Fracture in amorphous alloys: in search of a length scale

and their physical meaning

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er subtitle style

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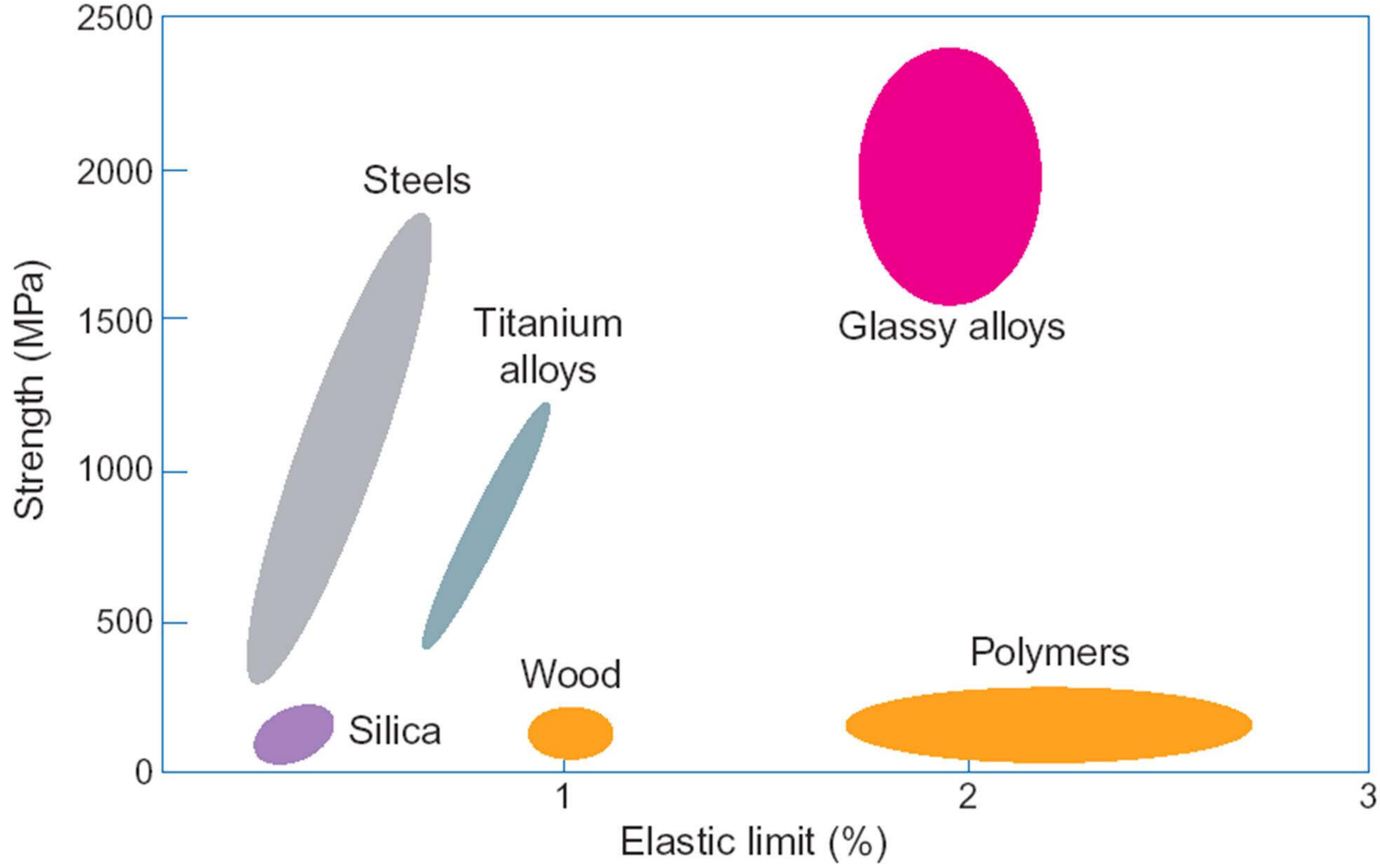
P. Tandaiya, R.L. Narayan, R. Narasimhan

JAKS Symposium, NCBS, Bangalore, 2012



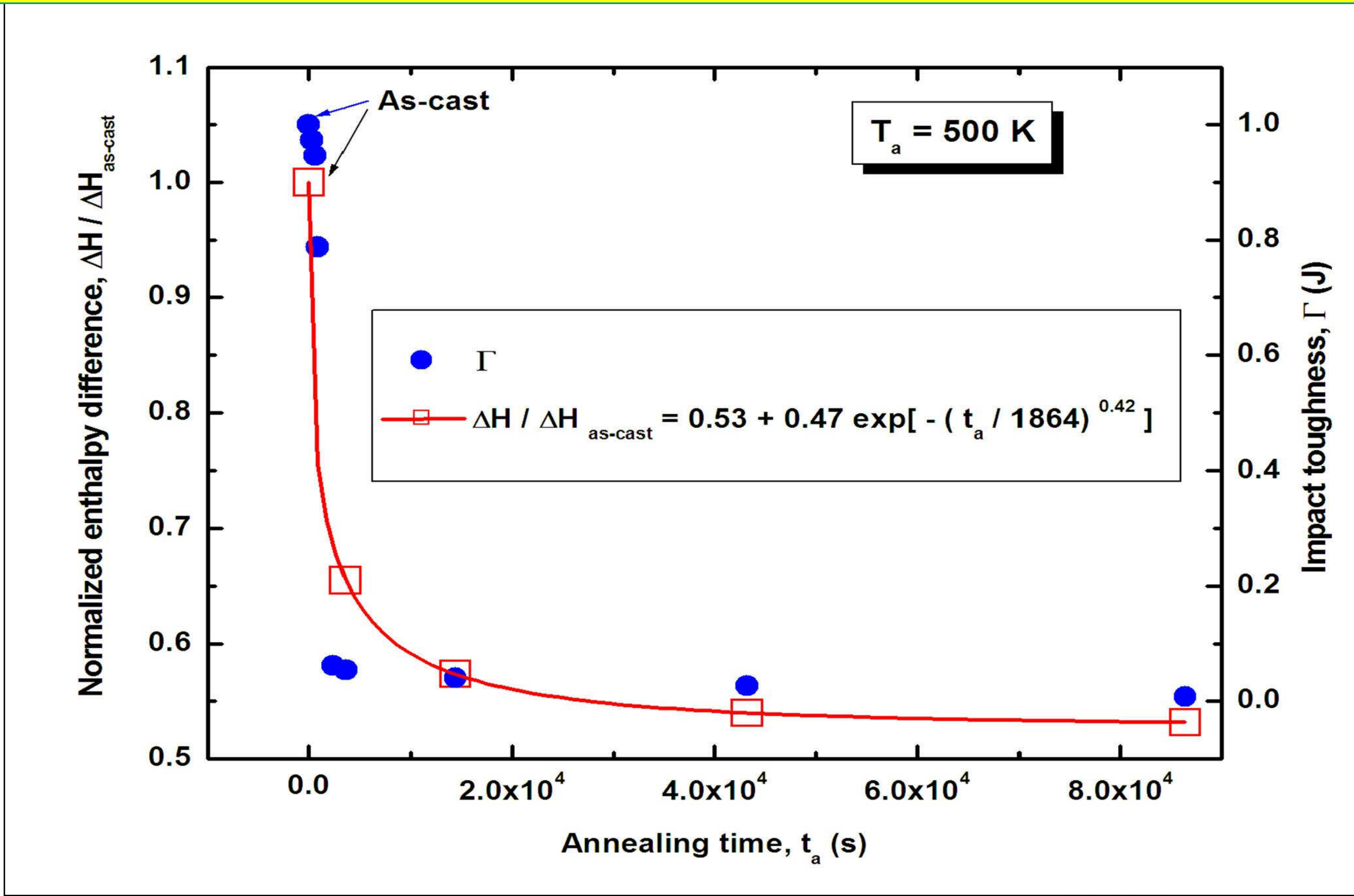
"The first thing you hear about a material is the best thing you will ever hear about it"

What controls the toughness of BMGs?

	Kc (MPa√m)	Hardness (GPa)
Vitreloy $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$		
Amorphous steel $Fe_{48}Cr_{15}Mo_{14}Er_{2}C_{15}B_{6}$		17.8±0.73

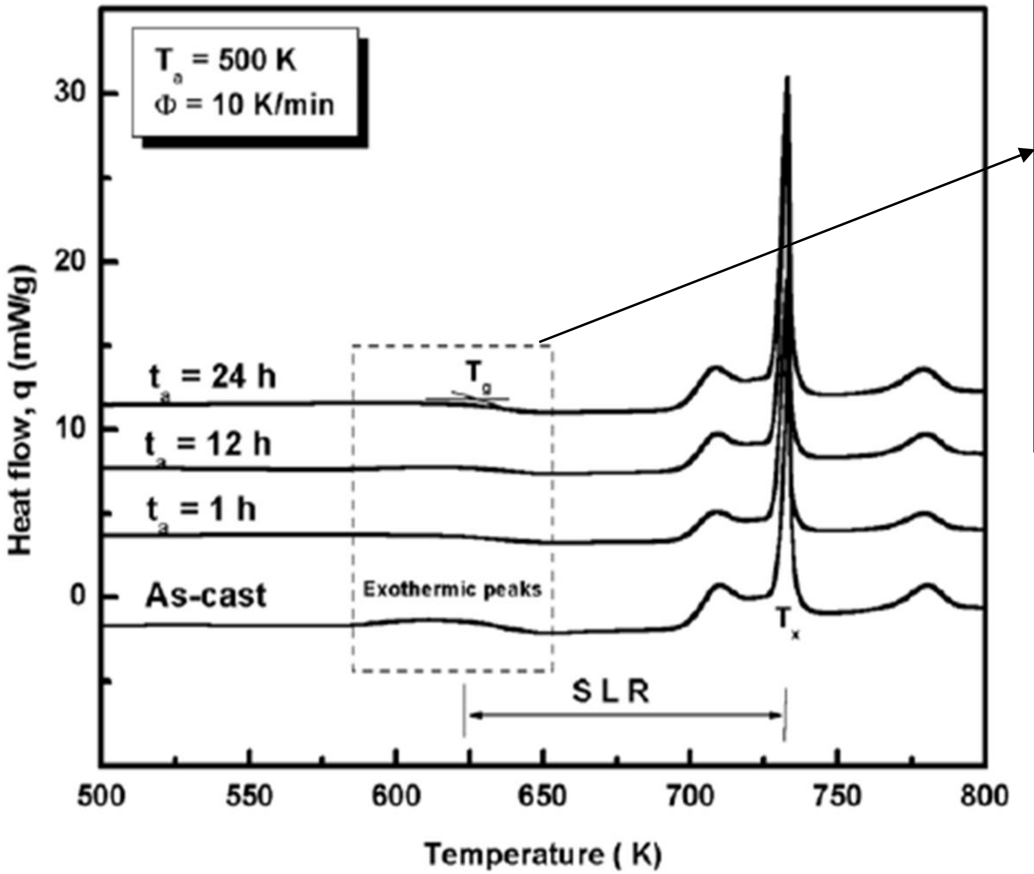
Bulk amorphous metal - An emerging engineering material
Johnson WL , JOM, Volume: 54, Pages: 40-43 , MAR 2002

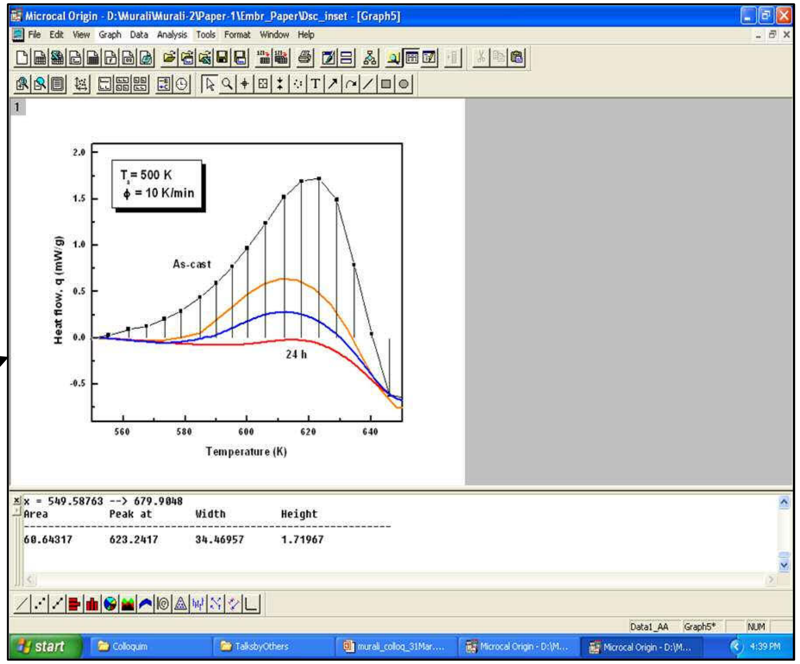
Free volume and toughness



Calorimetric observations

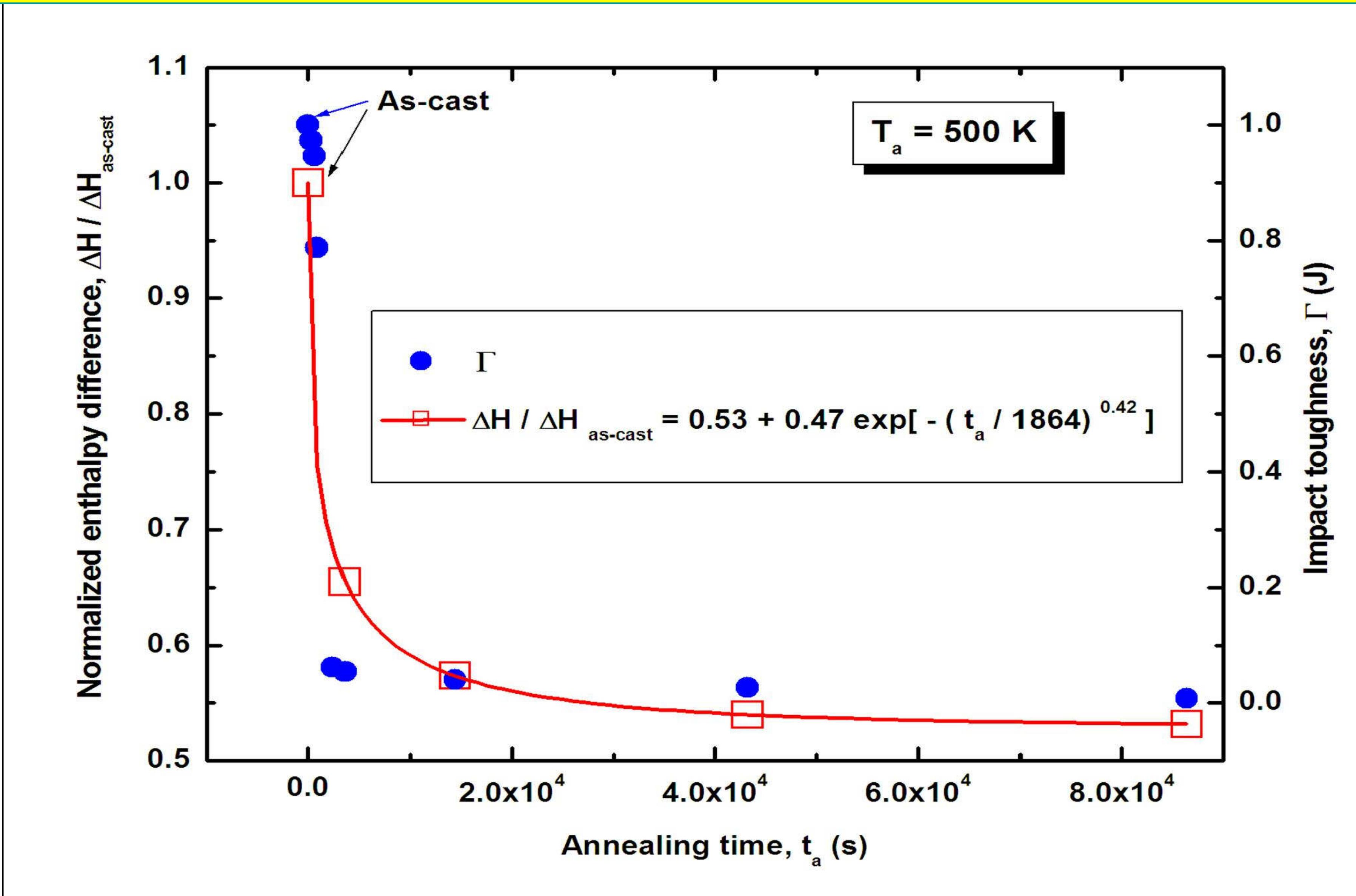
Isothermal Annealing





The decrease in the exothermic peak is used estimate free volume changes associated with structural relaxation

Free volume and toughness



Structure Performance Relationships

"Seeing is Believing"

Performance

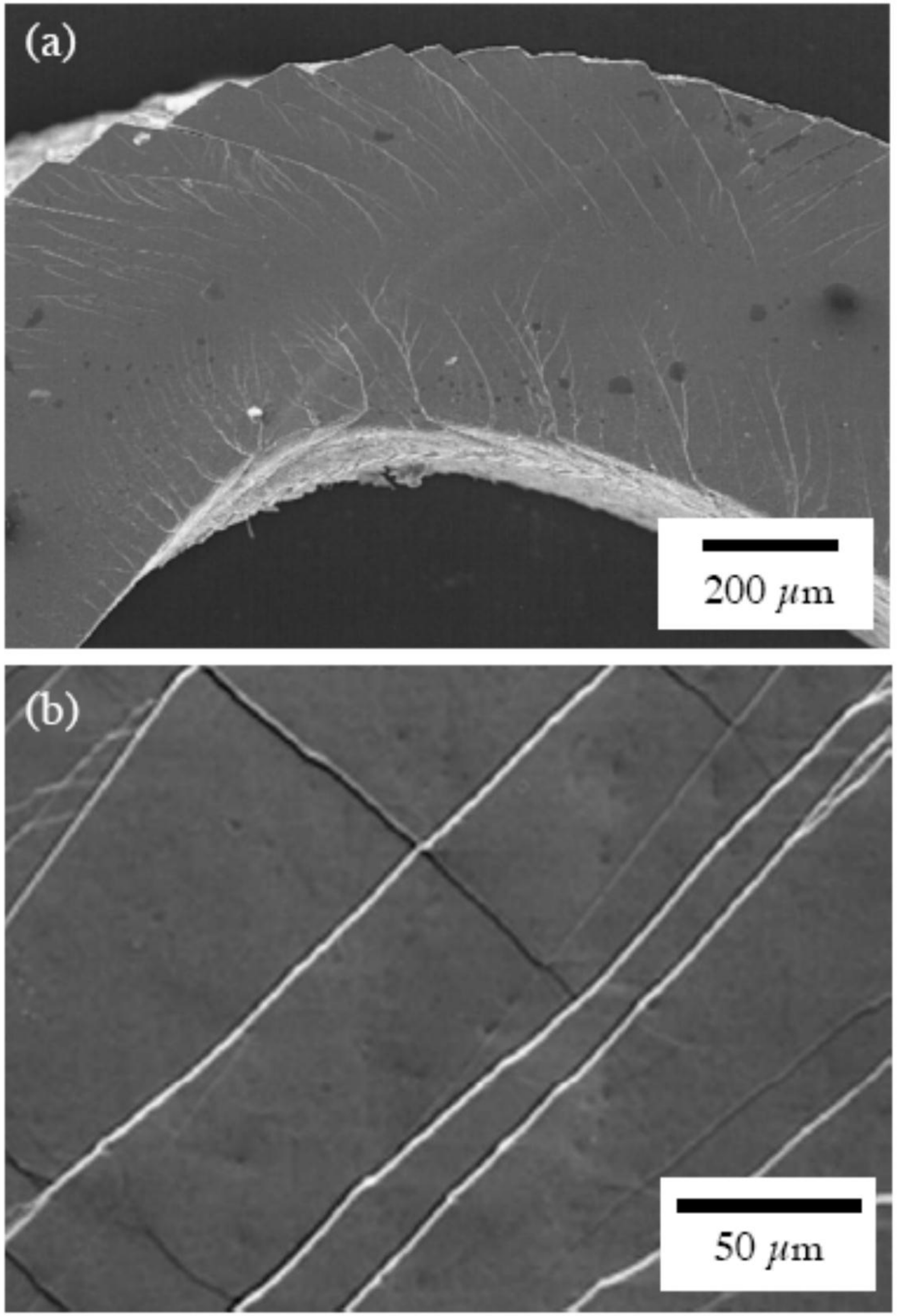
- Second Outline Level
- Stiffness
- Inelastic deformation
  - Third Outline Level
- Ultimate failure
  - Fourth Outline Level
- Reliability
  - Fifth Outline
- Life time

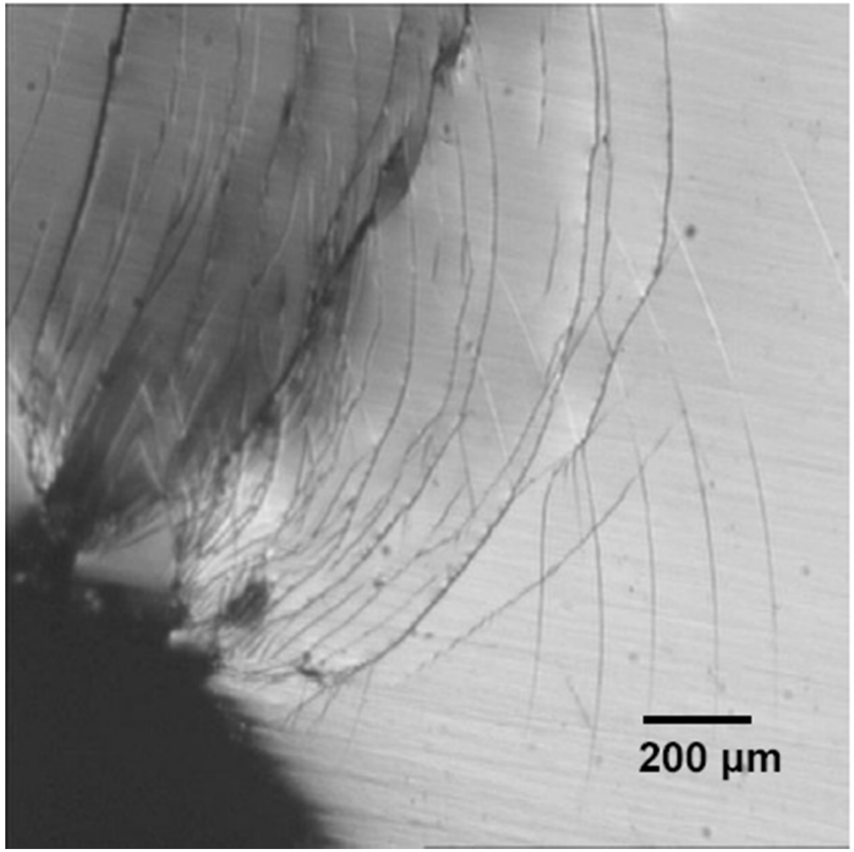
Microstructure

Processing

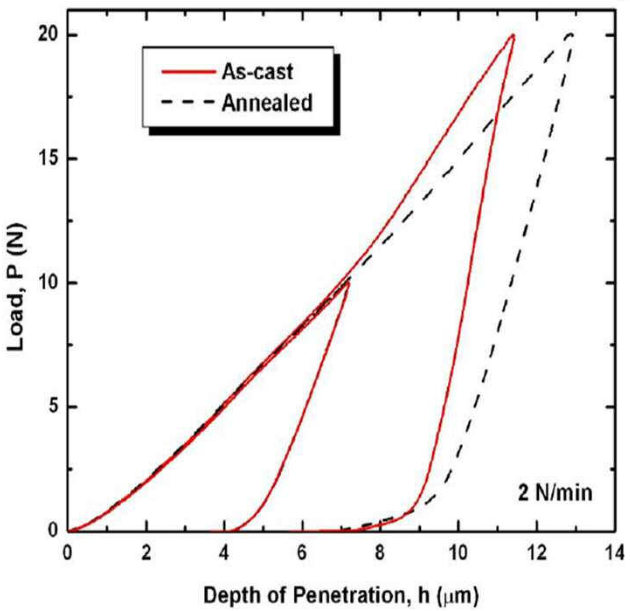
Allows for tailoring of the microstructure to obtain desired behavior

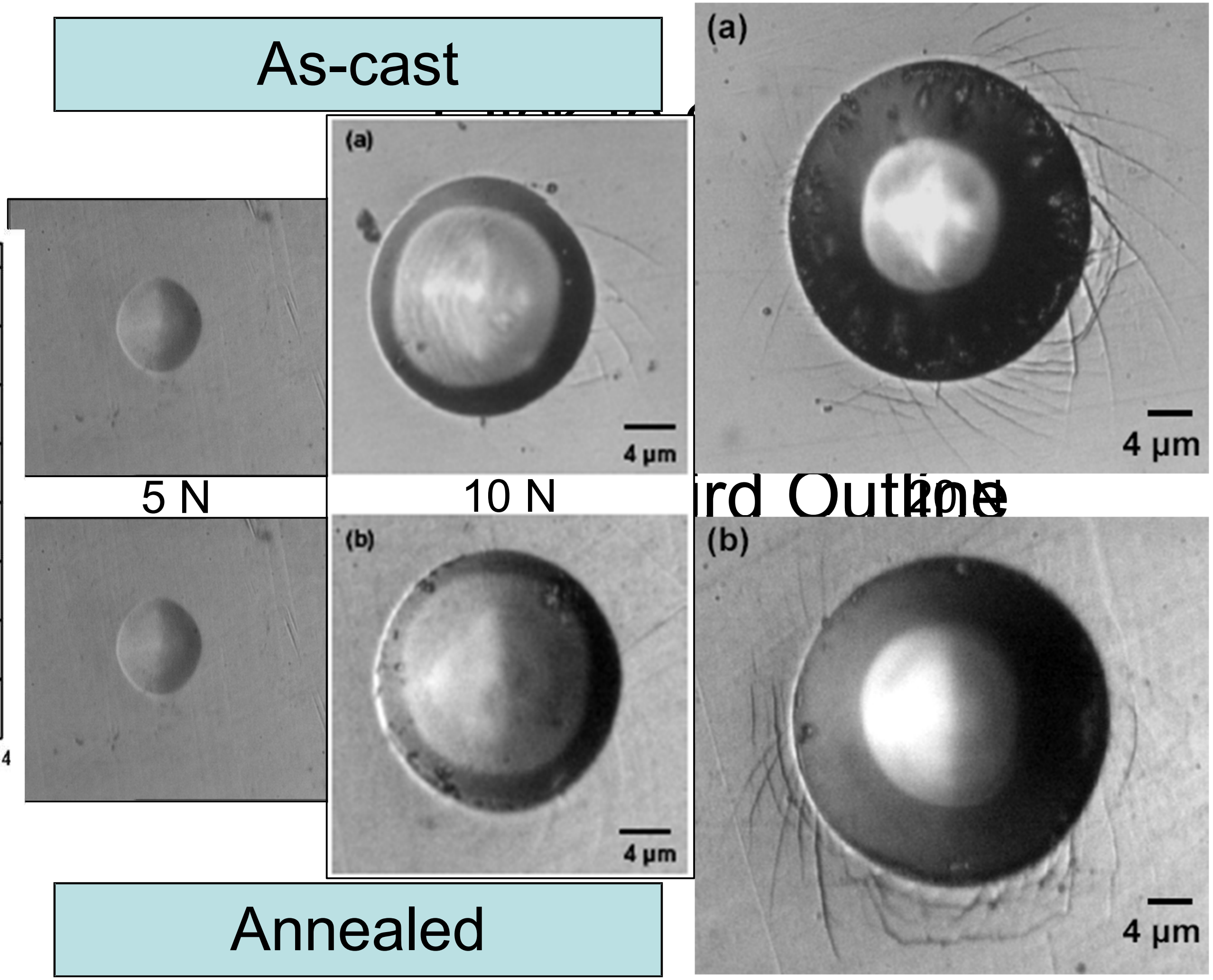
Deformation through shear localization





Spherical indentation



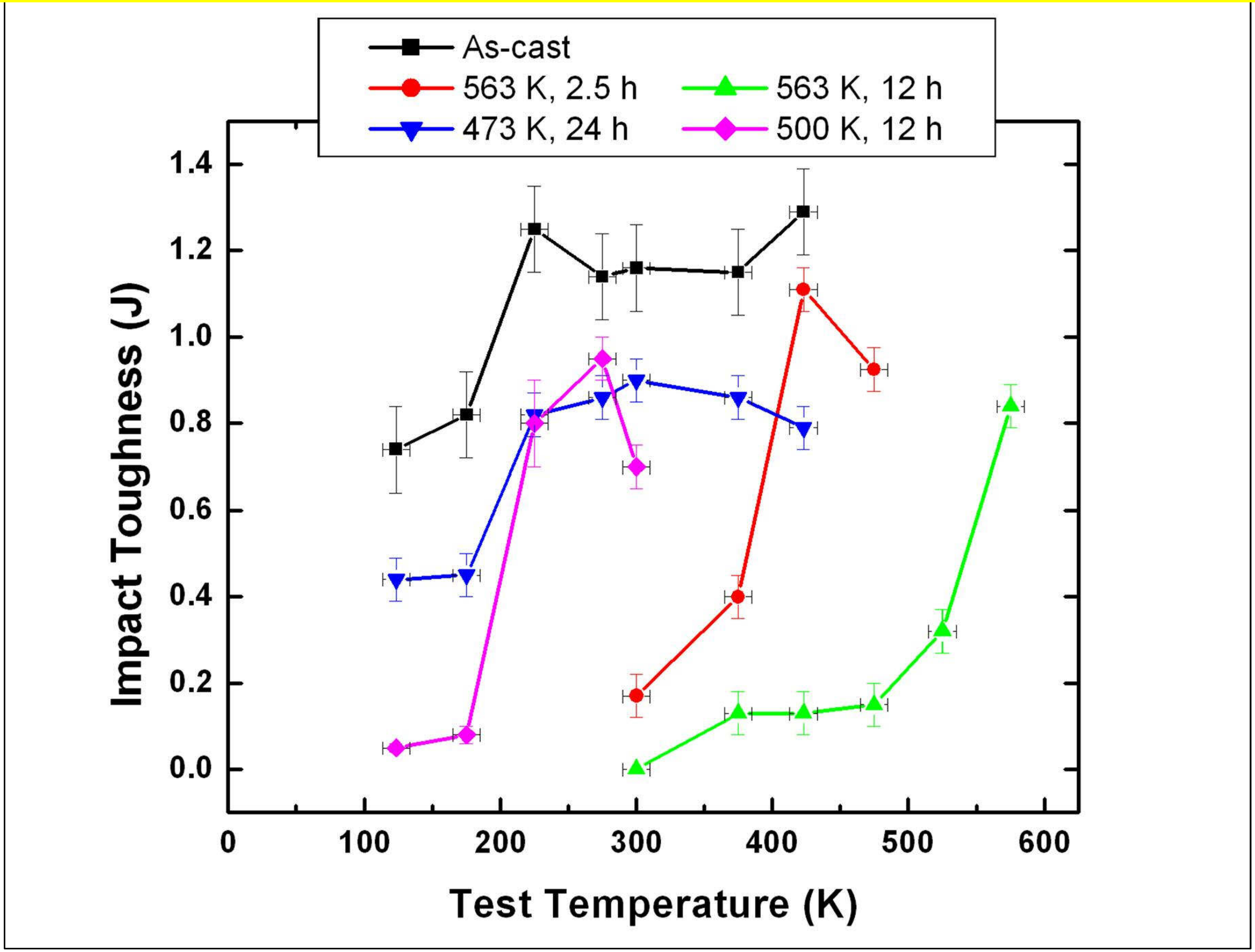


rd Outline

Level

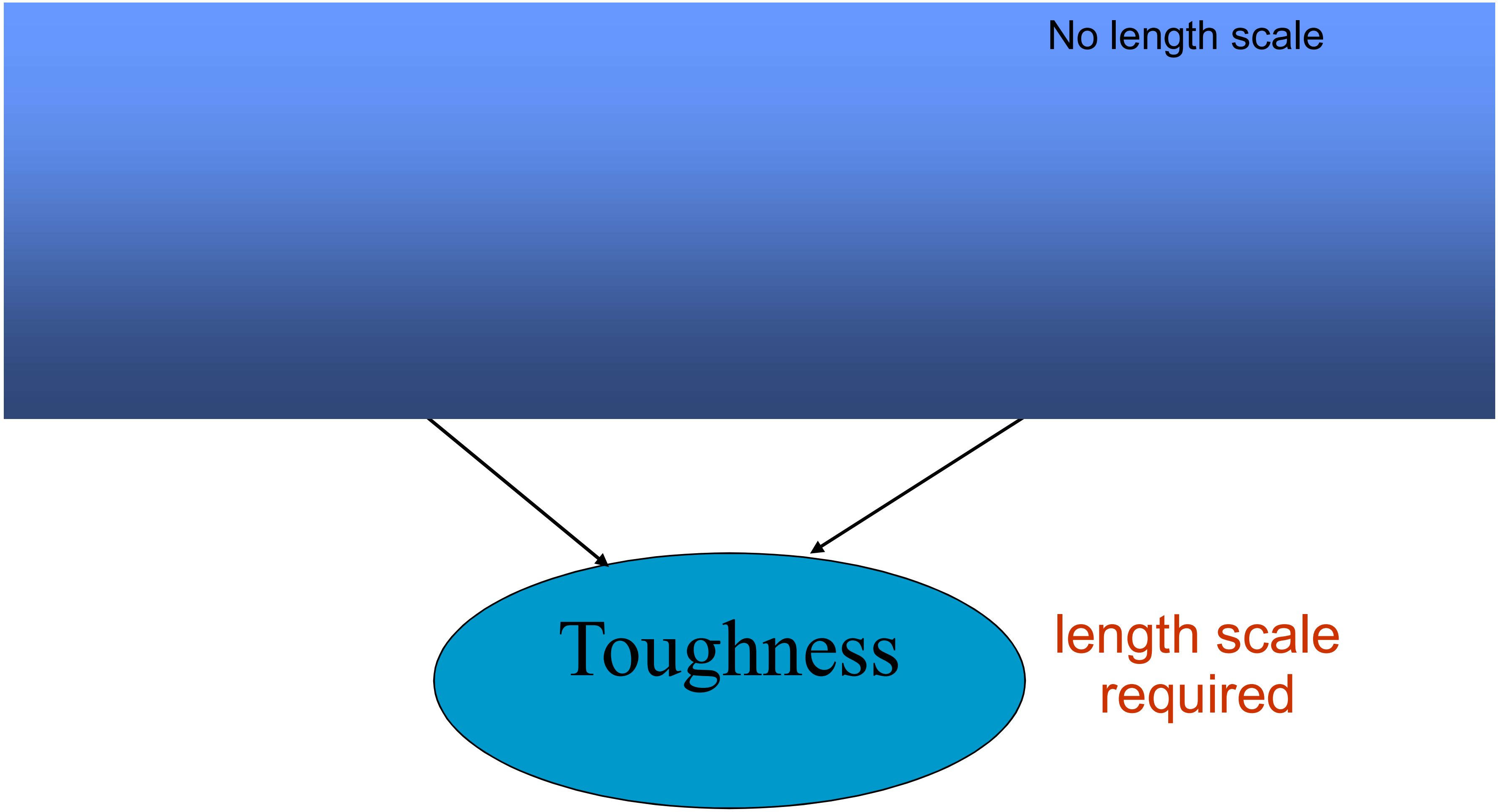
– Sixth

Ductile-to-brittle transition



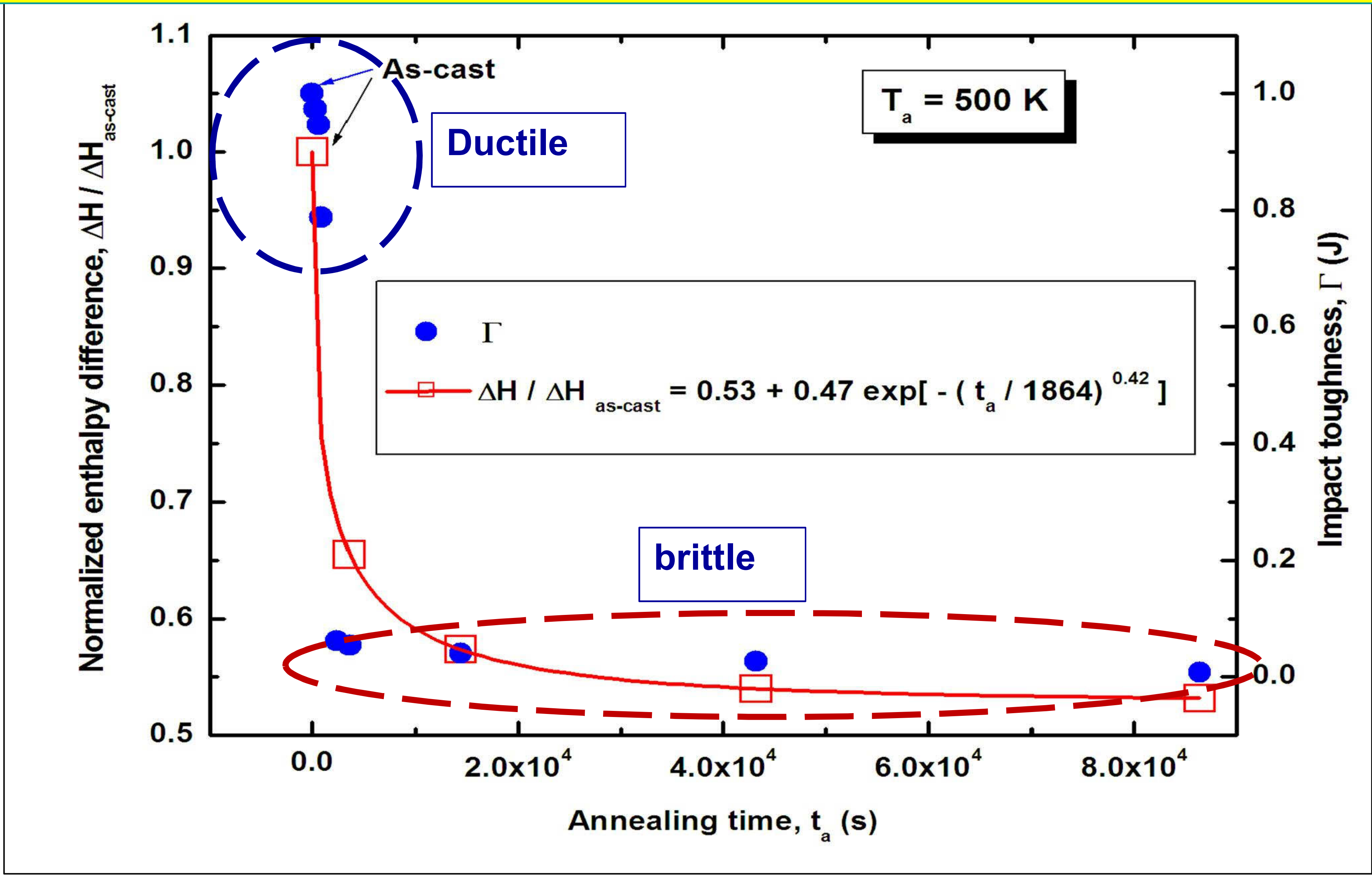
Raghavan, Murali, Ramamurty. Acta mat. 2009

Fundamental mechanical properties*



*Quasi-static loading, room temperature

Free volume and toughness



Murali & Ramamurty, Acta Mat. 2005

Sixth

Our approach

Fracture modeling and experiments

Simulations of crack-tip fields using FEM

Experiments to identify the fracture criterion

Material model

Anand-Su model for metallic glasses

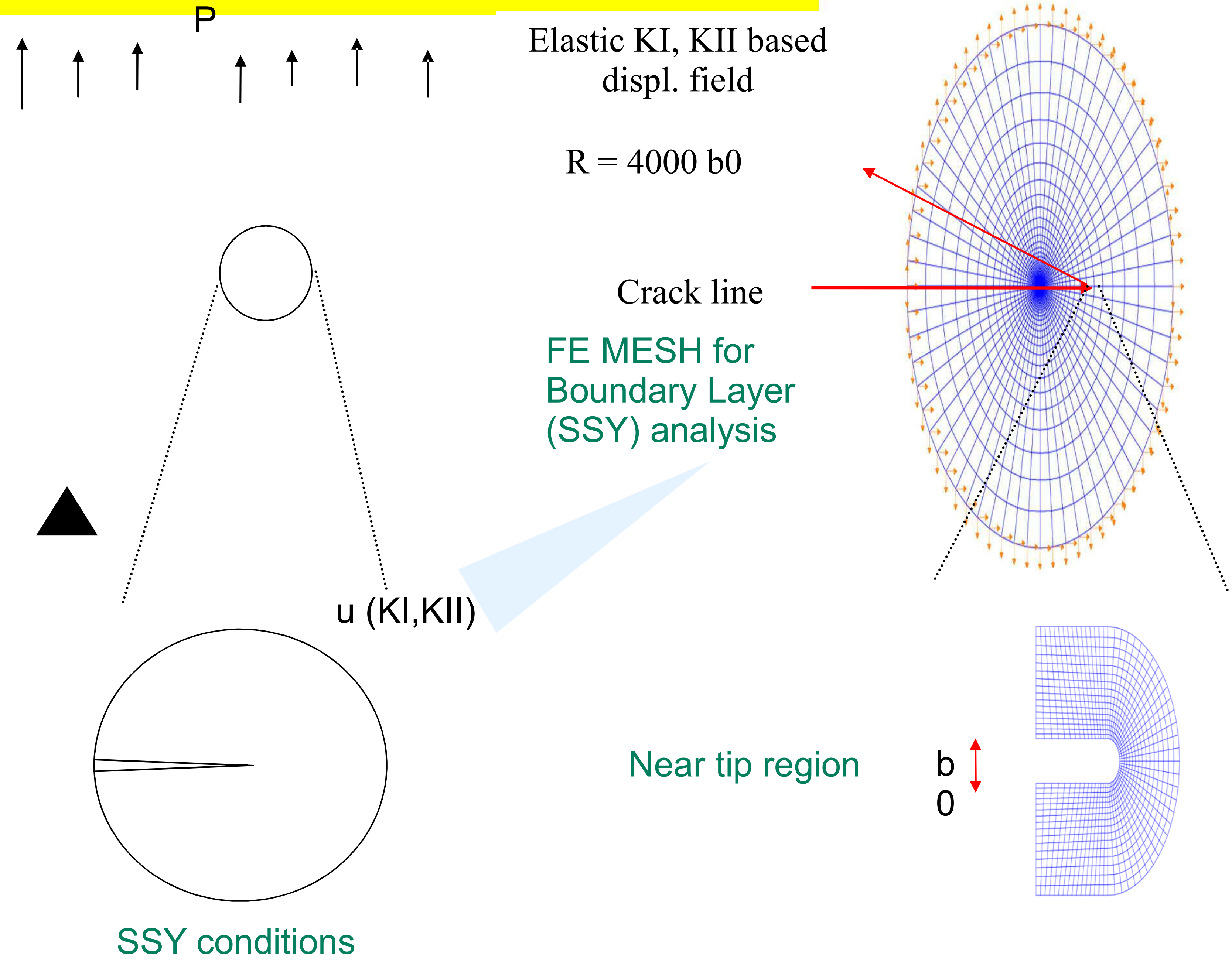
- based on Mohr-Coulomb yield criterion
- involves discrete shearing accompanied by dilatation
- dilatation induced strain softening
- captures inhomogeneous deformation of BMGs well

$$\theta = \left\{ \frac{\pi}{4} + \frac{\phi}{2} \right\} \qquad \phi = \tan^{-1} \mu$$

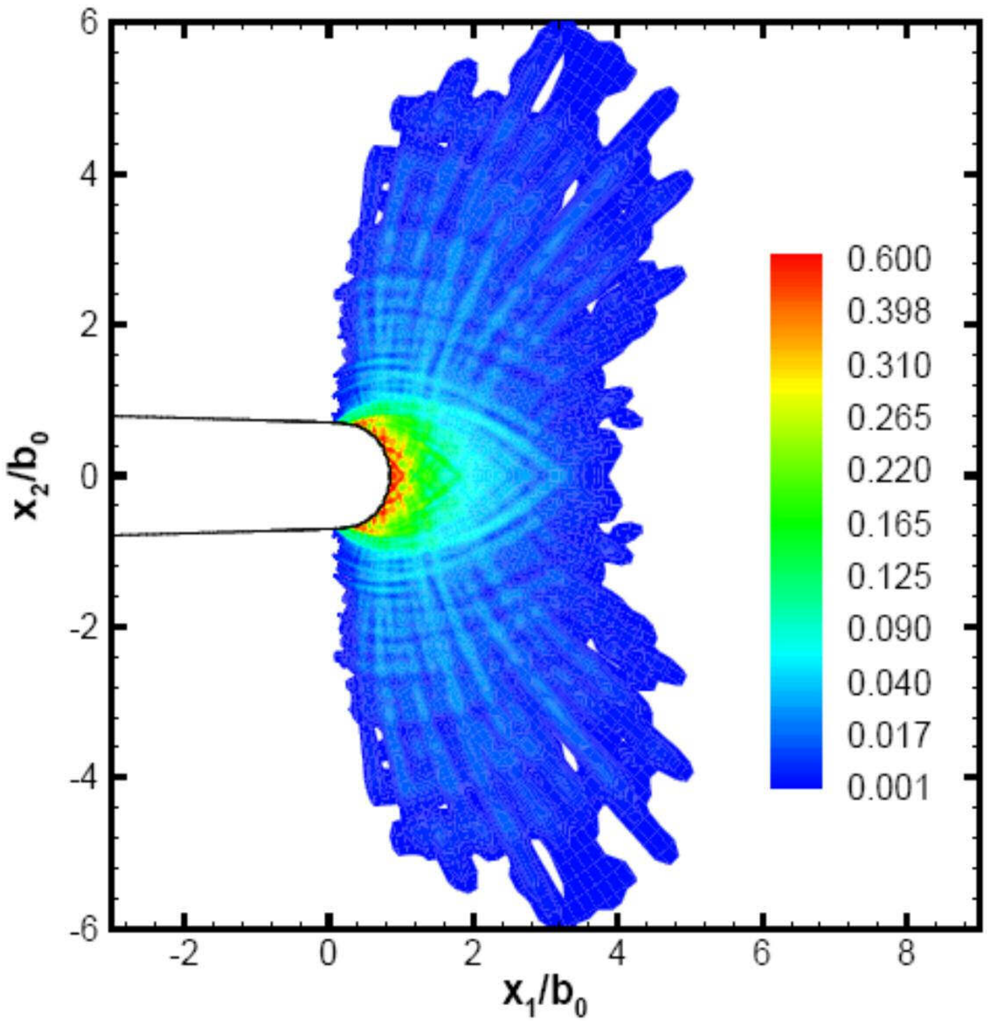
- Plastic dilatancy function (β)
- Cohesion function

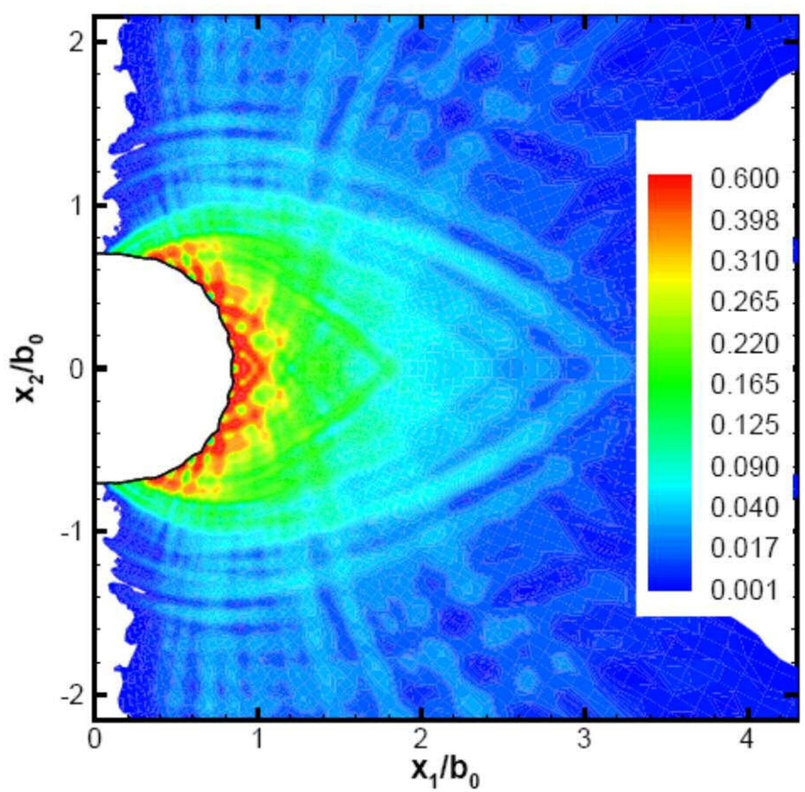
Anand and Su (JMPS, 2005)

FE analysis of stationary cracks



Simulation of shear bands around the notch root



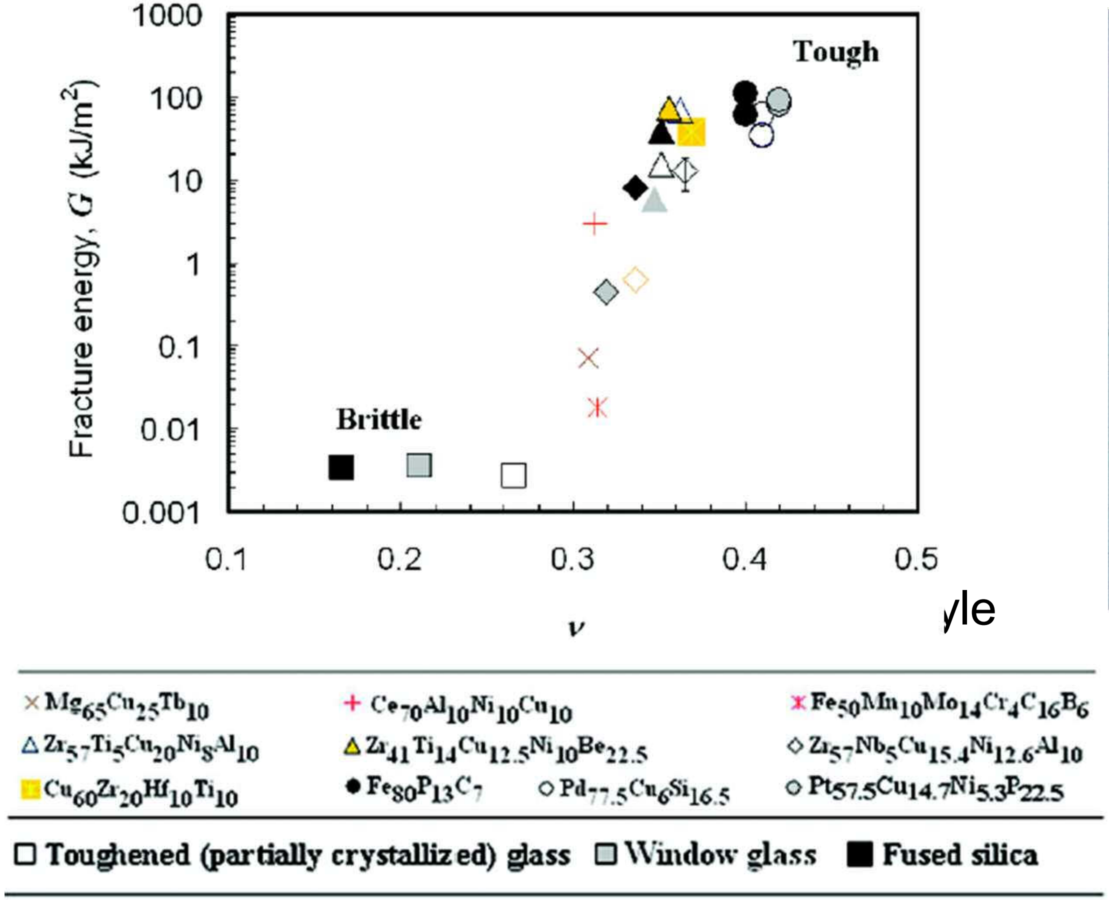


Simulation using statistical distribution of initial cohesion in the finite elements

Third Outline Level

- Fourth Outline Level
  - Fifth Outline Level
  - Sixth

Effect of Poisson's ratio



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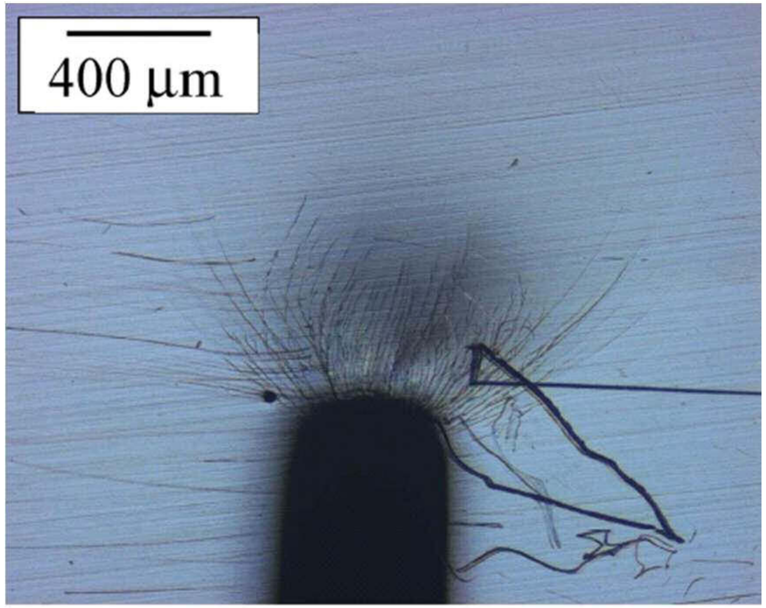


KIc = 80

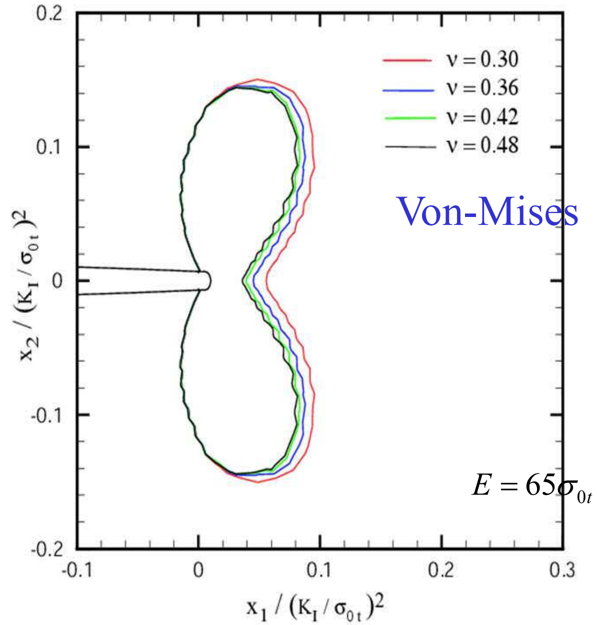
$Pt_{57.5}Cu_{14.7}Ni_{5.3}P_{22.5}$

Poisson's ratio =0.42

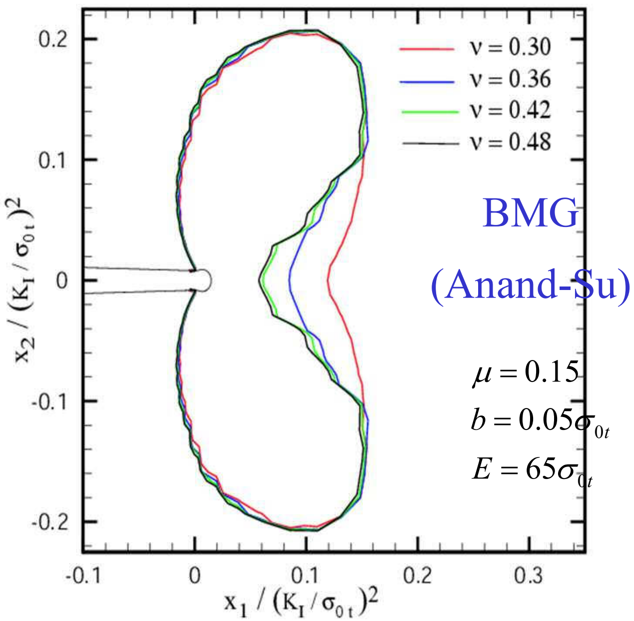
Lewandowski et al., Phil. Mag 2005

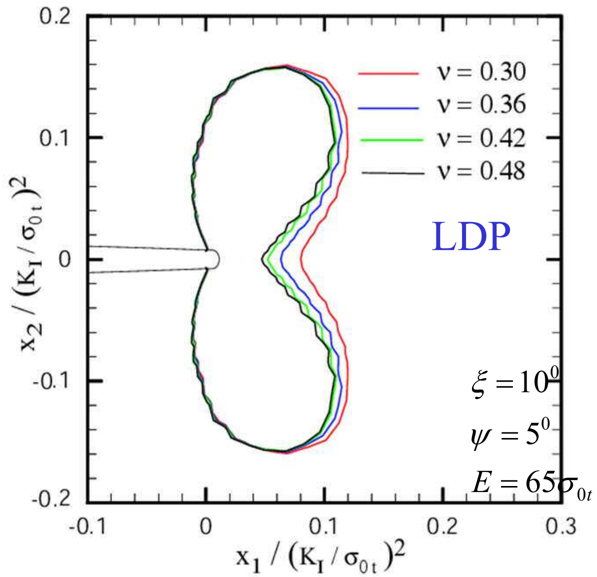
Schroers and Johnson, PRL 2004

Mode I plastic zones



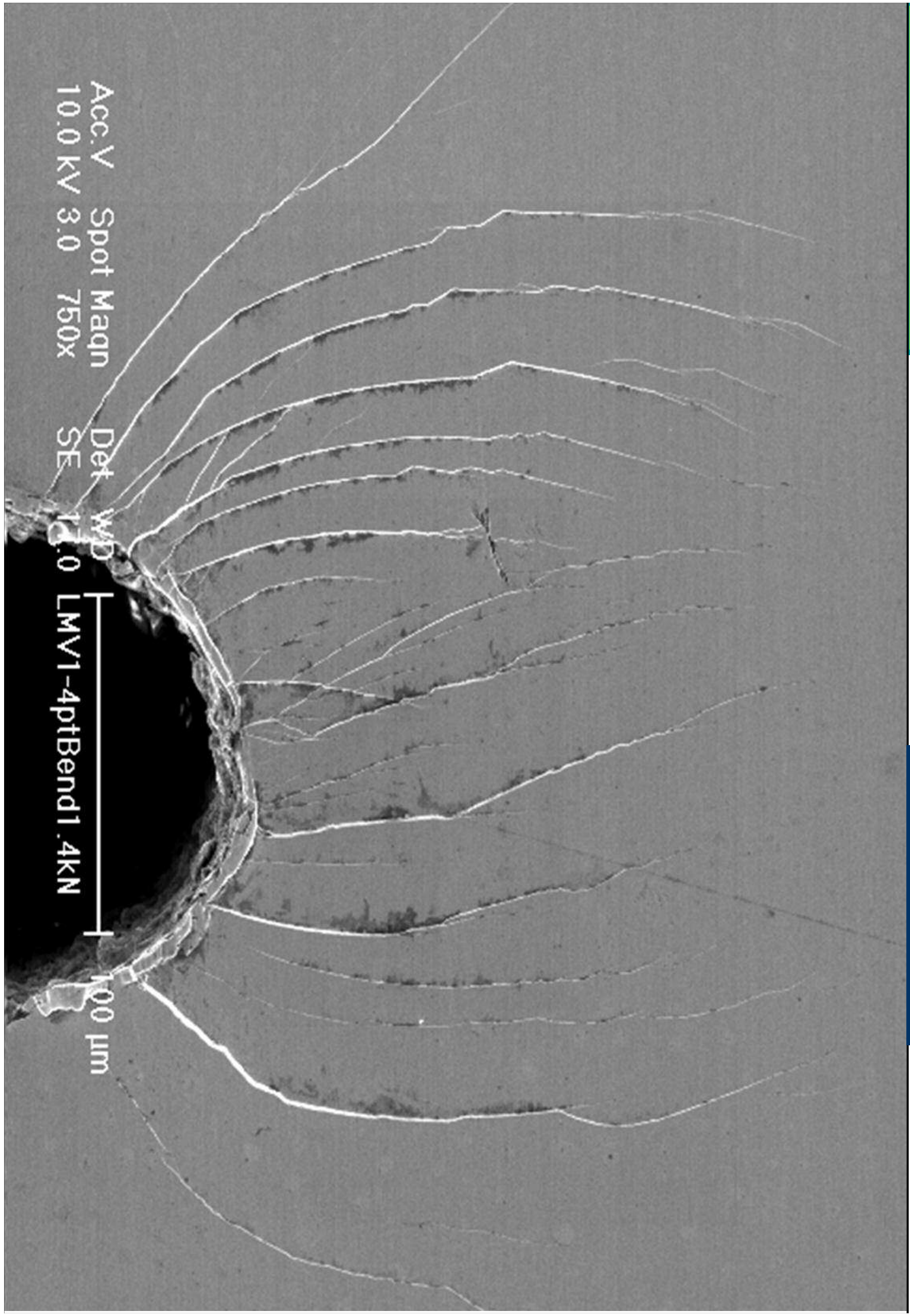
$= 0$





$: 0.05\sigma_{0t}$

Tandaiya *et. al.* Acta Mat (2008)



Fracture in metallic glasses

- Click to edit the outline text format
  - Second Outline Level

What is the governing fracture criterion?

Outline Level

– Fifth

Metallic glasses are schizophrenic in the fracture sense

Stress based (RKR) fracture criterion

Models failure by brittle micro-cracking

(Ritchie et. al, 1973 and MTS theory of mixed mode fracture)

Failure occurs when $\sigma_{\theta\theta}$ exceeds a critical value σ_c over a critical distance r_c from the notch tip

Suitable for brittle materials

Strain based fracture criterion

Models failure by ductile void nucleation and growth

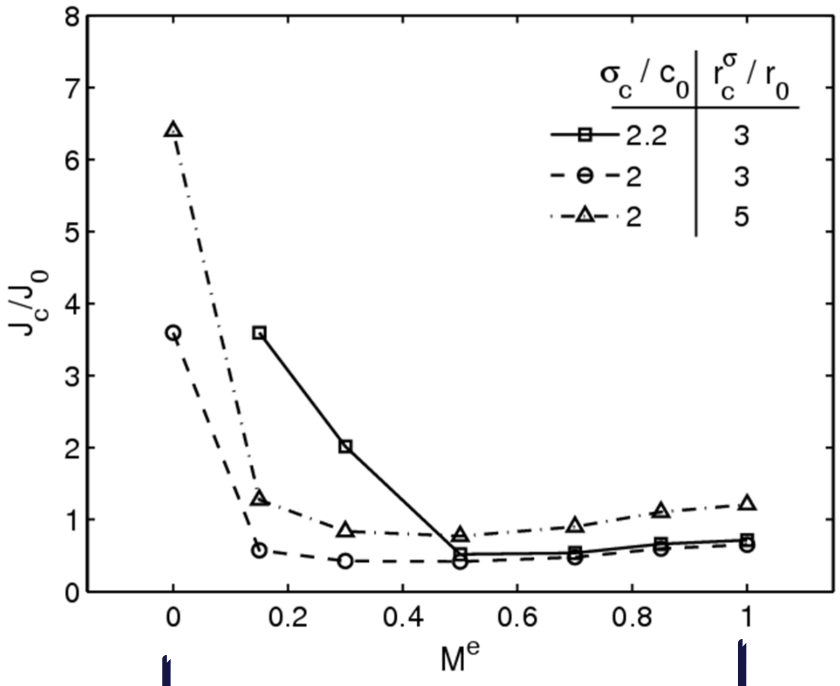
Failure occurs when $\ln\varepsilon_{p1}$ exceeds critical value ε_c over a critical distance r_c from the notch tip

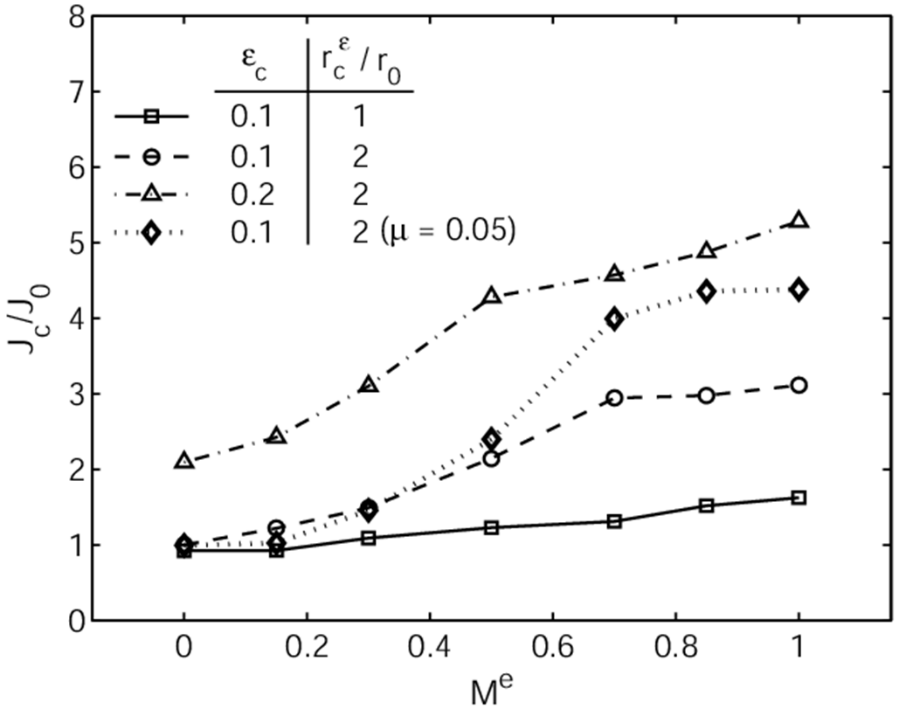
Suitable for ductile materials

Variation of *Jc* versus Me

Operative failure mechanism : RKR for all Me → *Jc* (Me=0)/*Jc* (Me=1) ≈ 5.5

Operative failure mechanism : ductile for all Me → *Jc* (Me=1)/*Jc* (Me=0) ≈ 1.75 to 3

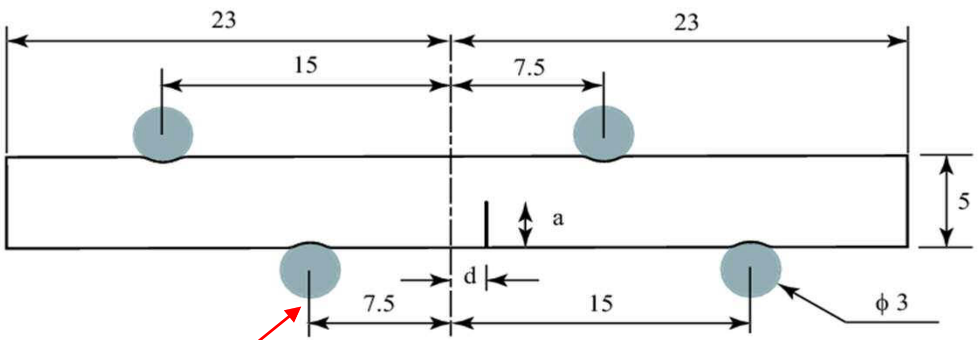




Mode II

Mode I

Mixed-mode (I and II) fracture experiments using asymmetric 4-point bend specimens



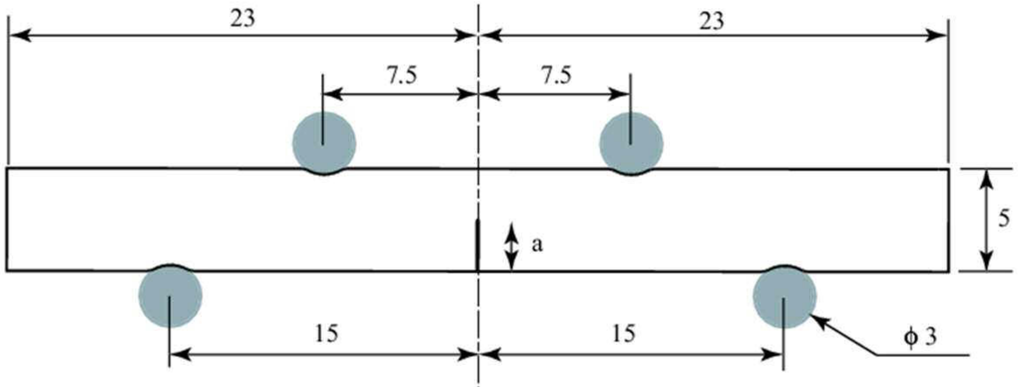
HSS Loading pins

Vitreloy 1

($Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$)

- Notch diameter : 60 μm
- d controls mode mixity

- Pure mode I tests: Symmetric four-point bend specimen



Specimen type	crack length, a (mm)	a/W	d (mm)	M^e	M^p	Initiation load, P_c (kN)	J_c (Elastic) (N/mm)	J_c (Elastic-plastic) (N/mm)
AS4PB-1	3.5	0.7	0	-0.105	-0.089	9.58 ±0.22	9.23 ±0.36	11.1 ±0.57
AS4PB-2	2.5	0.5	0.4	0.043	0.175	13.16 ±0.40	7.13 ±0.39	8.38 ±0.59
AS4PB-3	2.5	0.5	0.8	0.215	0.484	14.31 ±0.12	9.50 ±0.15	12.29 ±0.32
AS4PB-4	2.5	0.5	1.5	0.448	0.684	14.15 ±0.22	14.49 ±0.48	20.59 ±1.39
S4PB-1	2.5	0.5	-	1	1	2.66 ±0.33	32.27 ±6.48	35.03 ±7.73

(All dimensions are in mm)

Test setup

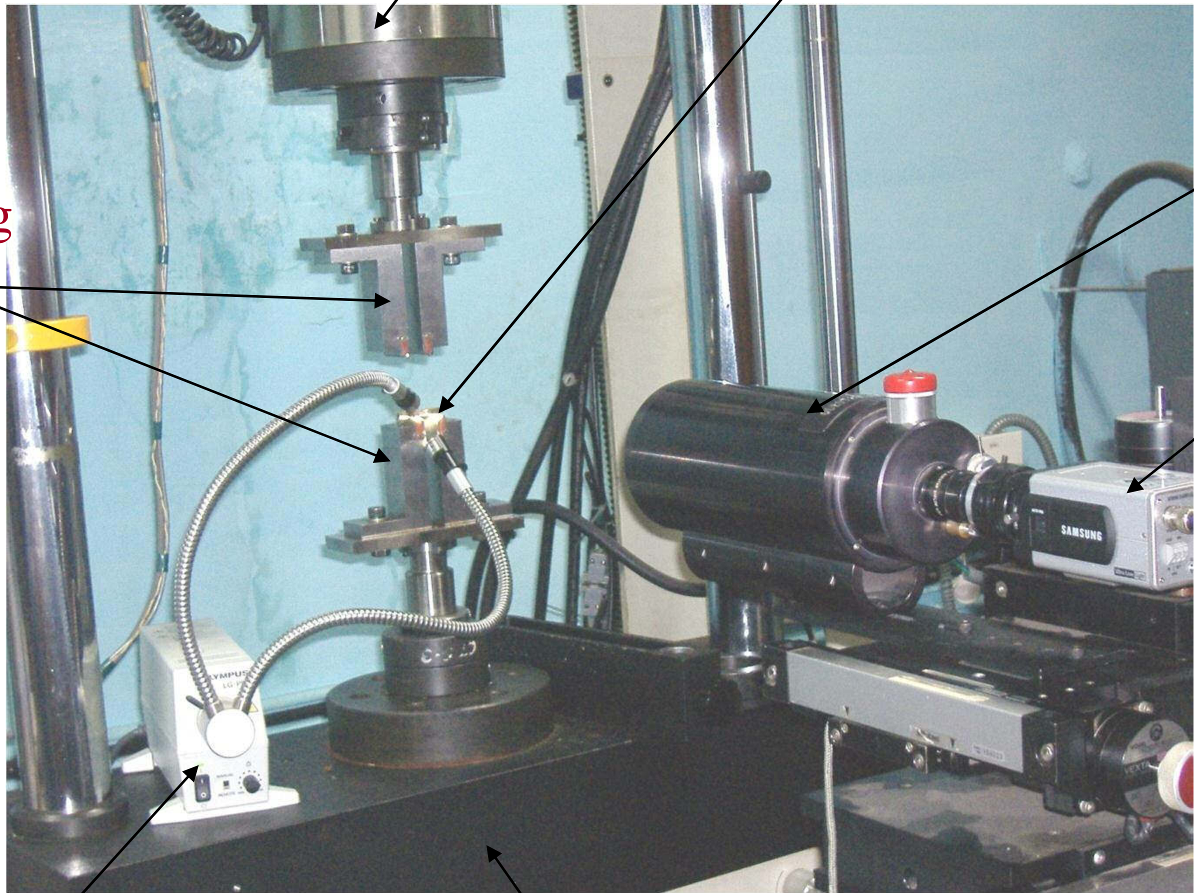
Load cell

Specimen

Questar QM100
long distance
microscope

Four-point
bend loading
fixture

CCD camera

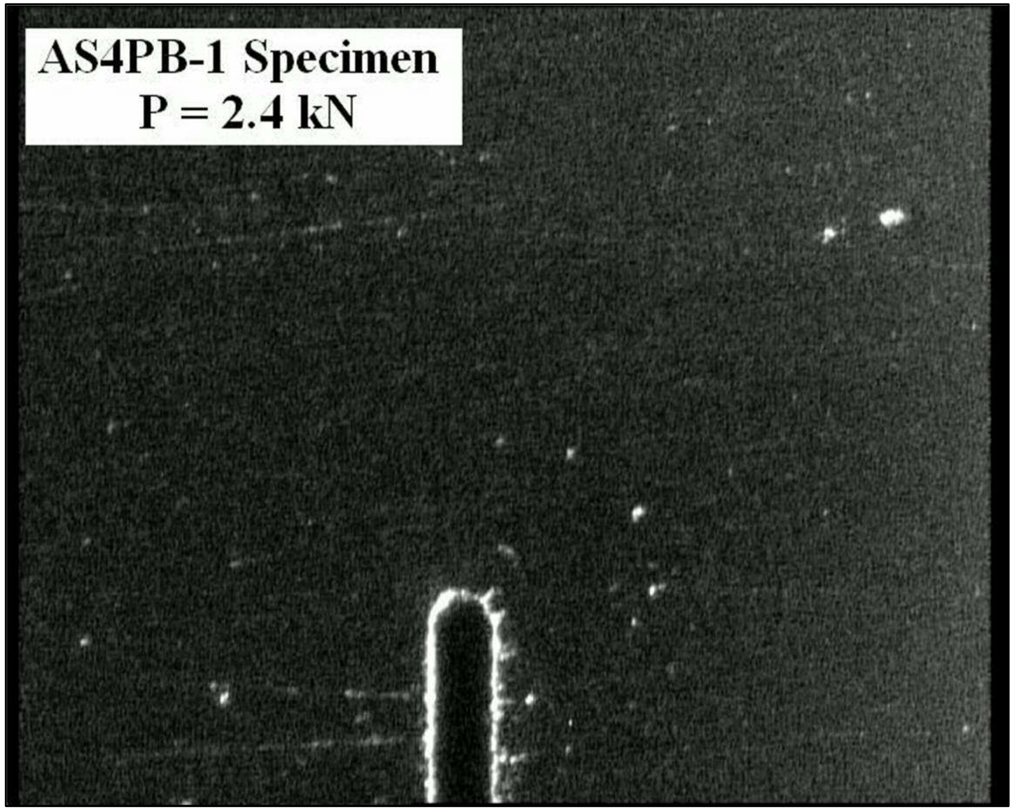


Light source

250 kN Instron 8502
servohydraulic testing machine

Cross-head speed = 2 μm/s

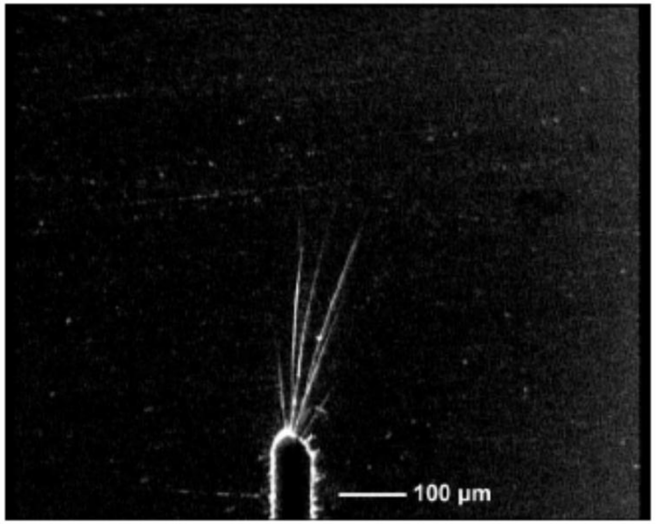
In-situ observations



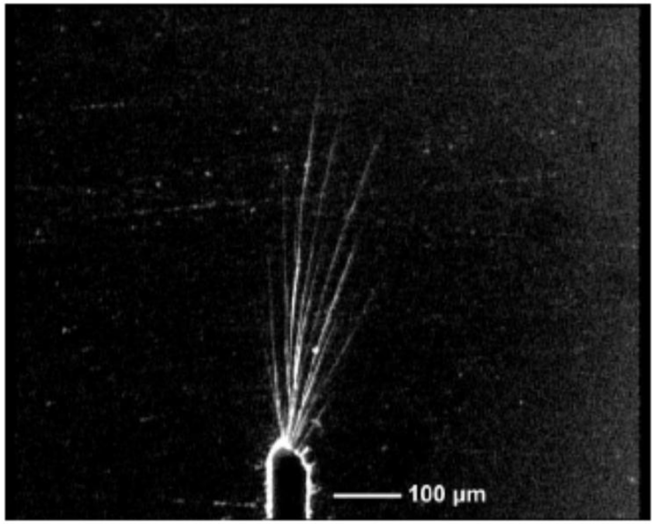
100 μm

Speed: 16x

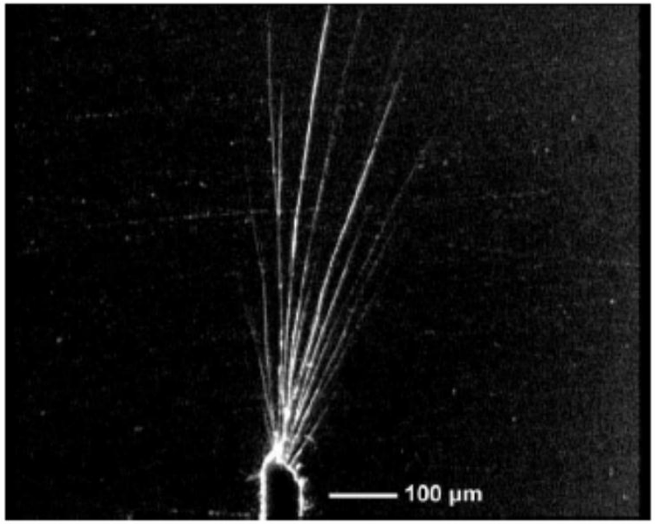
In-situ observations of AS4PB-1 specimen



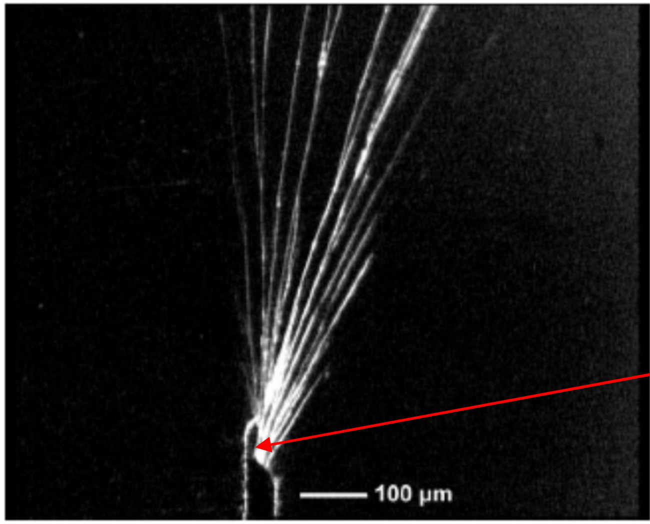
(a) 6.8 kN



(b) 7.7 kN



(c) 9.4 kN

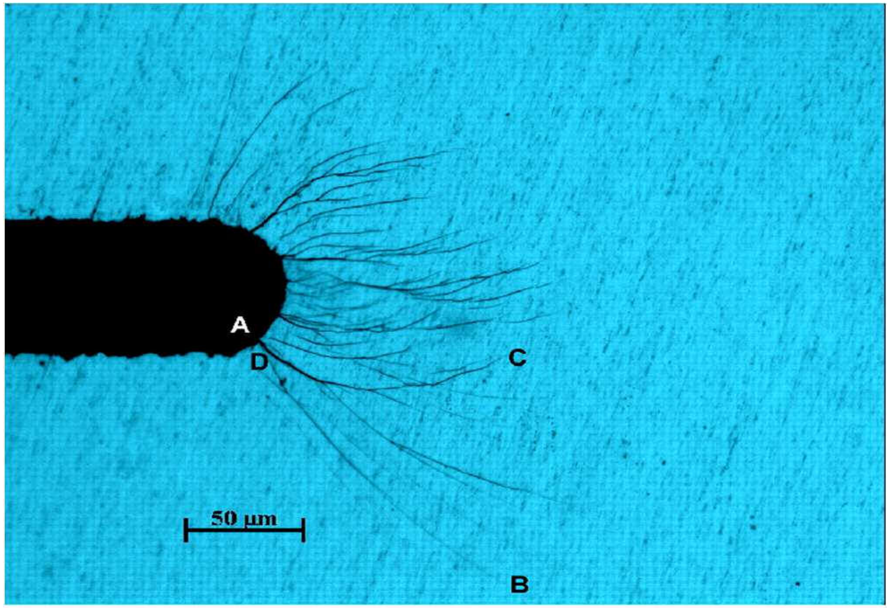


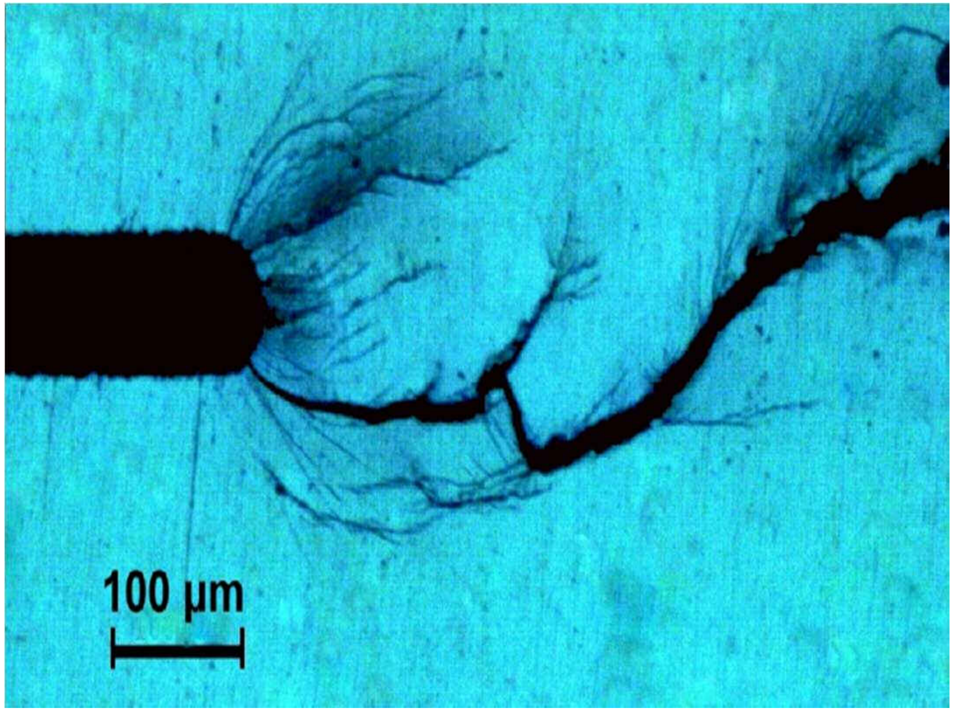
(d) 12.4 kN

- Notch deformation
- Shear banding
- Stable crack growth inside shear bands
- Final failure

Stable crack growth in a shear band

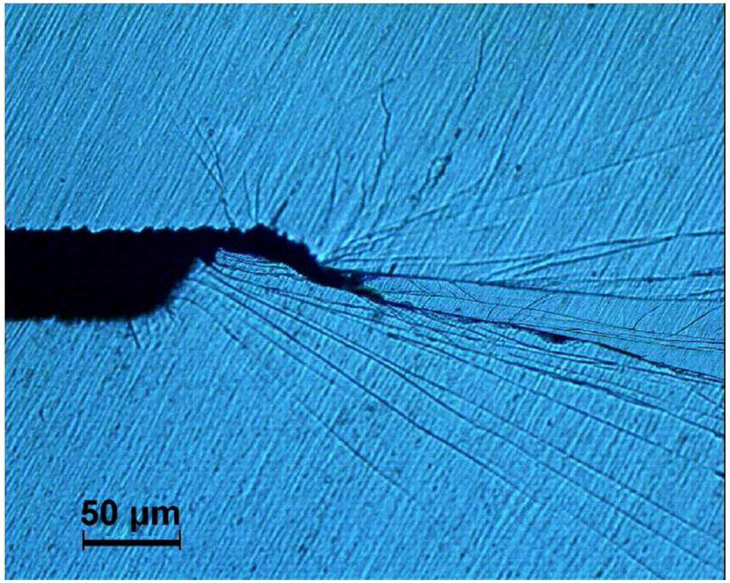
Crack grows within a shear band



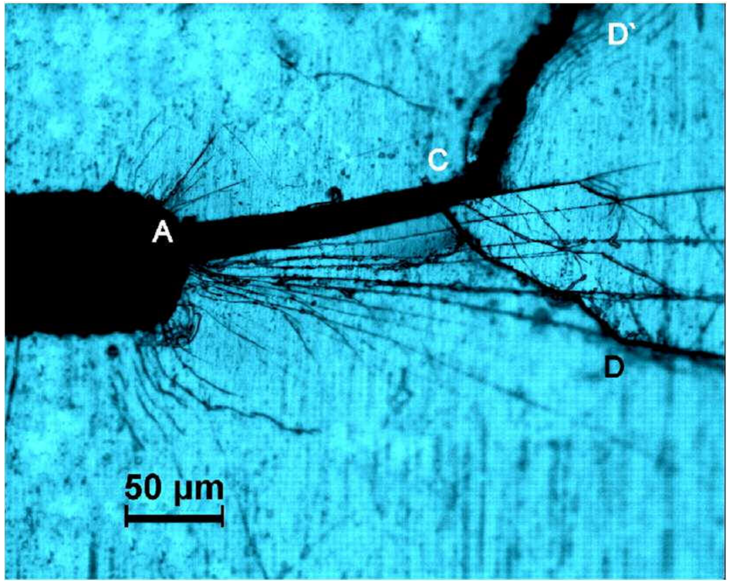


Me = 1 (pure mode I)

Crack trajectories

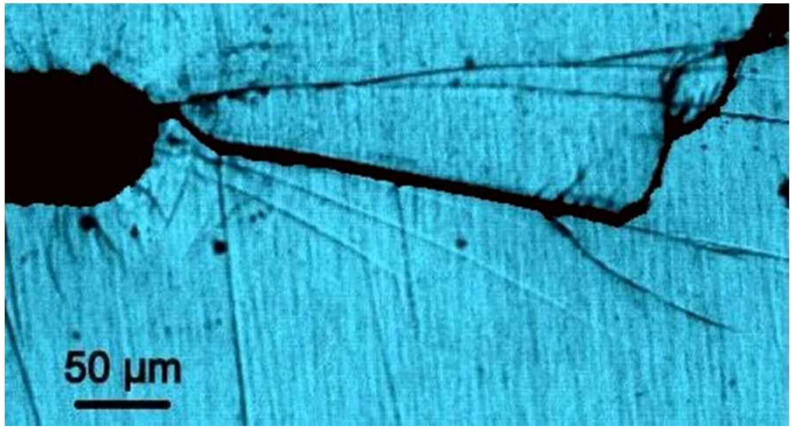


AS4PB-1

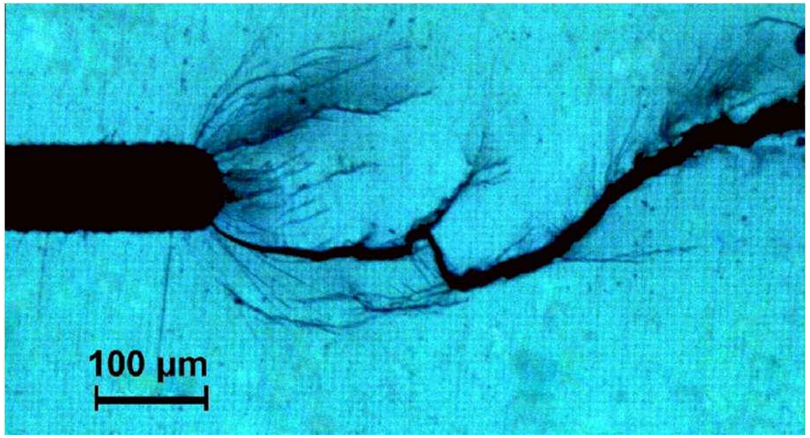


AS4PB-2

▶Incipient crack growth occurs inside a dominant shear band for all the specimens



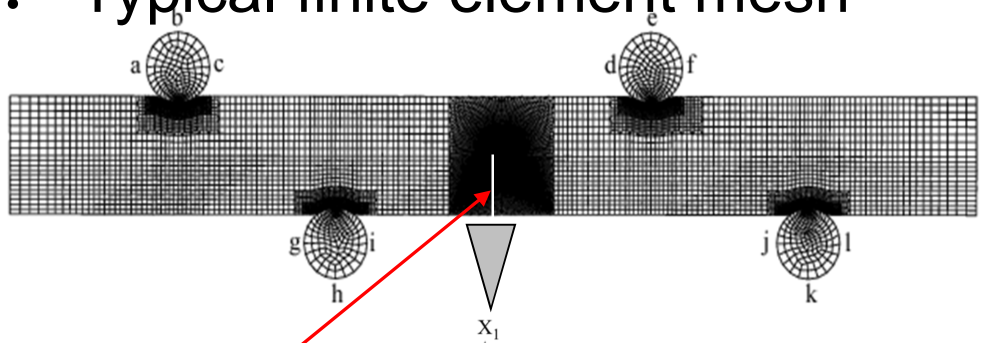
AS4PB-4



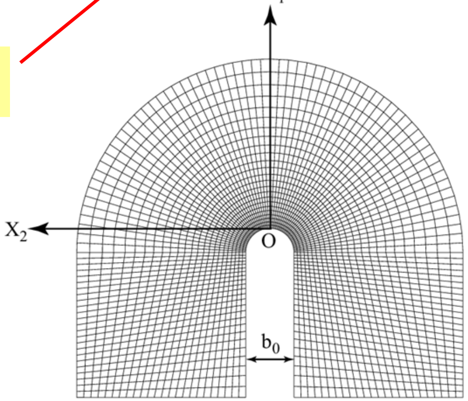
S4PB-1

Finite element analyses

- Typical finite element mesh



notch



Near tip mesh

- No. of elements = 14394
- 64 elements around the notch root
- Frictionless contact
- Downward displacement prescribed for nodes on arcs abc and def
- Nodes on arc ghi and jkl are fixed

➢Two analyses:
a. Linear elastic
b. Elastic-plastic

➢Constitutive model:
Anand and Su model implemented through UMAT in ABAQUS/Standard

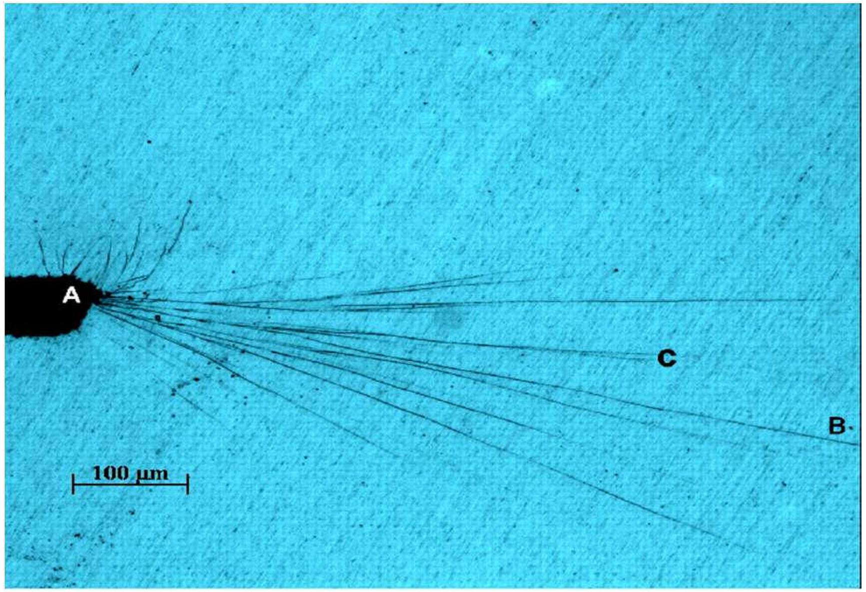
➢Material properties for Vitreloy 1:
E = 97 GPa; ν=0.36; c0=890 MPa; μ=0.06; b=120 MPa

➢Determine:
a. Elastic mode mixity parameter Me
b. Plastic mode mixity parameter Mp

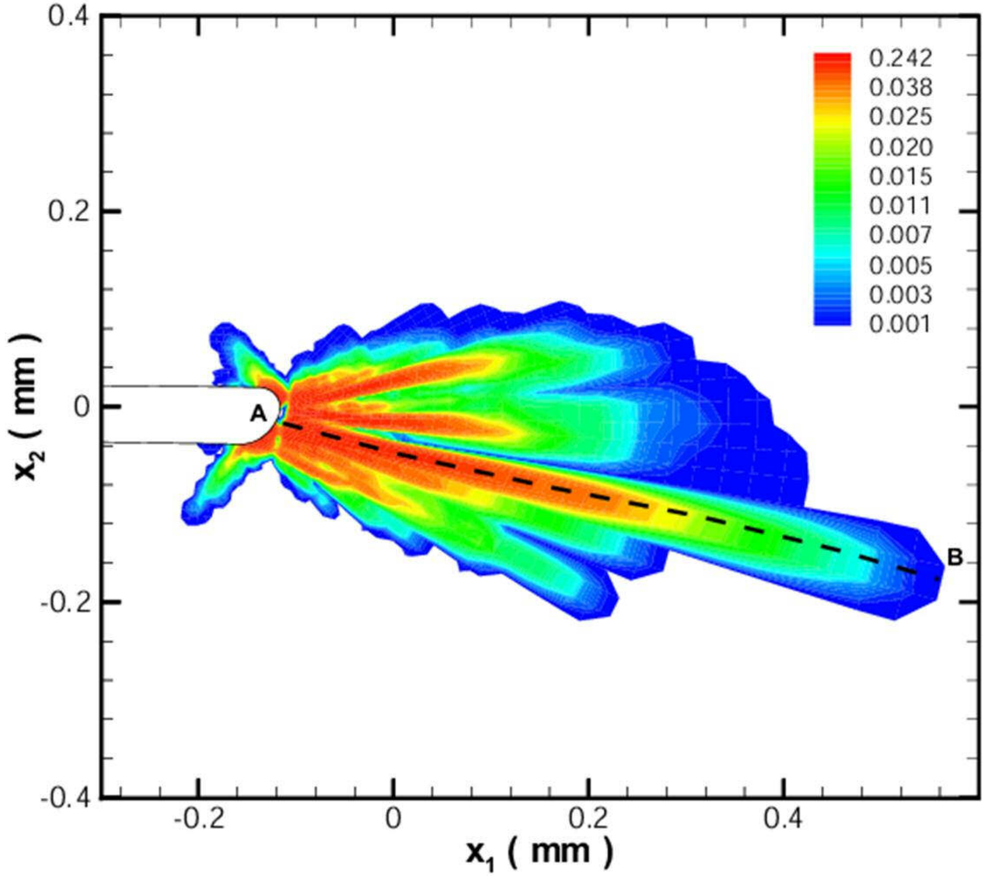
c. Calibrate of *J* against *P* for each specimen using both the above analyses
d. Find critical energy release rate *Jc*
e. Simulate near-tip shear band patterns

Mixed Mode Fracture

Experiment



Simulation

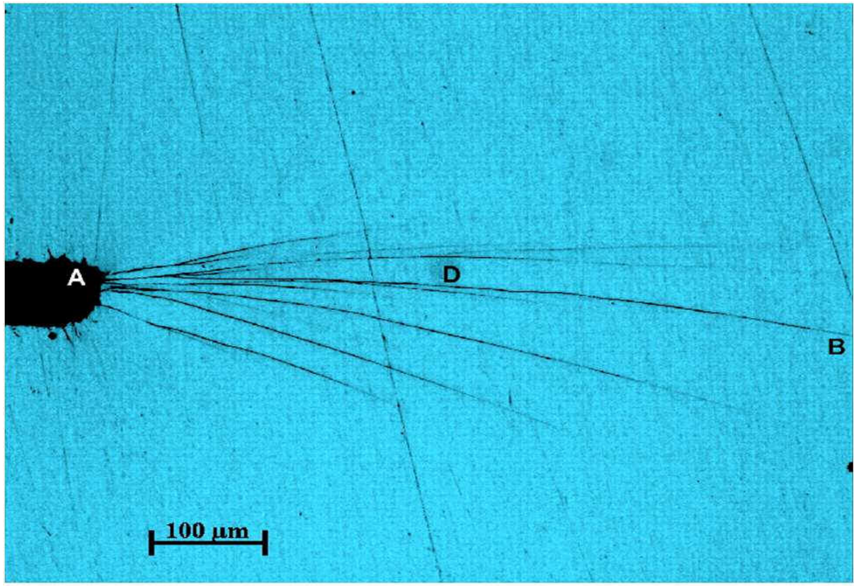


Me = -0.089 (~ pure mode II)

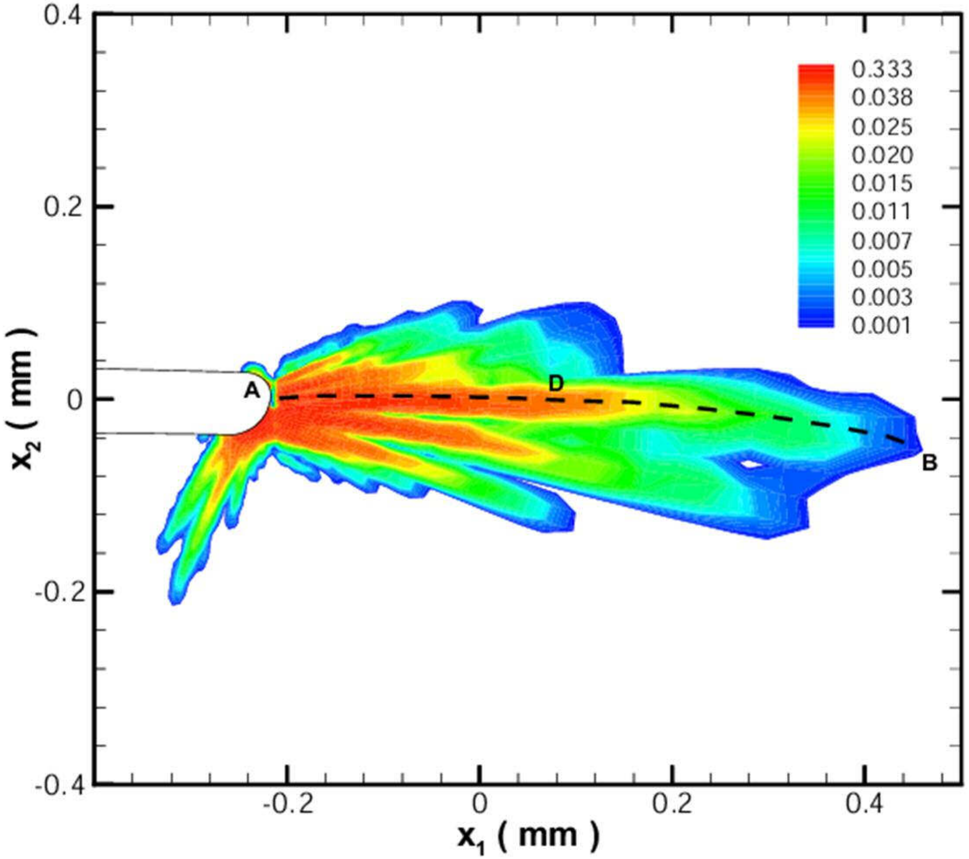
Tandaiya, Ramamurty, Narasimhan,

Mixed Mode Fracture

Experiment



Simulation

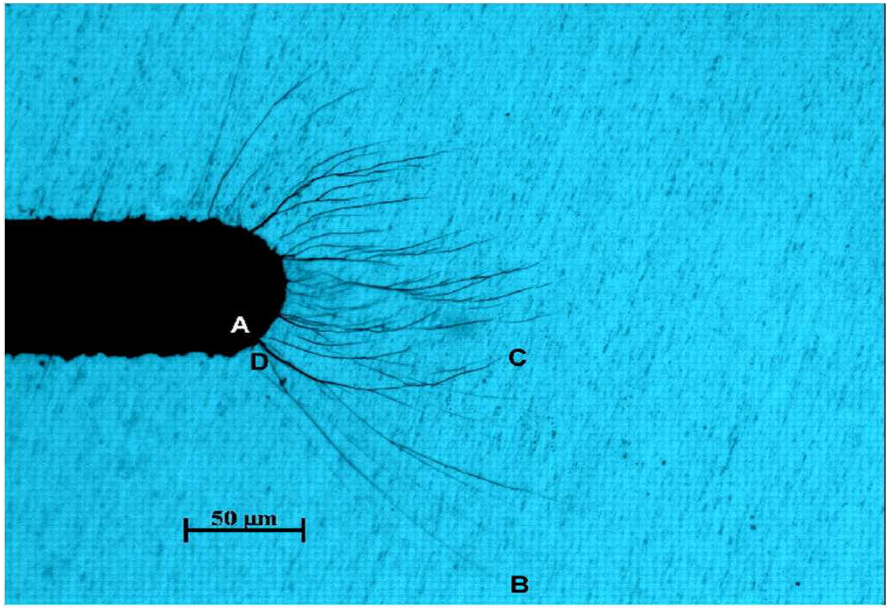


Mp= 0.484 (mixed mode)

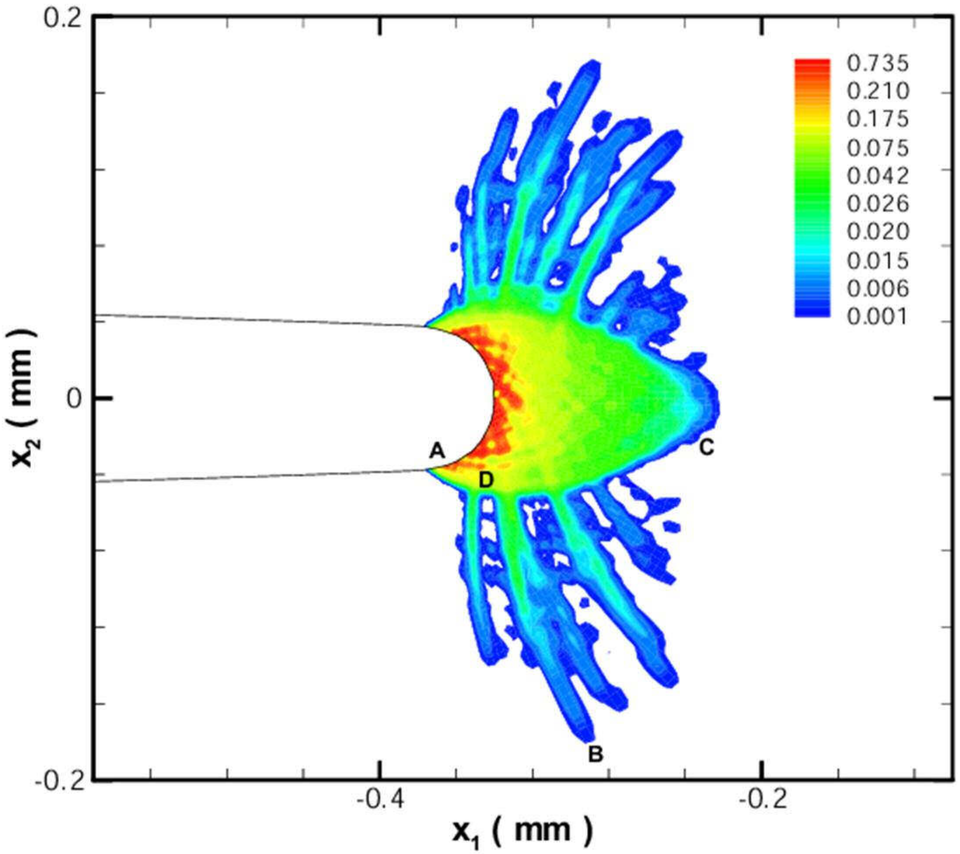
P = 14.1 kN

Shear band patterns near the notch root

Experiment



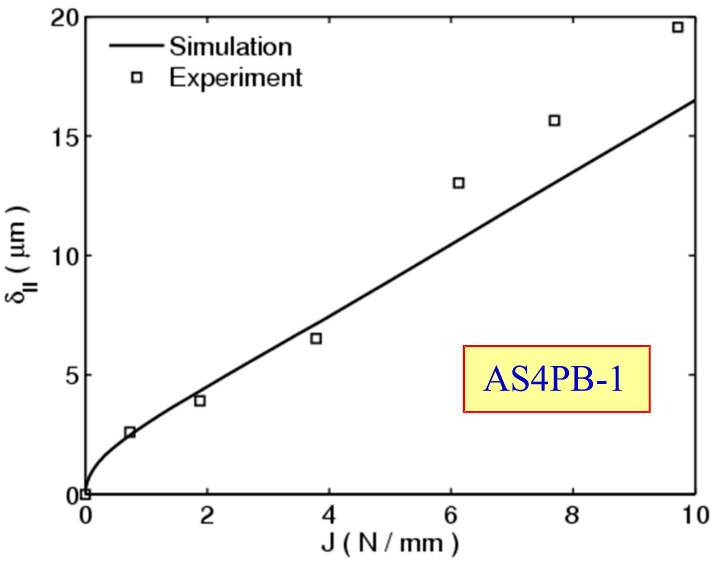
Simulation

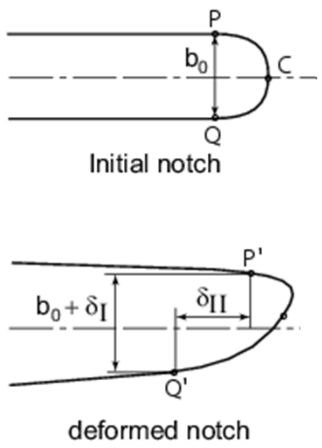


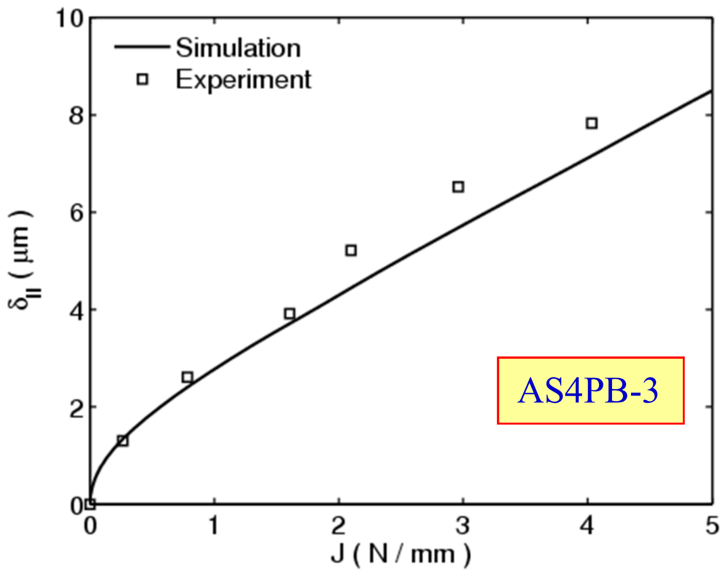
P = 2.3 kN

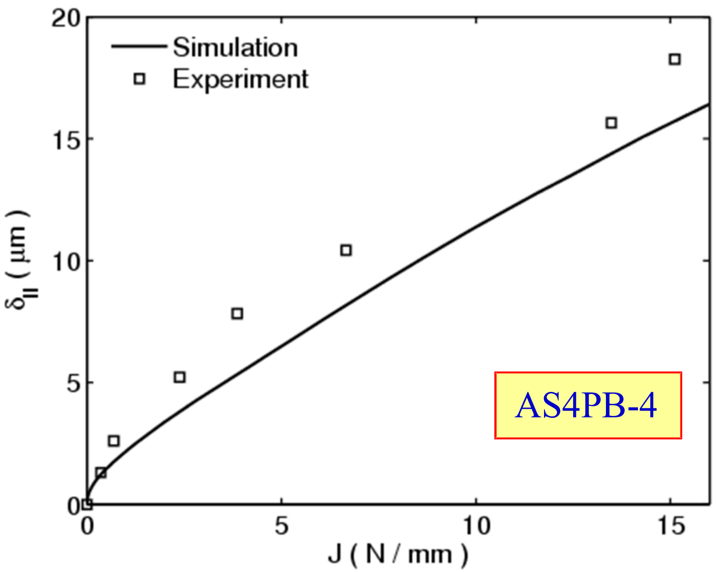
Me = 1 (pure mode I)

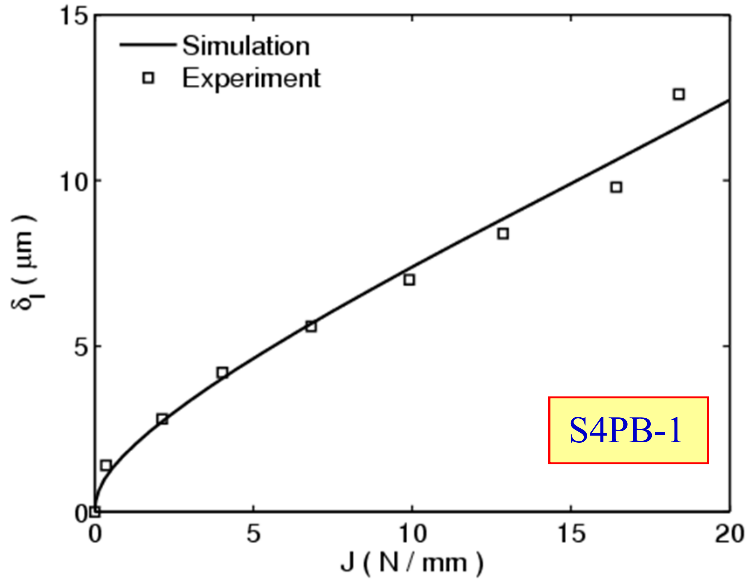
Notch opening (δI) and shear (δII) displacements with *J*



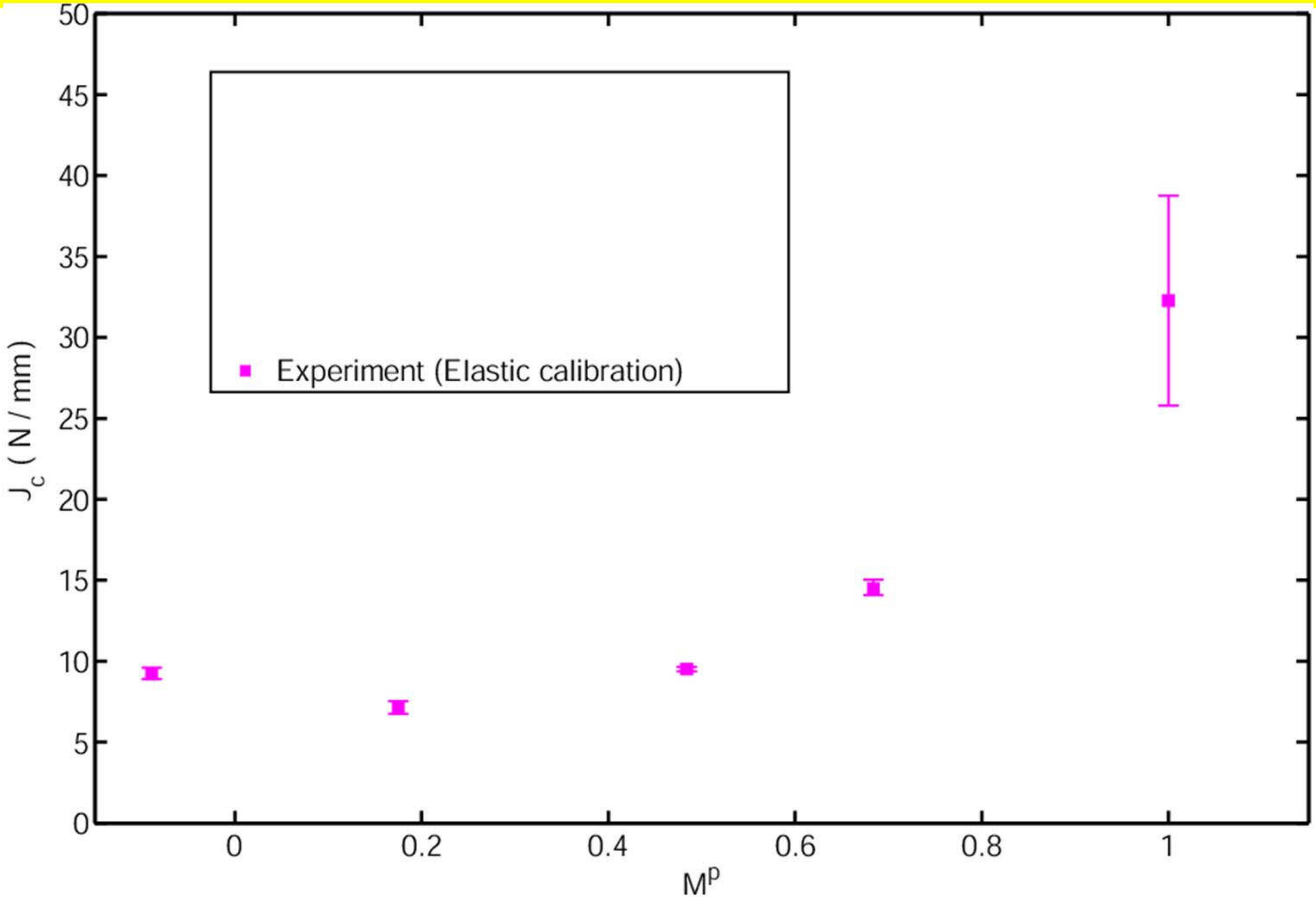






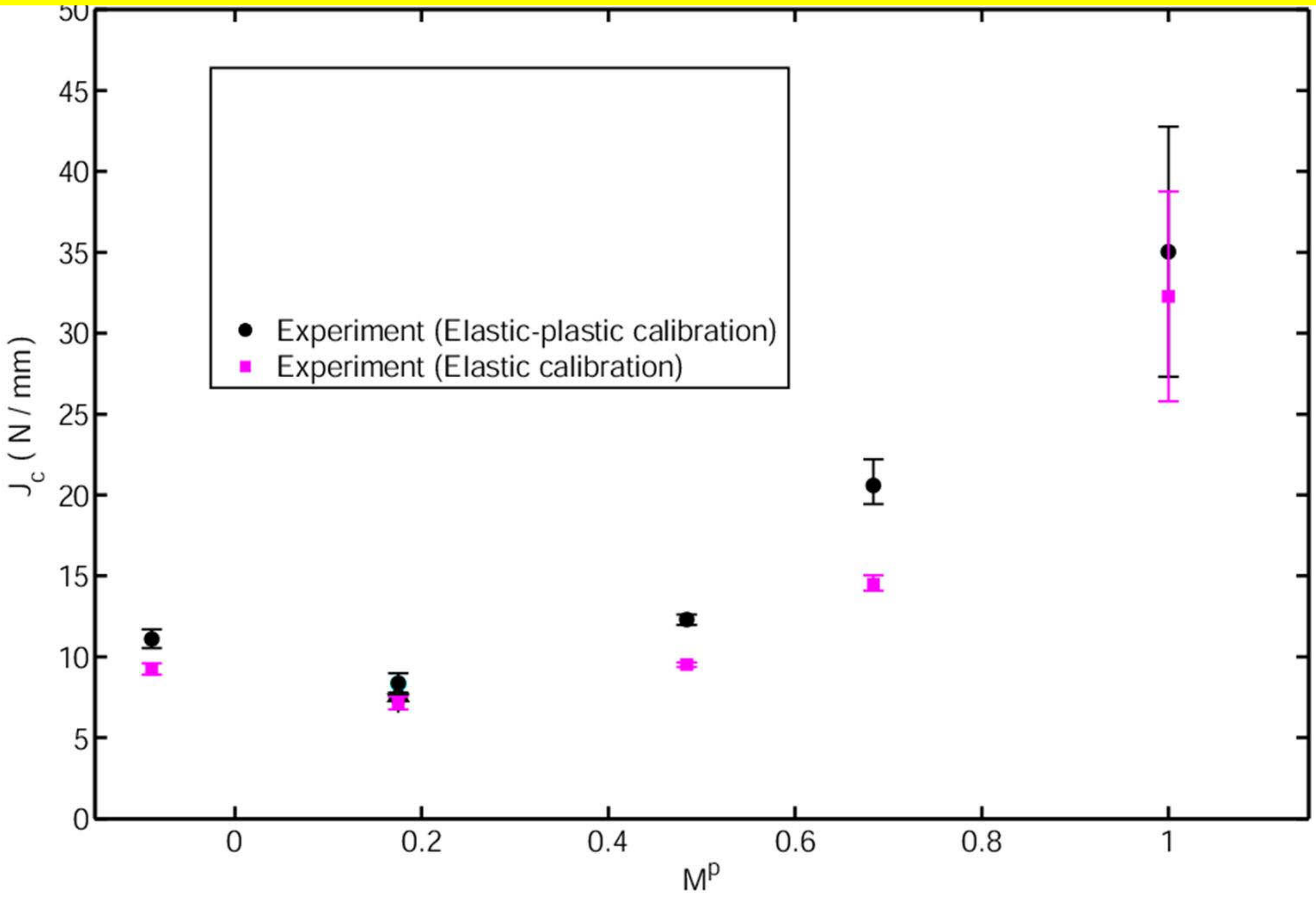


Variation of fracture toughness with mode mixity



- *Jc* increases with Mp
- *Jc* under mode I > 4 times that under mode II

Variation of fracture toughness with mode mixity



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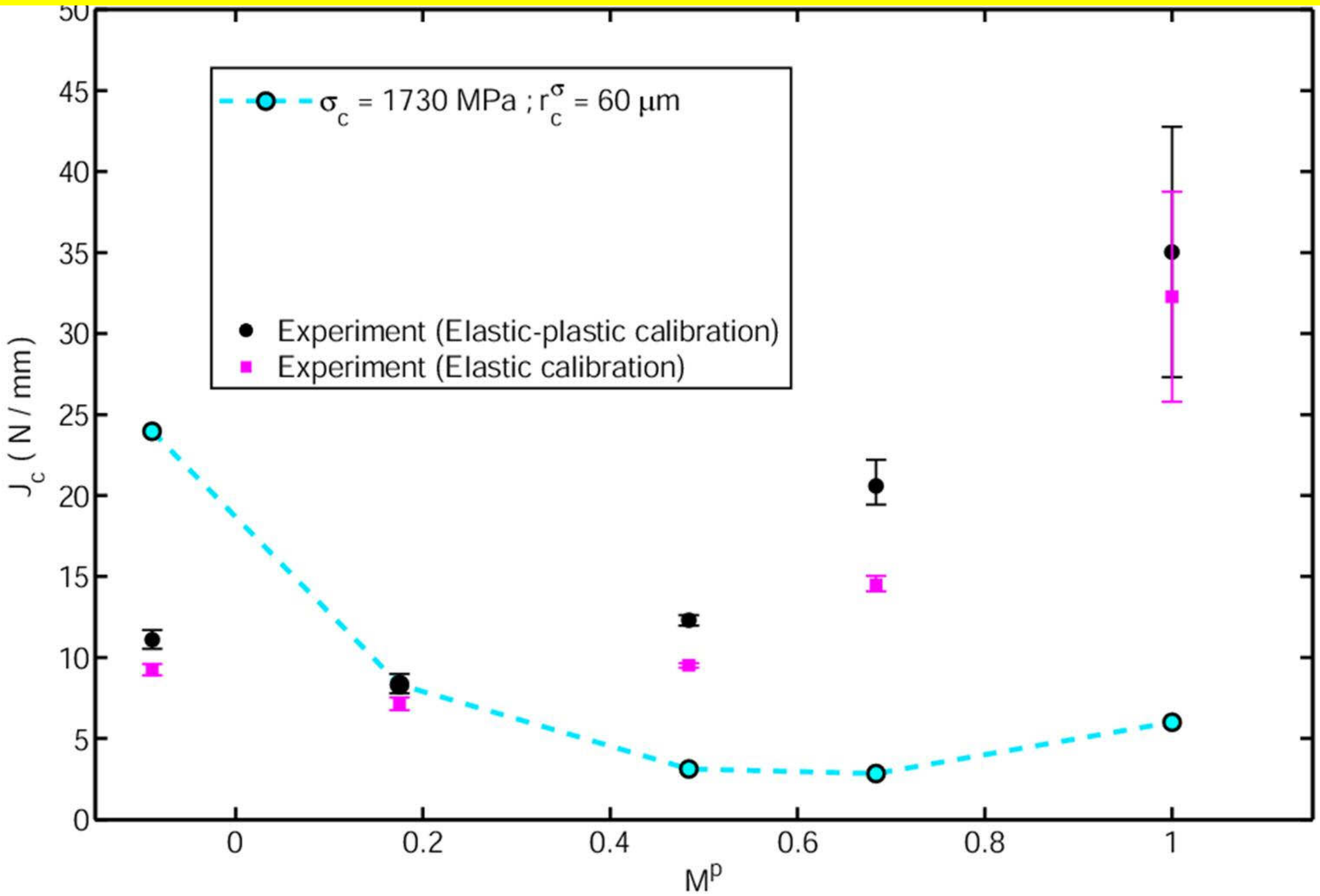
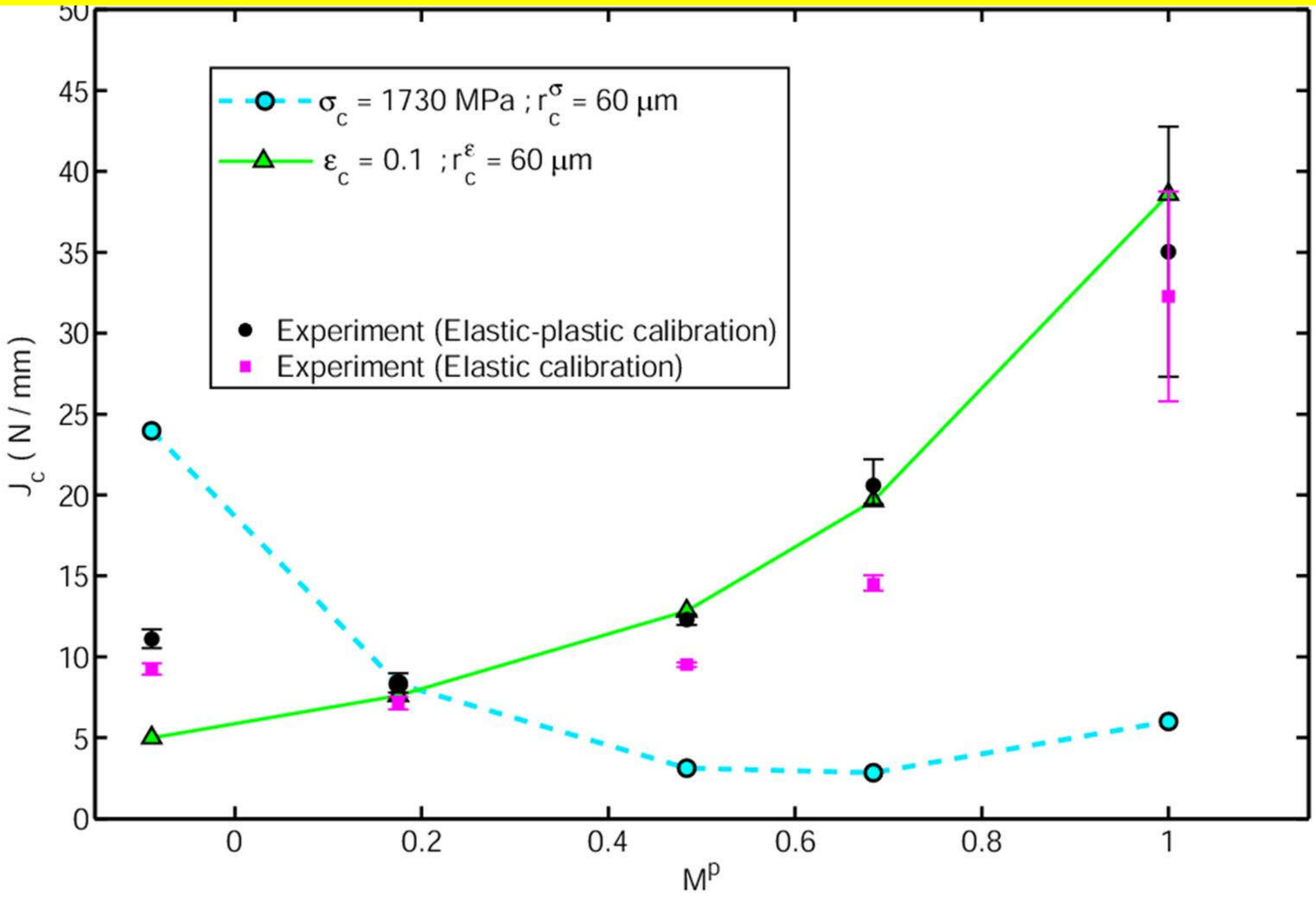


- *Jc* increases with Mp
- *Jc* under mode I > 4 times that under mode II
- Critical stress based criterion is not suitable

Variation of fracture toughness with mode mixity



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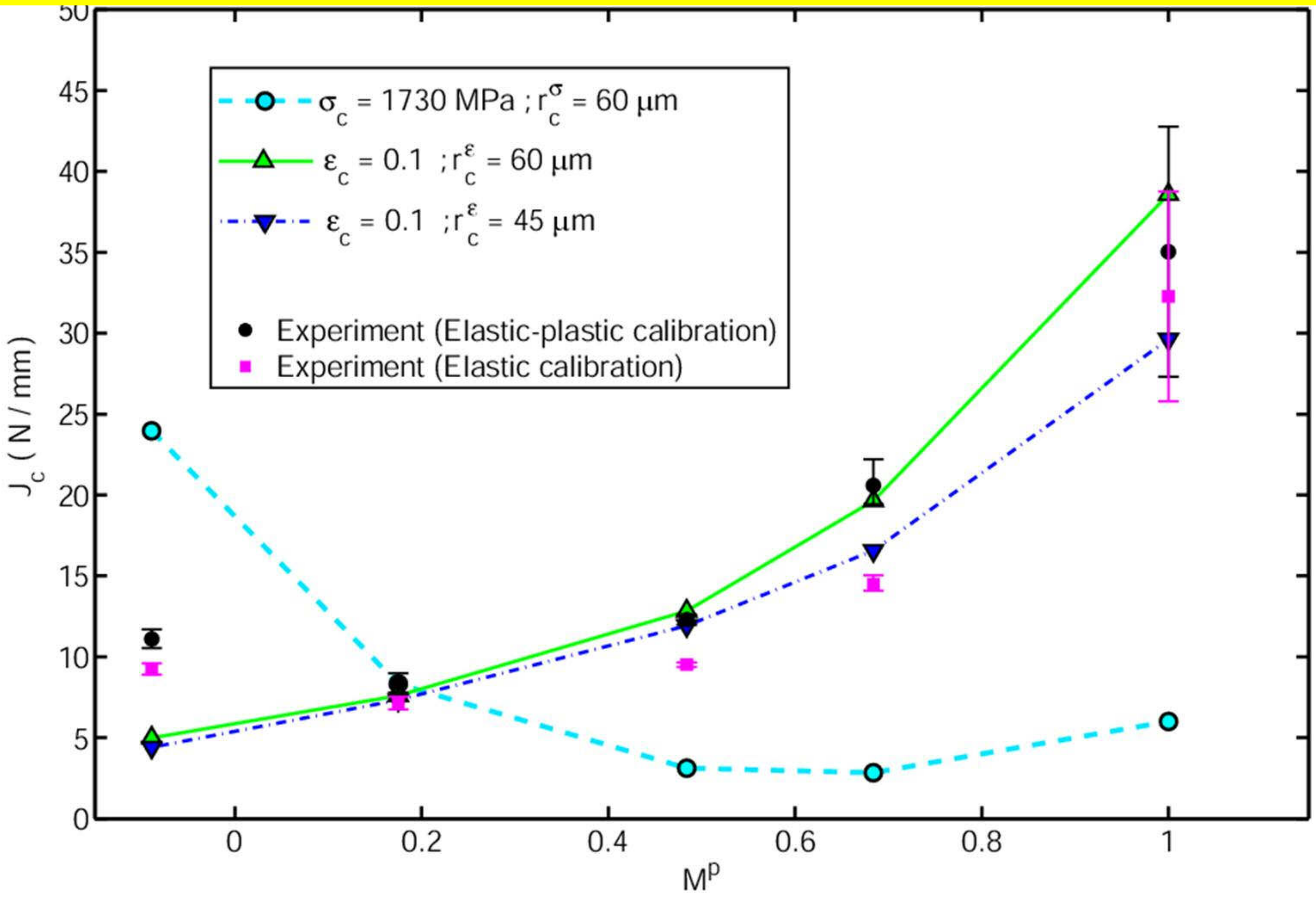
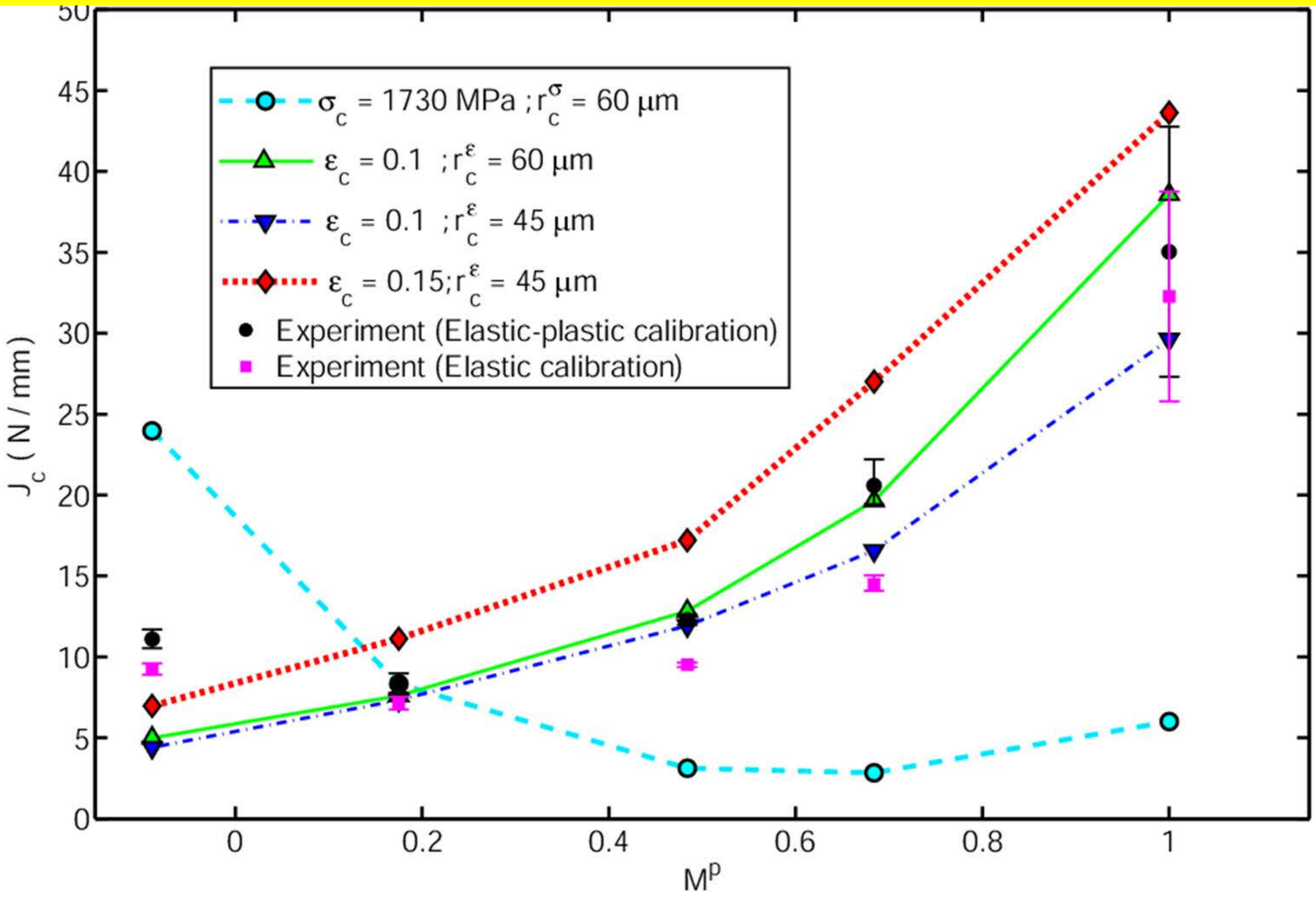


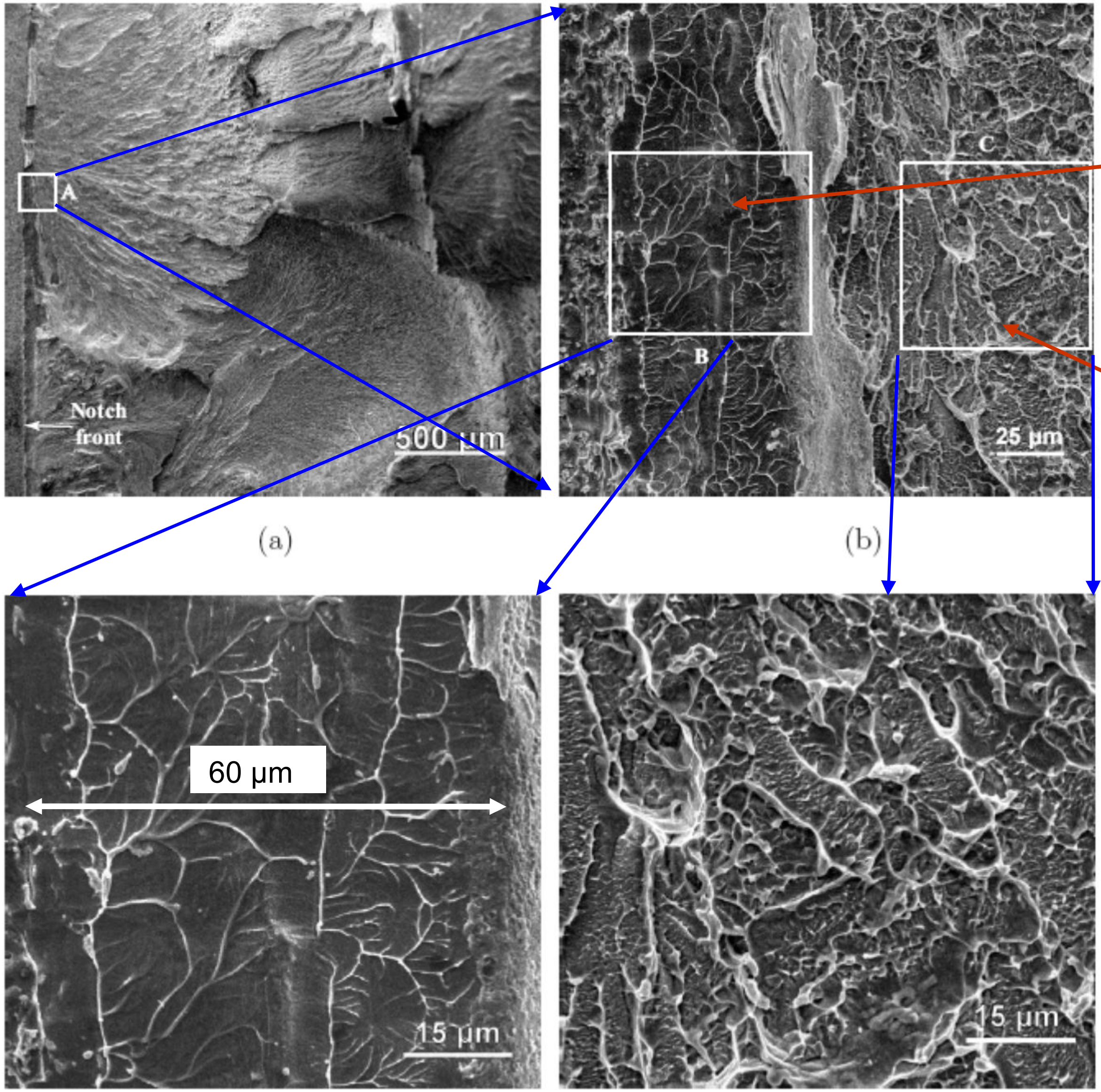
Variation of *Jc* with mode mixity



- *Jc* increases with Mp *Jc* under mode I > 4 times that under mode II

- εc=0.1; rcε = 60 µm match with the experimental data and is appropriate for Vitreloy 1 BMG.

Fractography



(a) (b)
(c) (d)

- Two types of morphologies

1.Smooth and shallow features involving highly smeared vein patterns within 45-60 µm from the notch front

2. Rough and deep features involving coarse dimple patterns superposed on ridges and valleys beyond 60 µm from the notch front

- Similar observations apply for other specimens also

Conclusions

- Experiments combined with FEM show that the fracture criterion for a ductile BMG is strain controlled with a critical length of 60 microns.
- At notch tips: shear bands turn into shear cracks, which grow stably before final fracture. Cracks grow inside shear bands!
- Still need to understand a lot of things w.r.t. fracture in amorphous solids!