving speed of the nanoindenter was 2 μm/s.

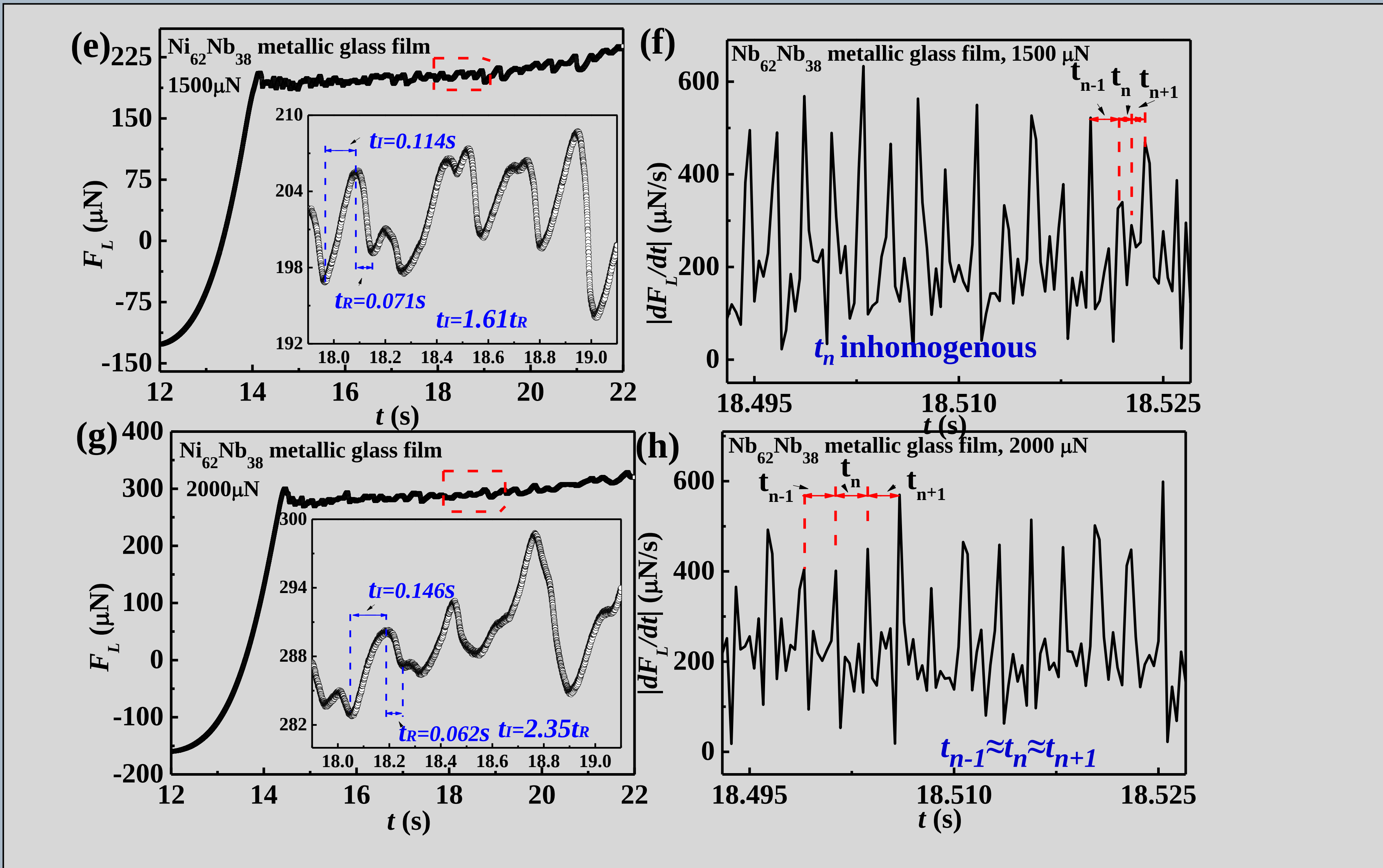
Part III Stick-slip behavior in nanoscratch



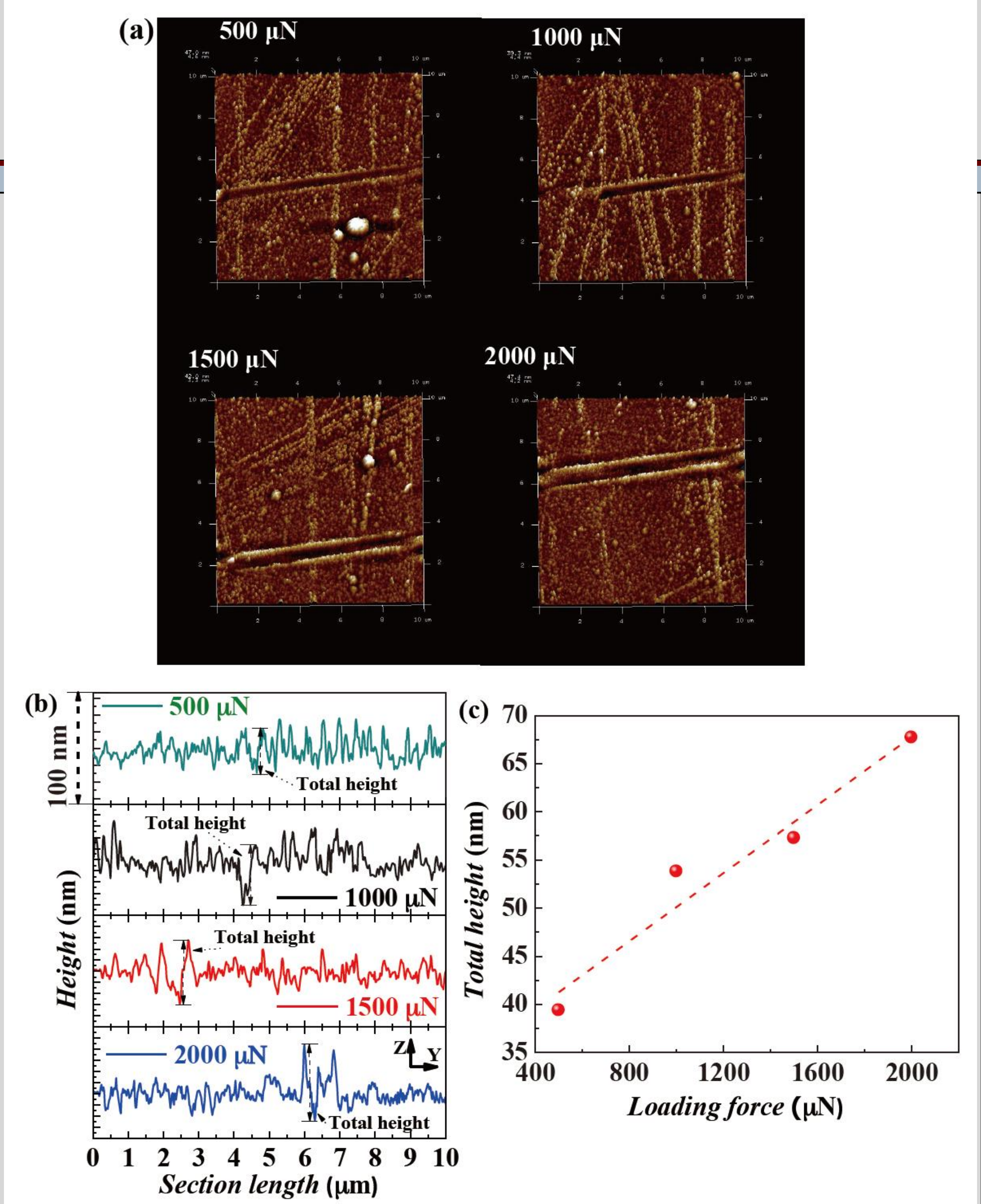
Part III Stick-slip behavior in nanoscratch



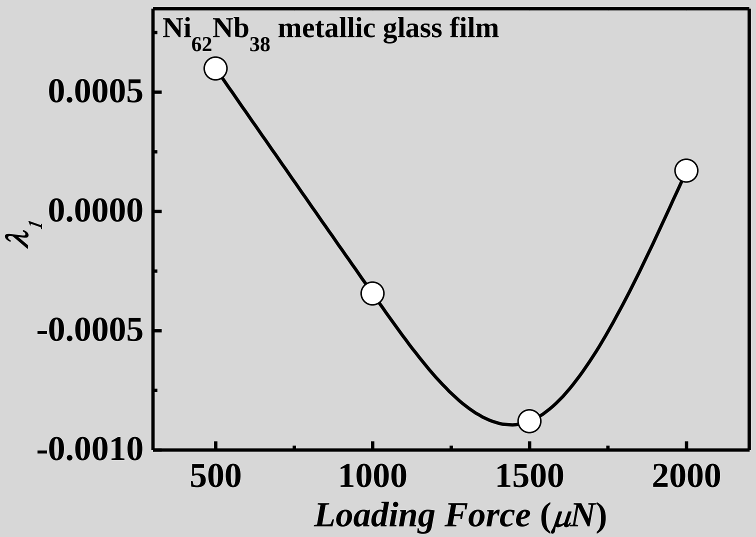
Part III Stick-slip behavior in nanoscratch



500 μN: without pile-up



Part III Stick-slip behavior in nanoscratch



λ <0, the phase-space adjacent track is convergent
λ >0, the phase-space adjacent track is diverging

Lyapunov exponent

Loading Force (μN)	*500*	*1000*	*1500*	*2000*
$t_I(s)$	**0.068**	**0.050**	**0.078**	**0.211**
$t_R(s)$	**0.028**	**0.028**	**0.420**	**0.099**
R	**2.403**	**1.799**	**1.850**	**2.135**

$t_I(s)$: lateral force accumulation time
$t_R(s)$: lateral force relaxation time

Part III Stick-slip behavior in nanoscratch

⌧ Plastic dynamics analysis (Load-time sequence analysis)

The Lyapunov exponent in a dynamical system is a quantity that characterizes the rate of separation of infinitesimally close trajectories.

Method: Phase space reconstructoion

[D.A. Egolf, Nature Phys. 9, 288 (2013).]

Features of SOC behavior

- **Negative largest Lyapunov exponent means that the stress –time sequence evolution is convergent.**
- **Stable state**

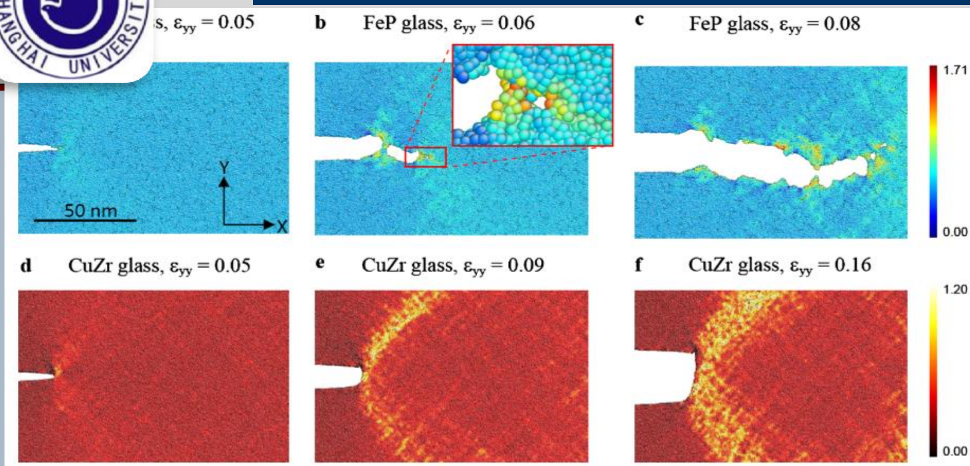
Features of chaotic behavior

- **Positive largest Lyapunov exponent means that the stress- time sequence evolves separately.**

[J.L. Ren and G. Wang, et al .Phys. Rev. B. 86, 134303 (2012)]

[Z.Y. Liu and G. Wang et al. J. Applied Physics. 114, 033521 (2013)]

Part IV Discontinuous crack propagation



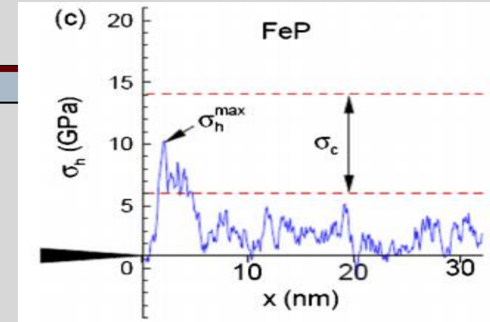
Brittle:

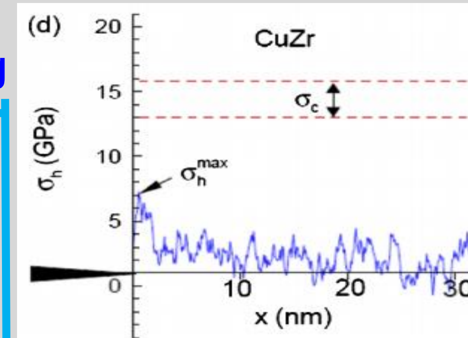
Cavitation, Nanoscale void nucleation and coalescence

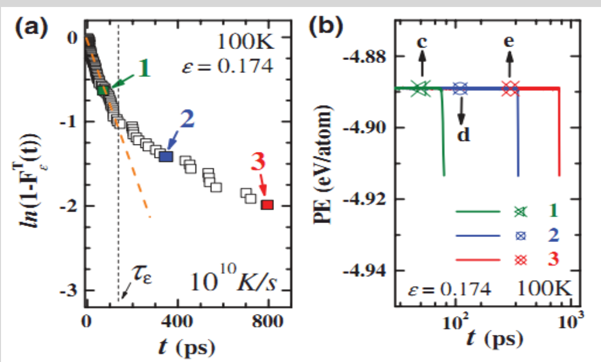
Nanoscale density fluctuations, high free volume.

Ductile:

Extensive shear banding





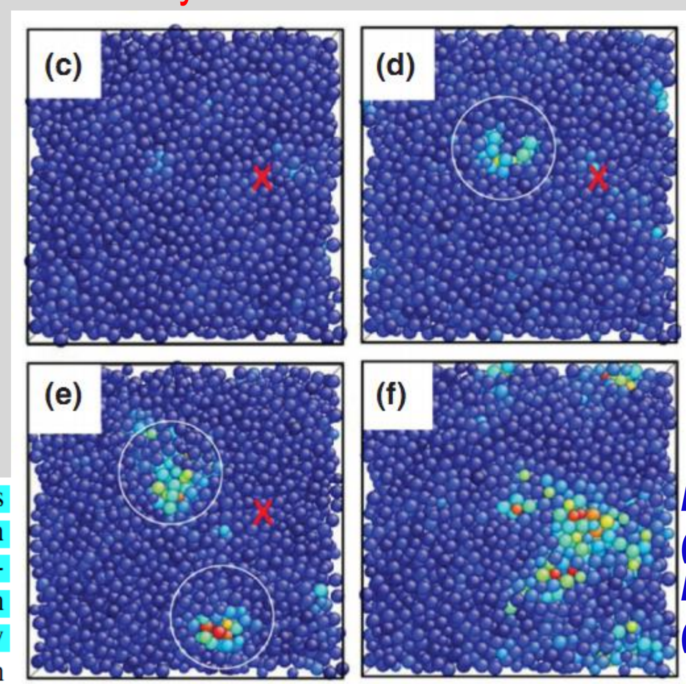


Free energy barrier to cavitation

$$\Delta F_c = \frac{4}{3}\pi r_c^3 K(\varepsilon - \varepsilon_c) - 4\pi\gamma r_c^2.$$

nucleation event. We conclude that cavitation in MG is controlled by the spatial heterogeneity in the glass with preferential nucleation sites able to cavitate by surmounting a free energy barrier that is significantly lower than would be expected in the absence of the effect of cavity radius on surface energy. The relatively smaller activation

Sudden decrease of PE: cavity nucleation event

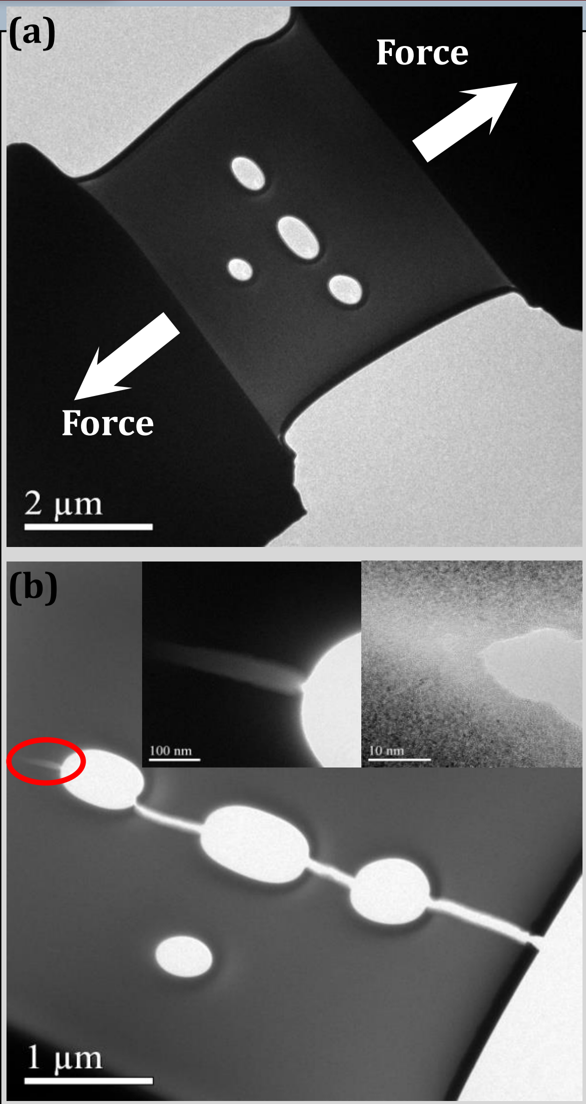


High strain regions

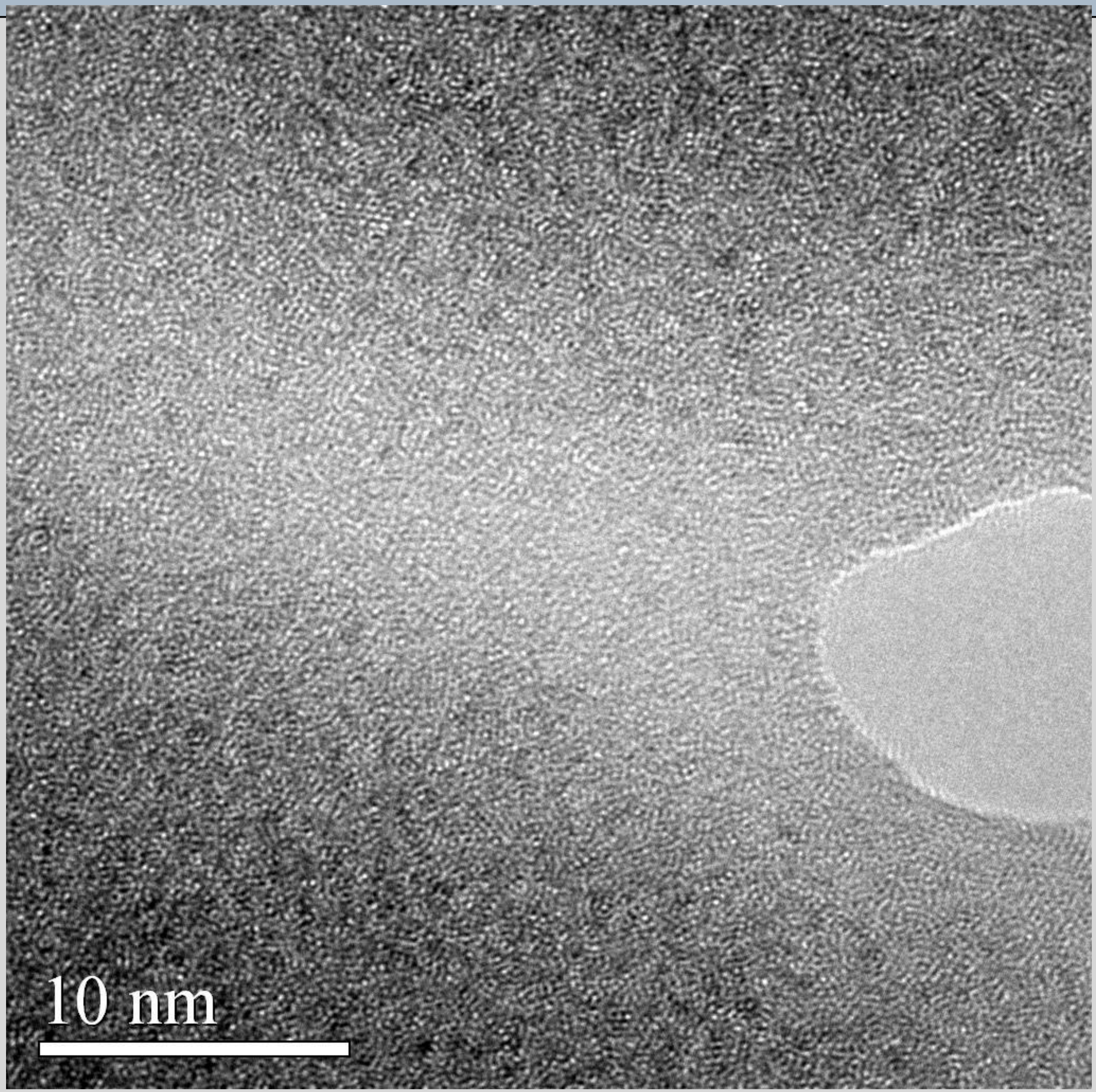
Phys. Rev. Lett. 107, 215501 (2011)

Phys. Rev. Lett. 110, 185502 (2013)

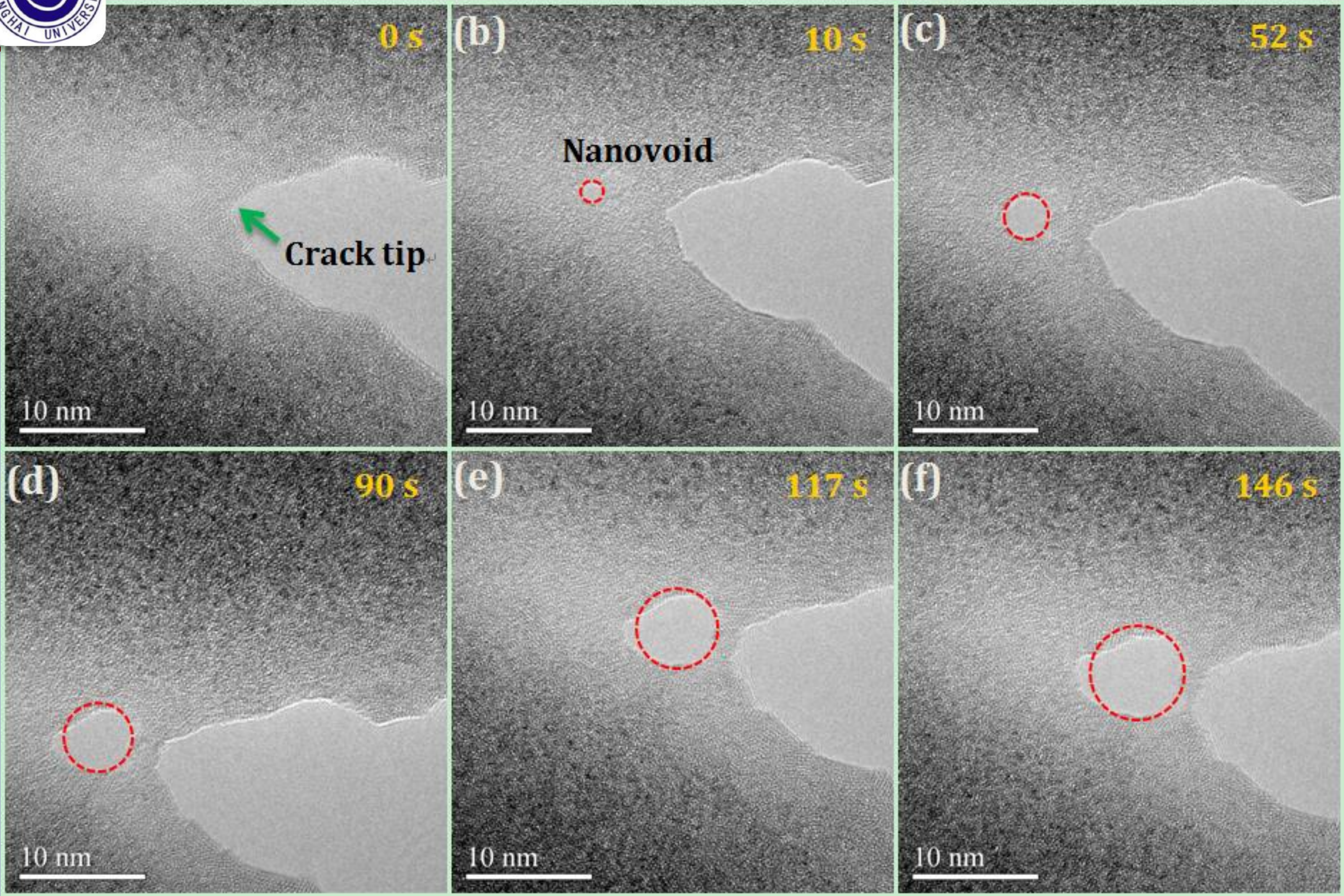
Part IV Discontinuous crack propagation



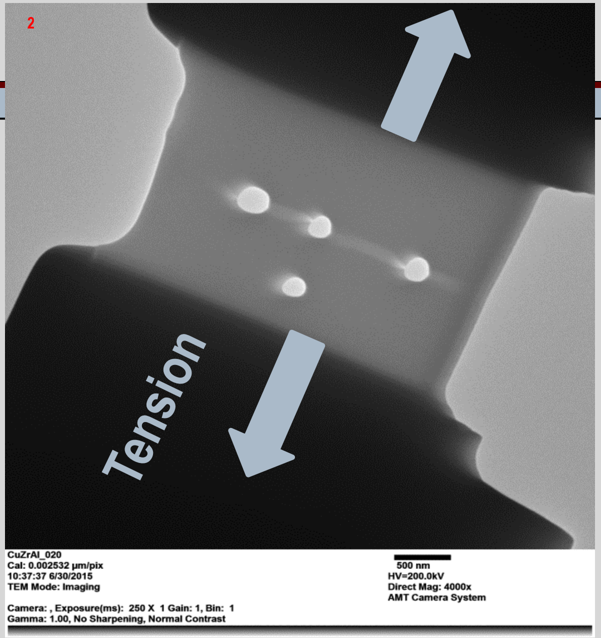
$Cu_{47.5}Zr_{47.5}Al_5$

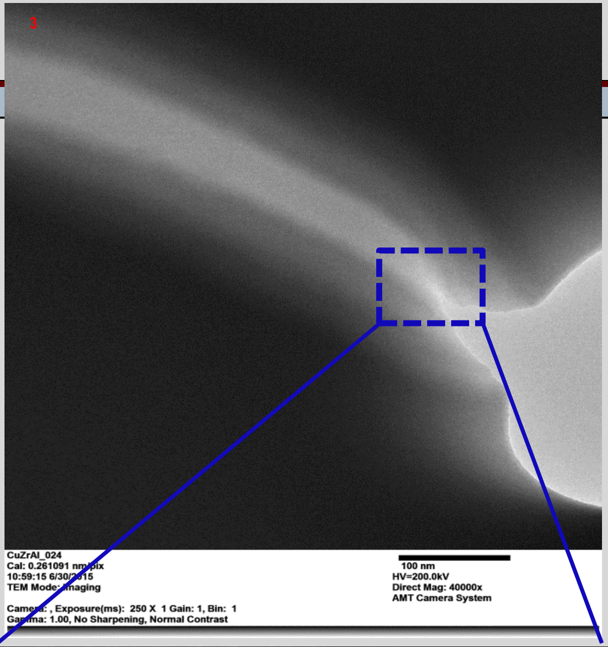


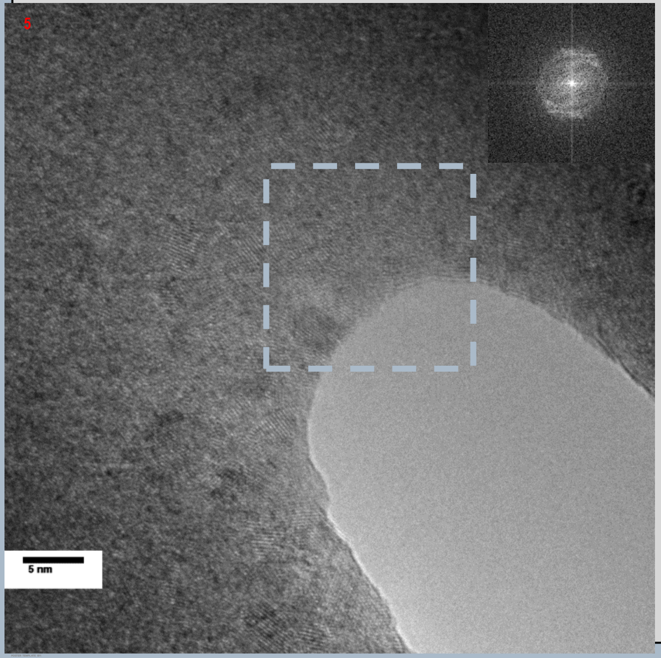
Part IV Discontinuous crack propagation



In-situ TEM tension tests (E-beam irradiation)

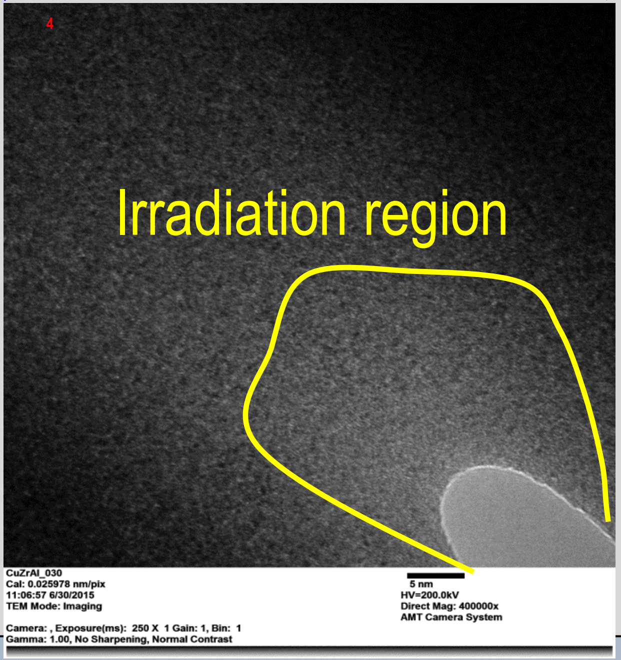


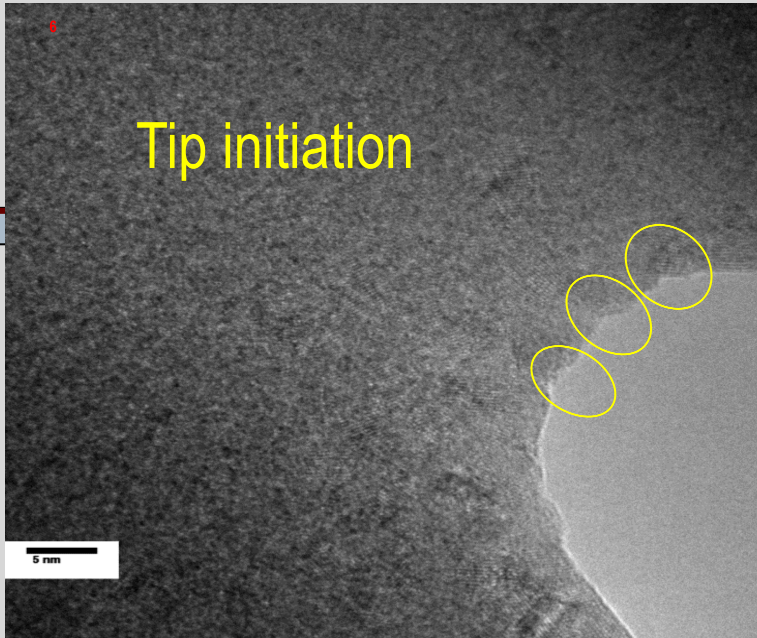


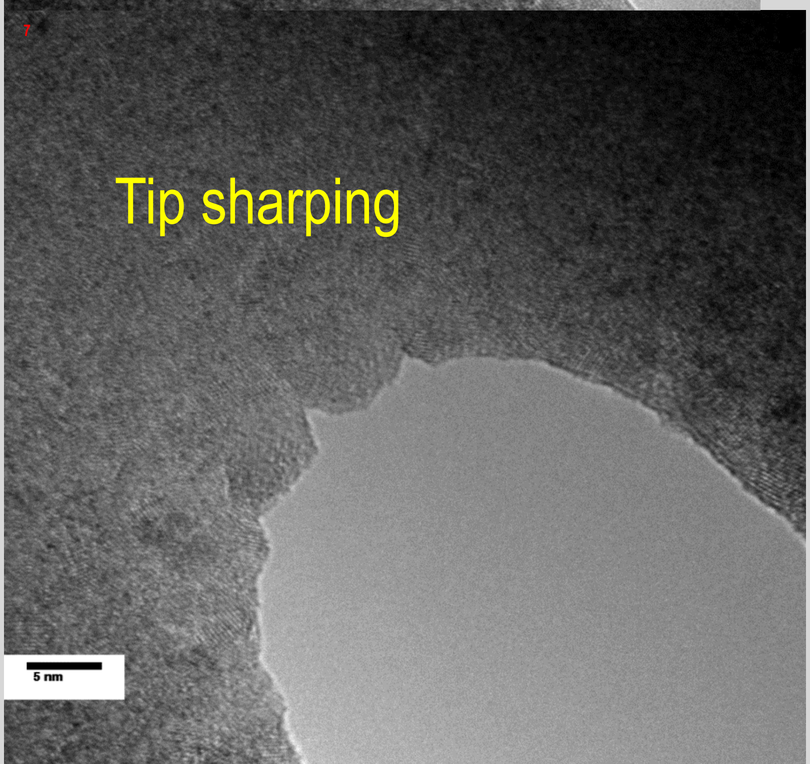


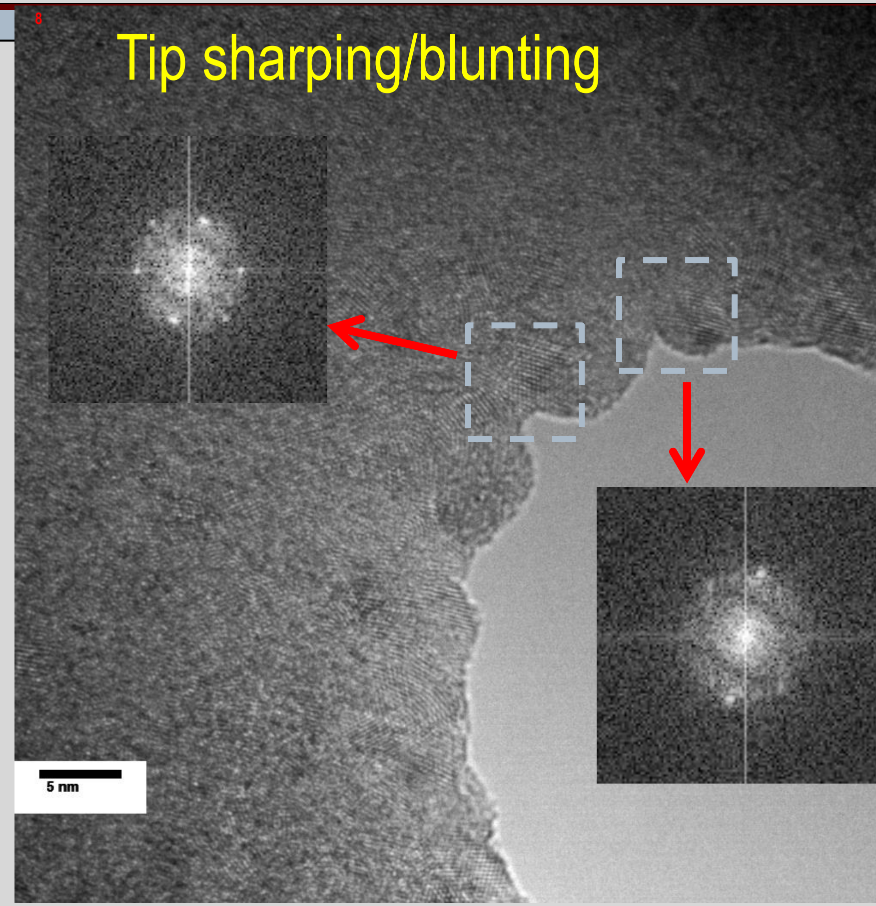
Beam current: 20-30 pA/cm²

Irradiation time: 30 min

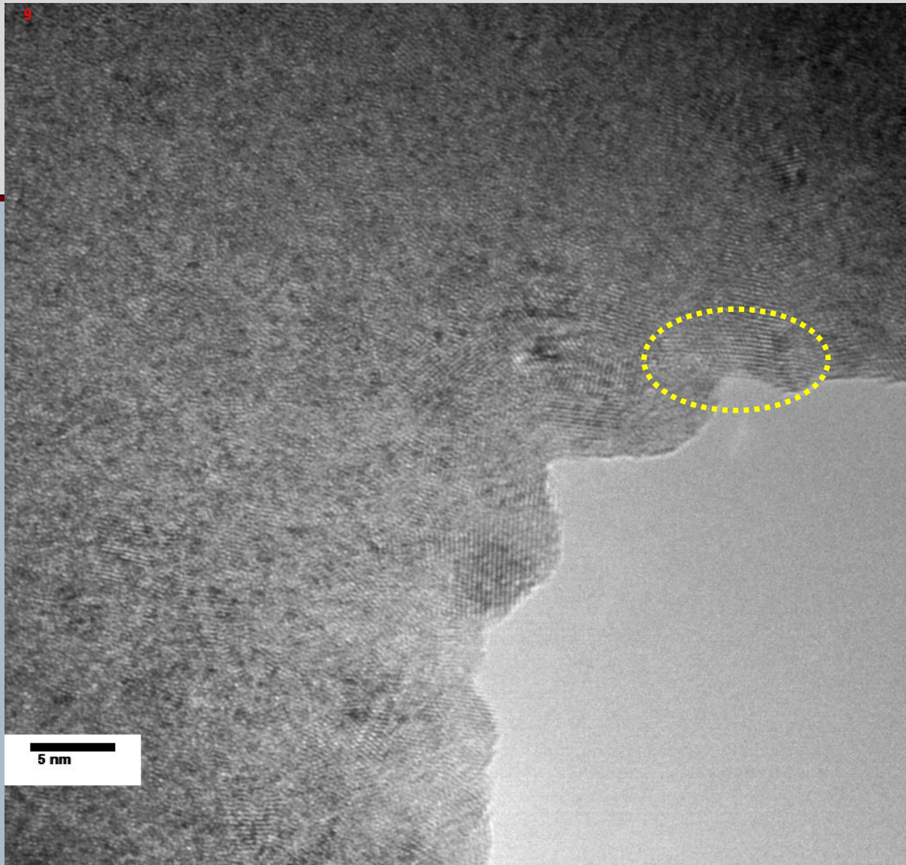



Tip initiation
5 nm


Tip sharping
5 nm

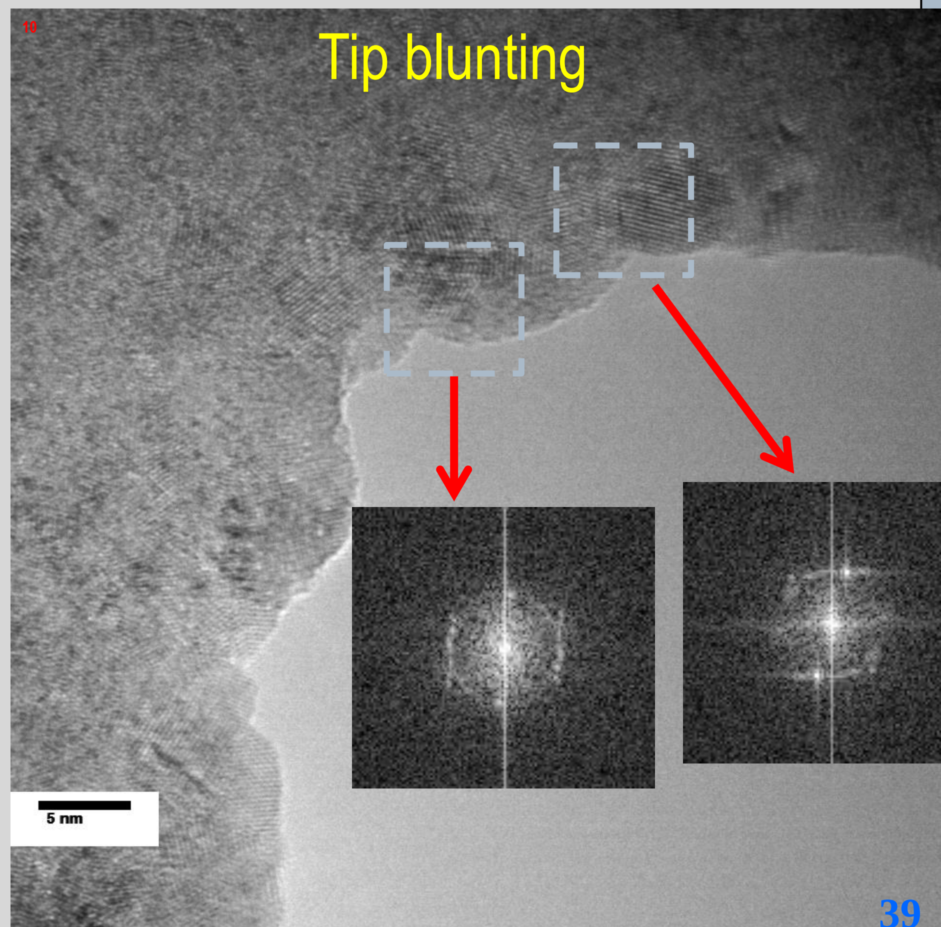

Tip sharping/blunting
5 nm

$$\sigma_{\mathrm{effective}}(\mathrm{tip}) = \sigma_{\mathrm{applied}}(a/R_{\mathrm{tip}})^{1/2}$$



The effective stress $\sigma_{\mathrm{ffective}}$ at the tip drops and the crack is blunted, leading to increased toughness

Nanocrystals grow on the tip, and then hinder the crack propagation (delocalization of shear bands).



Conclusions

I. Plastic dynamics of metallic glasses is correlated with chemical components, structures, loading rates and temperatures. SOC behavior can enhance the ductility of metallic glasses.

[1] Shear avalanche in plastic deformation of a metallic glass composite. International Journal of Plasticity. 2016, 77: 141-155.
[2] Liaw. Manipulation of free volumes in a metallic glass through Xe-ion irradiation. Acta Materialia. 2016, 106: 66-77.
[3] Scaling behavior and complexity of plastic deformation for a bulk metallic glass at cryogenic temperatures. Physical Review E. 2015, 92: 012113 (1-5).
[4] Plastic Flow of a $Cu_{50}Zr_{45}Ti_5$ Bulk Metallic Glass Composite. Journal of Materials Science and Technology. 2014, 30(6): 609-615.
[5] Various Sizes of Sliding Event Bursts in the Plastic Flow of Metallic Glasses Based on a Spatiotemporal Dynamic Model. Journal of Applied Physics. 2014, 116: 033520 (1-7).
[6] Low temperature dependent Dynamics Transition of Intermittent Plastic Flow in a Metallic Glass. I. Experimental Investigations. Journal of Applied Physics. 2013, 114: 033520 (1-8).
[7] Low Temperature dependent Dynamics Transition of Intermittent Plastic Flow in a Metallic Glass. II. Dynamics Analysis. Journal of Applied Physics. 2013, 114: 033521 (1-8).
[8] Plastic Dynamics Transition between Chaotic and Self-Organized Critical States in a Glassy Metal via a Multifractal Intermediate. Physical Review B. 2012, 86: 134303 (1-8).
[9] Self-organized Intermittent Plastic Flow in Bulk Metallic Glasses. Acta Materialia. 2009, 57: 6146.

II. Nanoscratch tests suggest a discontinuous slip occurring on the surface.

[1] Cutting Characteristics of Zr-Based Bulk Metallic Glass. Journal of Materials Science and Technology. 2015, 31: 153-158.
[2] Shear Avalanches in Metallic Glasses under Nanoindentation: Deformation Units and Rate Dependent Strain Burst Cut-off. Applied Physics Letters. 2013, 103: 101907.
[3] Stick-slip dynamics in a $Ni_{62}Nb_{38}$ metallic glass film during nanoscratching. Acta Materialia. 2017 .

III. Crack propagation is a discontinuous process.

Thank you for your attention!