2014.03.25. Current Status of Structural Materials

Development of high toughness Bulk metallic glass composite with Transformation mediated 2nd phase

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→ 2 different deformation behaviors of BMGCs depending on 2nd phases

work-softening vs work-hardening behavior → Self healing?

- Development of "Work-hardenable" BMGCs with transformable 2nd phases

1) Fabrication of BMGCs with transformable 2nd phases

2) Evaluation of deformation mechanism in BMGCs

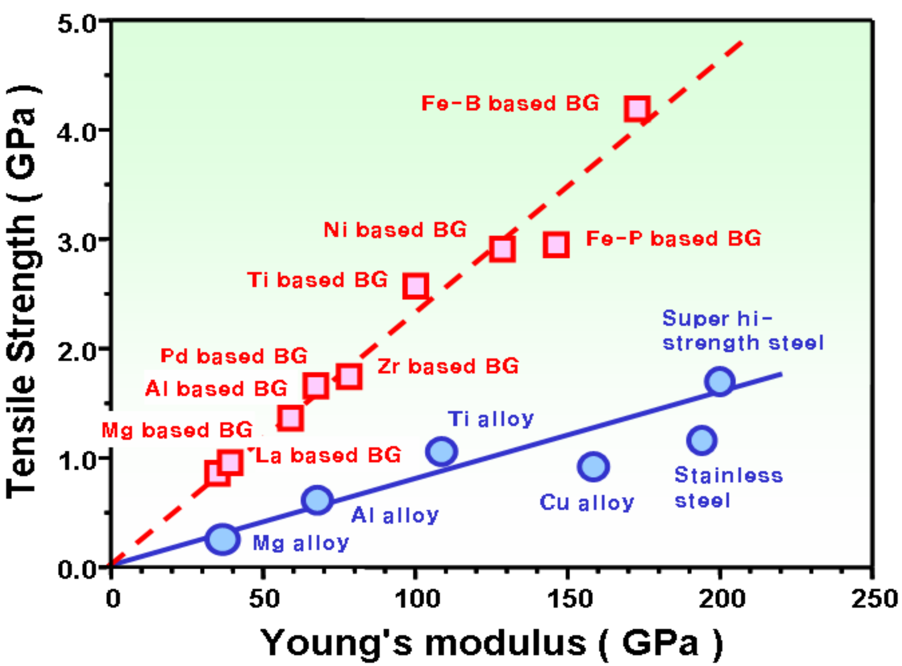
- Comparison of Work-hardenability depending on 2nd Phases

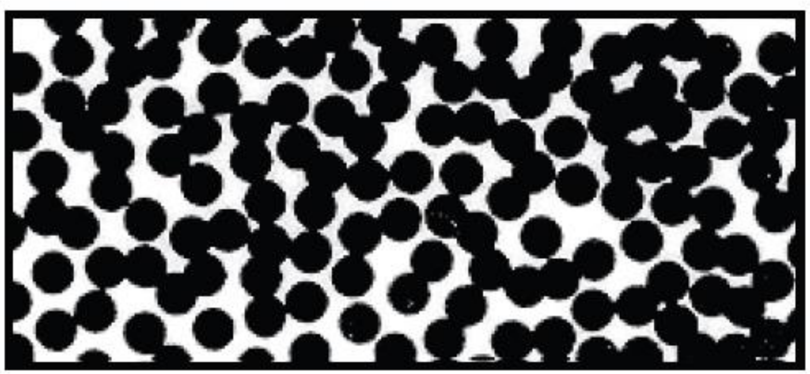
3) Hard ceramic, Soft crystalline, Transformation mediated

4) Different martensitic transformation temperature

⇨ Optimization of work-hardenability in BMGCs with transformable 2nd phases by controlling V_f and M_S temp.

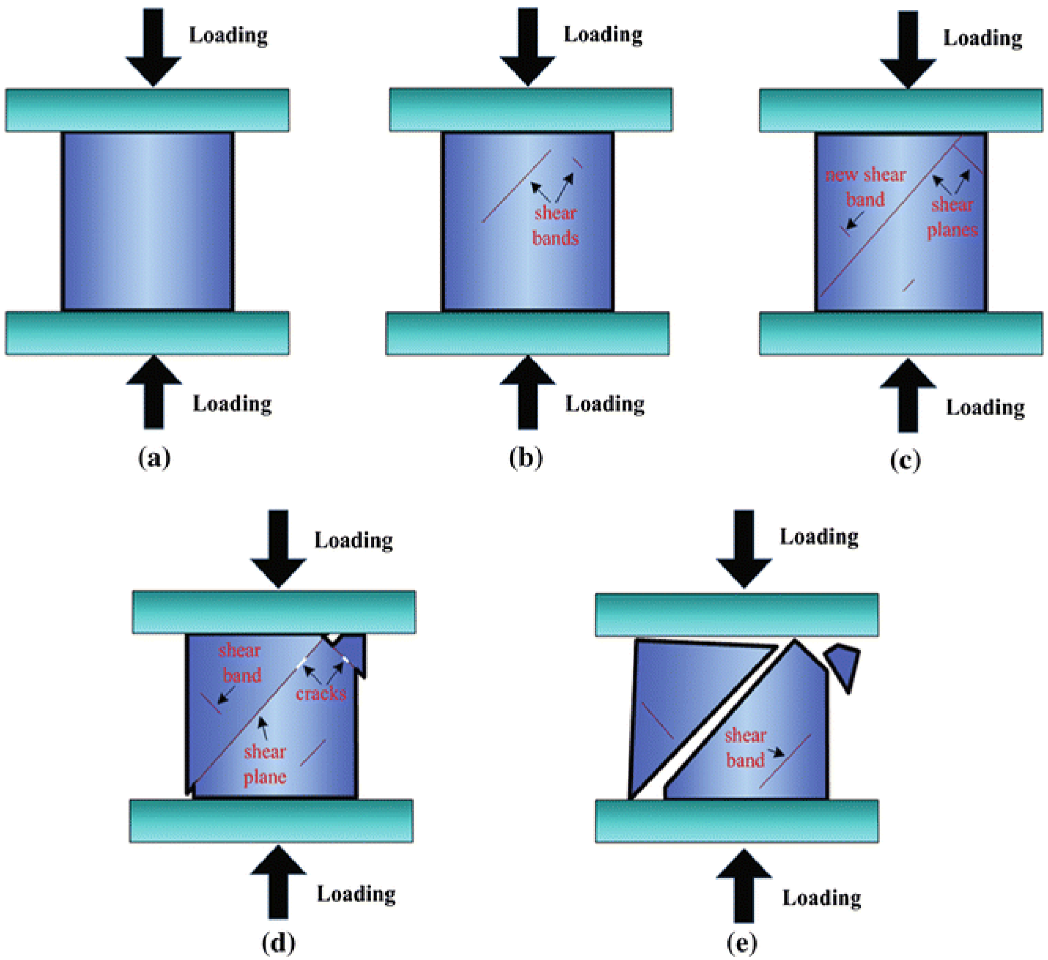
Necessity of work hardenable bulk metallic glass composites



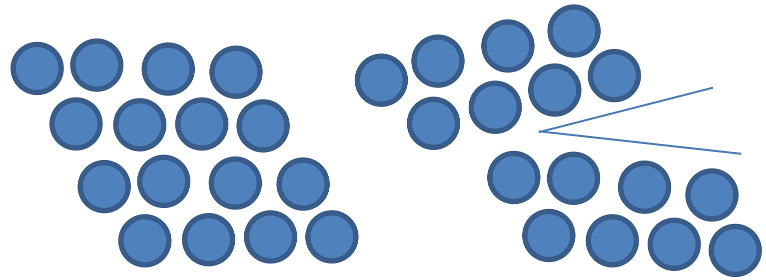


: Metallic Glasses Offer a Unique Combination of High Strength and High Elastic Limit

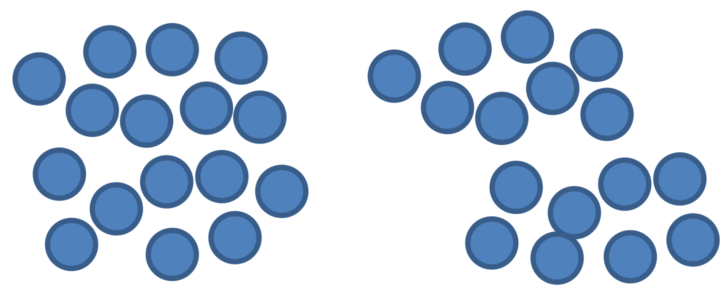
Necessity of work hardenable bulk metallic glass composites



Ceramic : Broken



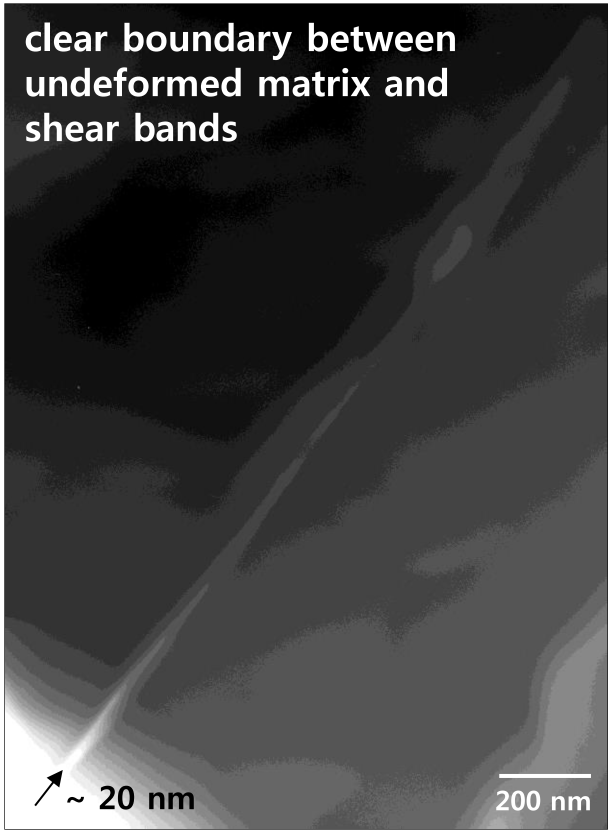
Metallic glass : Weaken

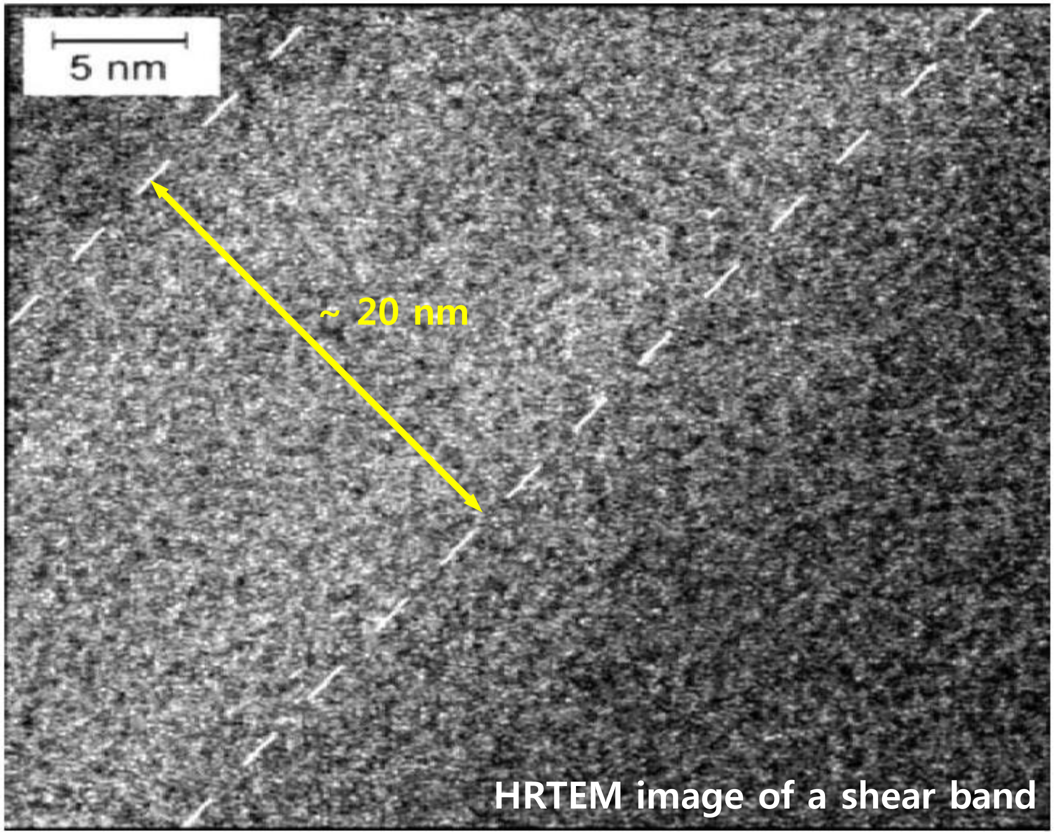


Possibility : Metallic Glasses has an intrinsic plasticity

Necessity of work hardenable bulk metallic glass composites

Shear bands form by accumulation of defects during deformation.



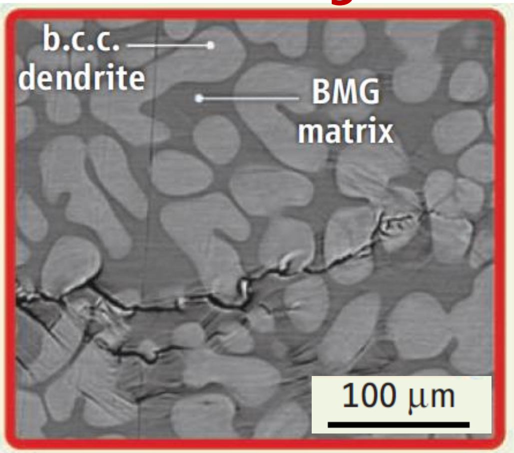


Ref : Prof. Park

Shear deformed areas with the same composition & different density of free volume

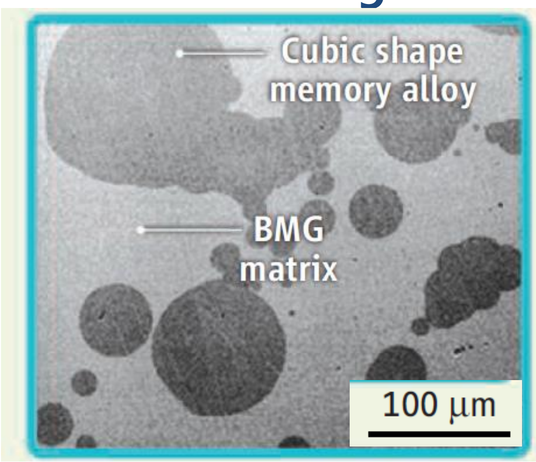
Necessity of work hardenable bulk metallic glass composites

1) Ductile phase
→ Work softening



$Zr_{39.6}Ti_{33.9}Nb_{7.6}Cu_{0.5}Be_{12.5}$

2) Transformation media
→ Work hardening



$Zr_{48}Cu_{47.5}Al_{4}Co_{0.5}$

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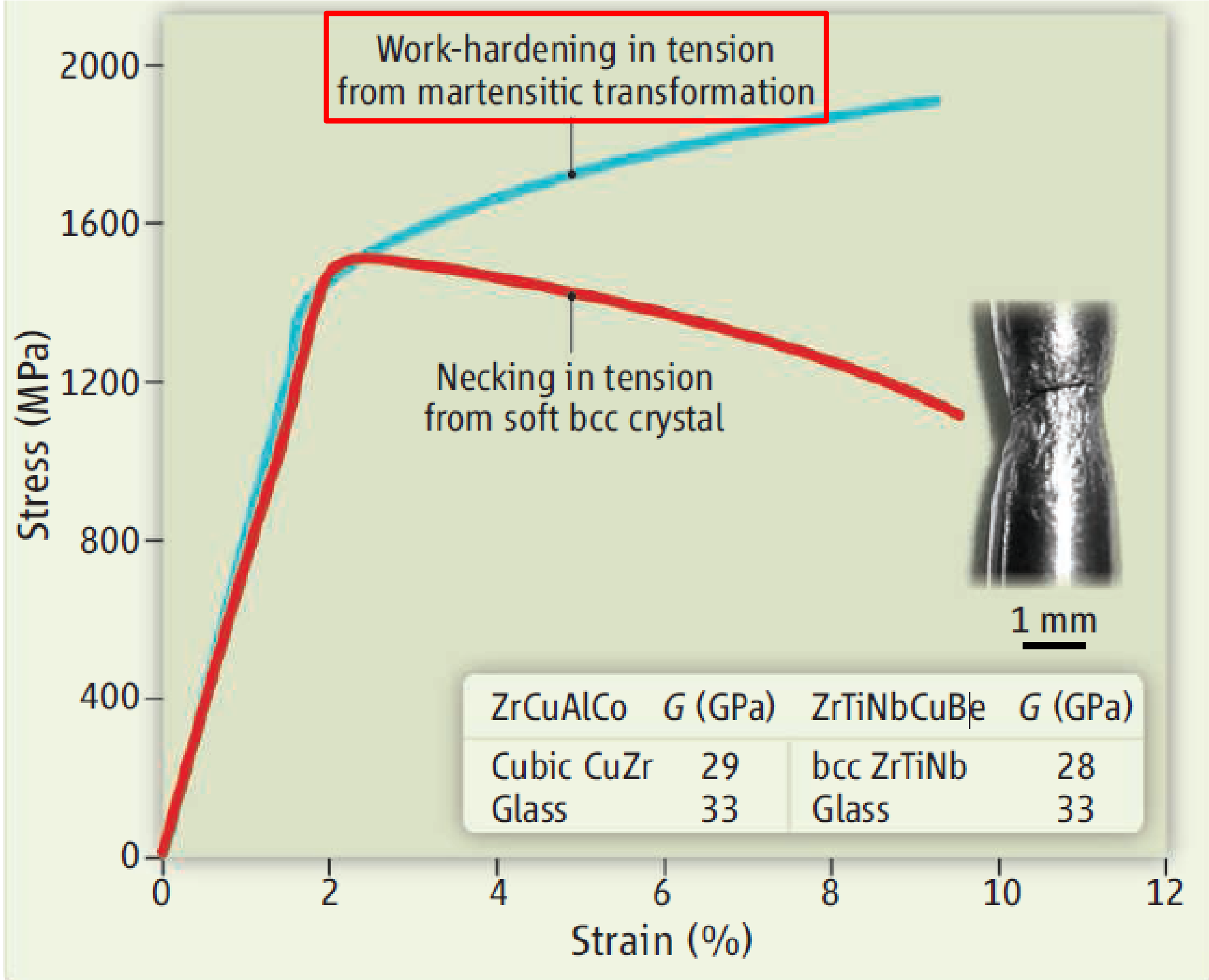
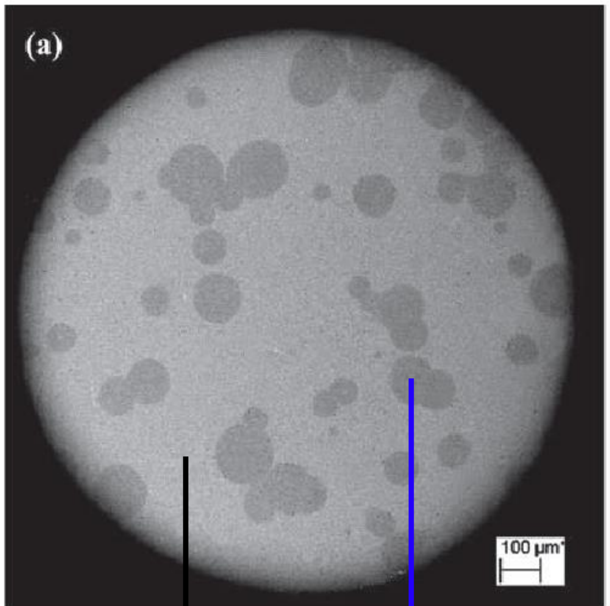


Necessity of work hardenable bulk metallic glass composites

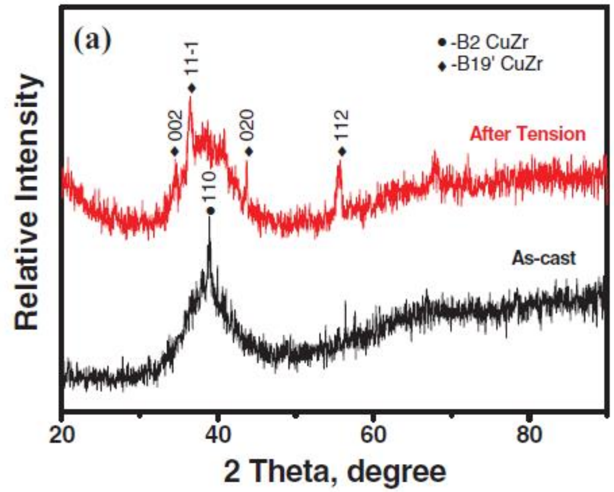
Work-hardening behavior of BMGCs in tension

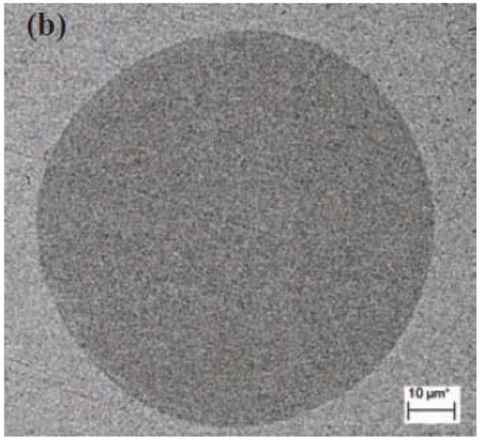
www.MaterialsViews.com

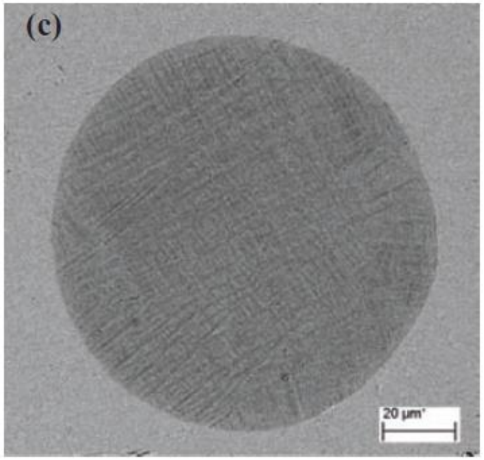
B2 ⟷ B19′ (temperature / stress)



BMG matrix **CuZr B2**
Transformation media







Yuan Wu, et al. Adv. Mater. 2010, 22, 2770–2773

[XRD pattern & Morphology of secondary phase before / after tensile test]

Necessity of work hardenable bulk metallic glass composites

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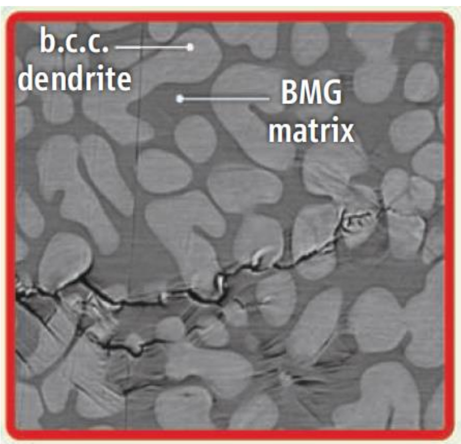
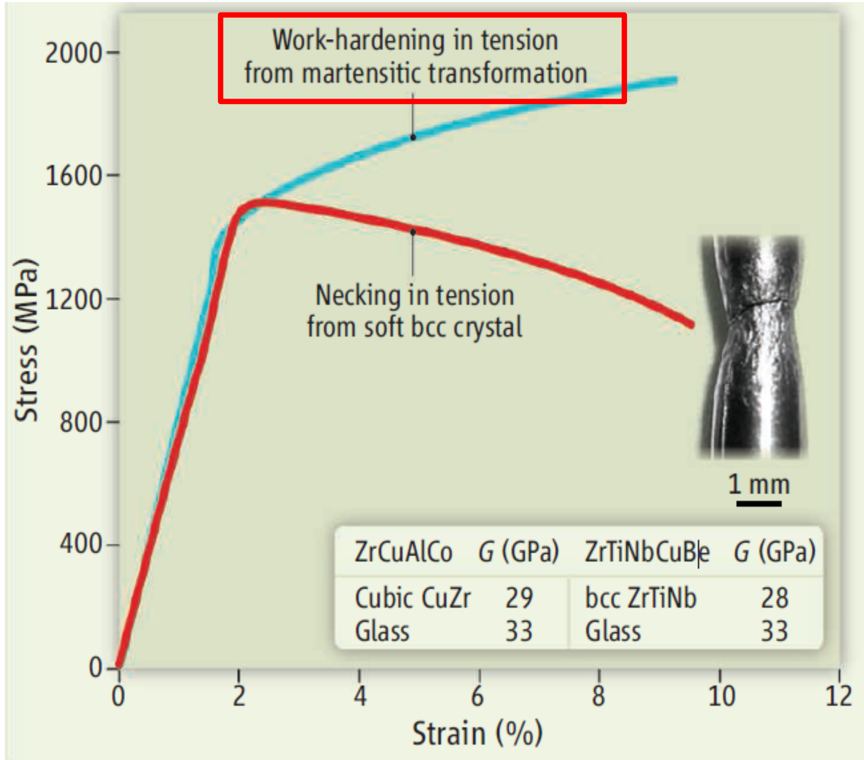
1) Ductile phase
→ Work softening

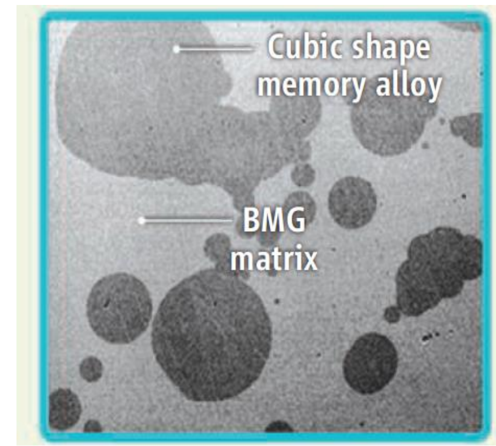
$Zr_{39.6}Ti_{33.9}Nb_{7.6}Cu_{0.5}Be_{12.5}$





2) Transformation media
→ Work hardening

$Zr_{48}Cu_{47.5}Al_{4}Co_{0.5}$



To develop ultra tough BMGCs : Control the characteristics of 2nd phase

1. **Size & Distribution**
2. **Volume fraction**
3. **Transformability:** Martensitic transformation

→ **Modulated Ex-situ Composite**

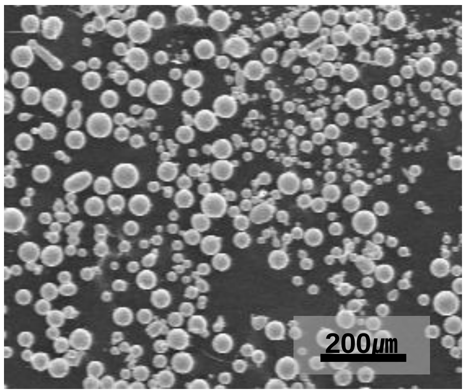
Preparation of metallic glass and SMA powders

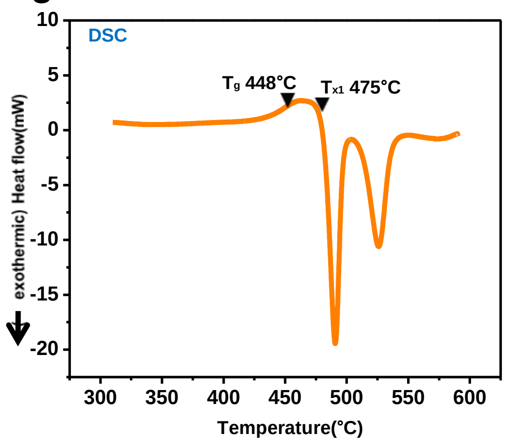
Preparation of Gas atomized powders

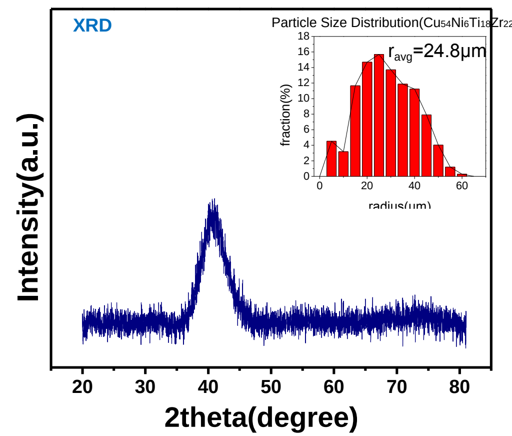
1. Matrix — Cu-based system
2. 2nd phase — TiNiCu B2 phase

TiNi ~ Commercialized transformation media with high performance

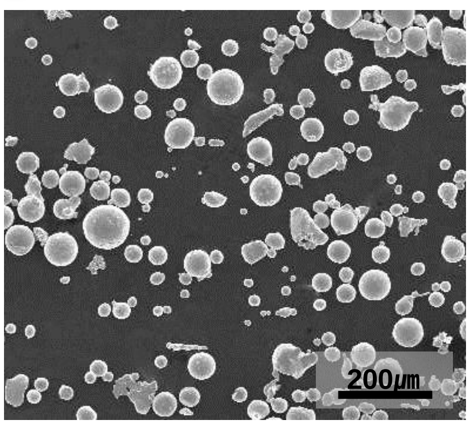
Matrix : Cu based metallic glass

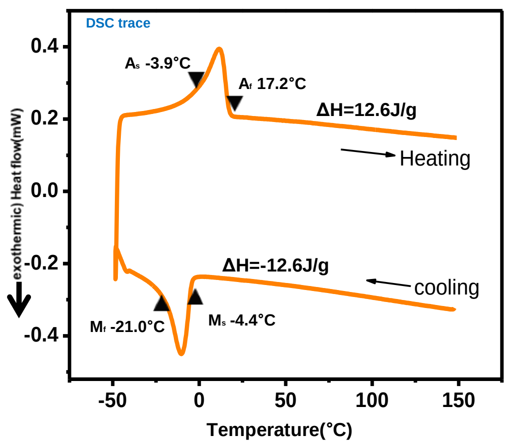


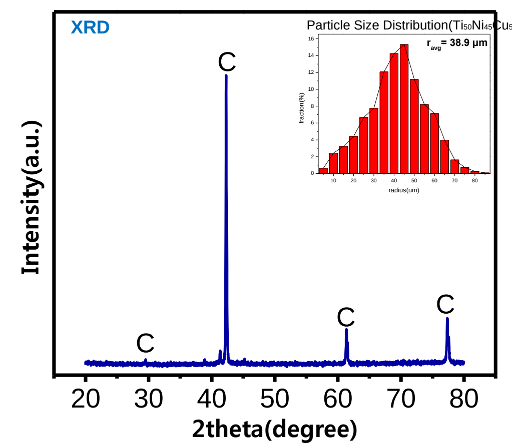




Secondary phase : TiNiCu powder B2 ⟷ B19



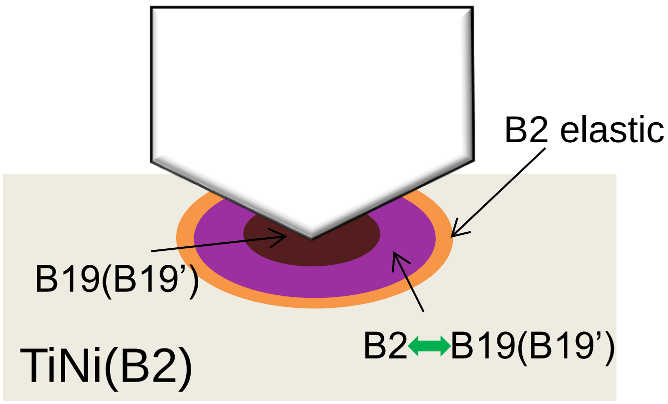


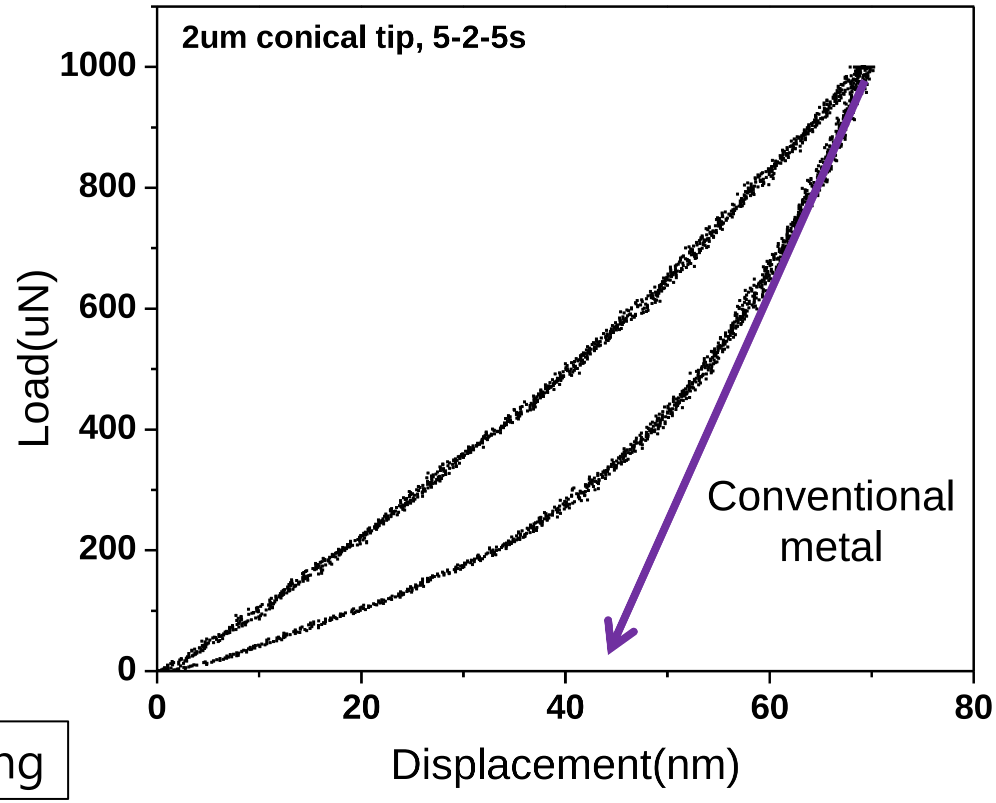


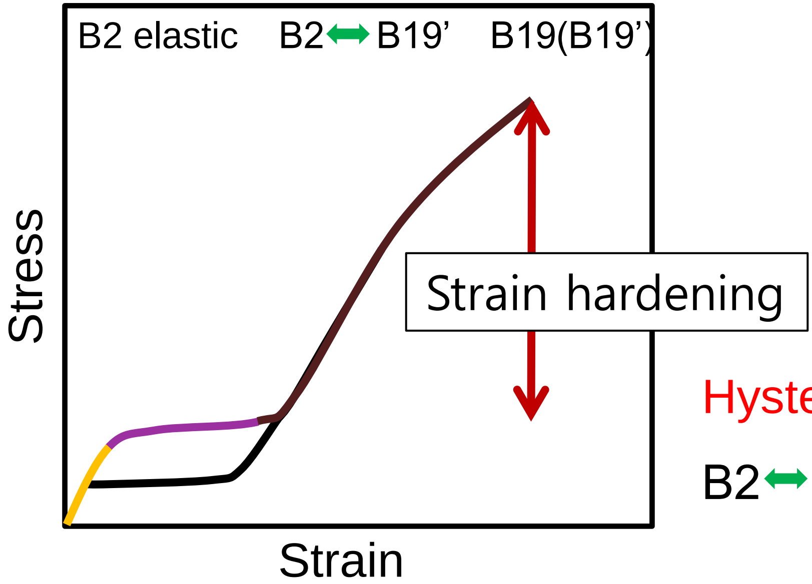
Superelastic property of TiNiCu 2nd phase

- Stress induced transformation

Nano-indentation



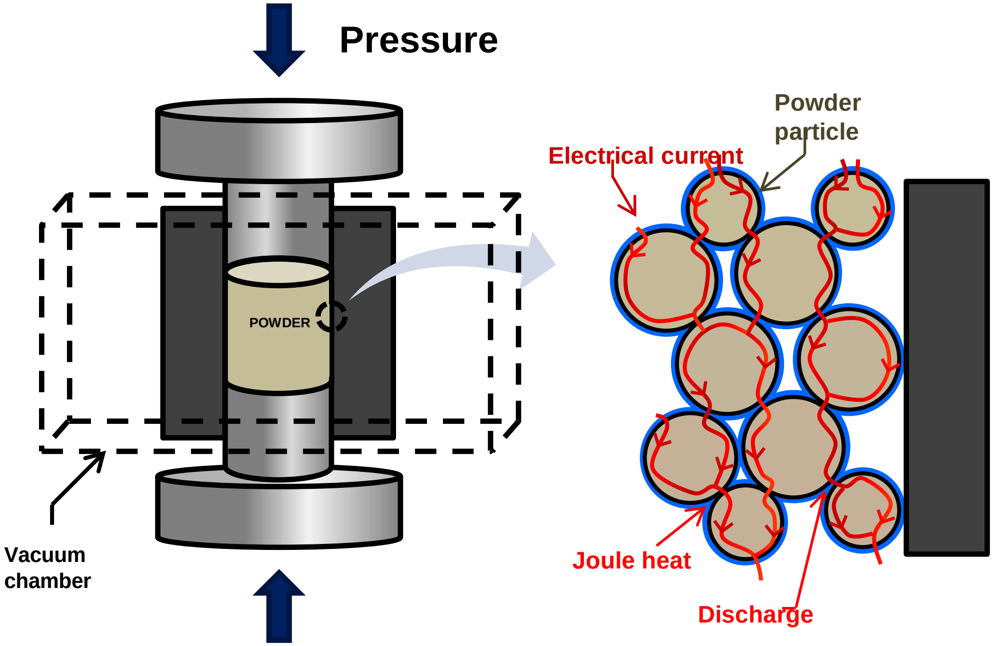




Hysteresis loop : Superelasticity

B2↔B19(B19') reversible martensitic transformation

Preparation of BMGC by Spark Plasma Sintering Method



Temperature : 440~470°C

Time : 15min

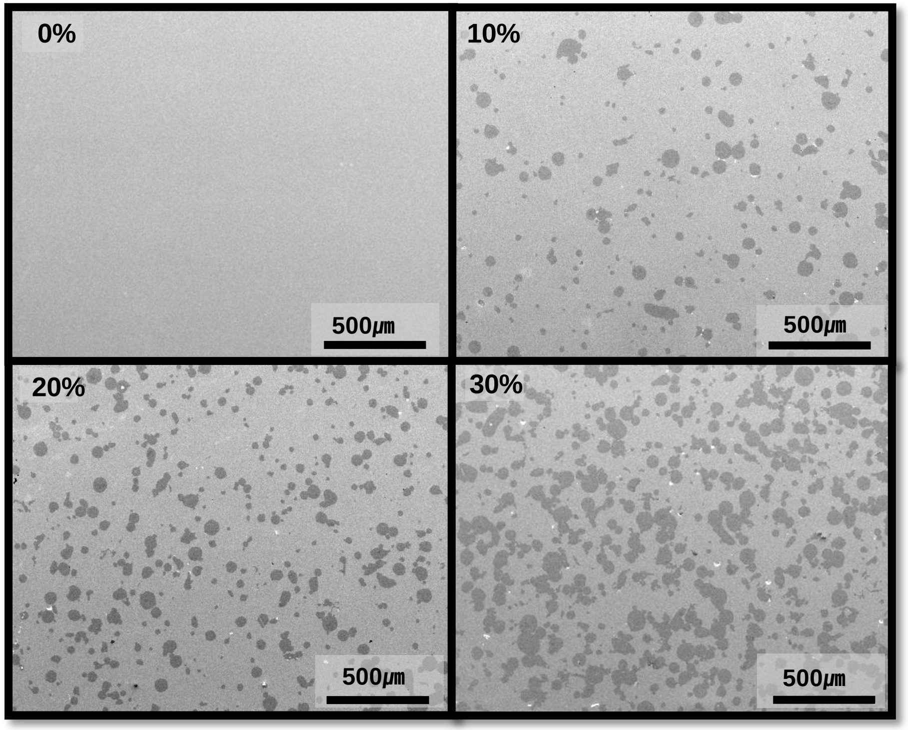
13mm disc, 7mm height

Fabrication : Spark plasma sintering

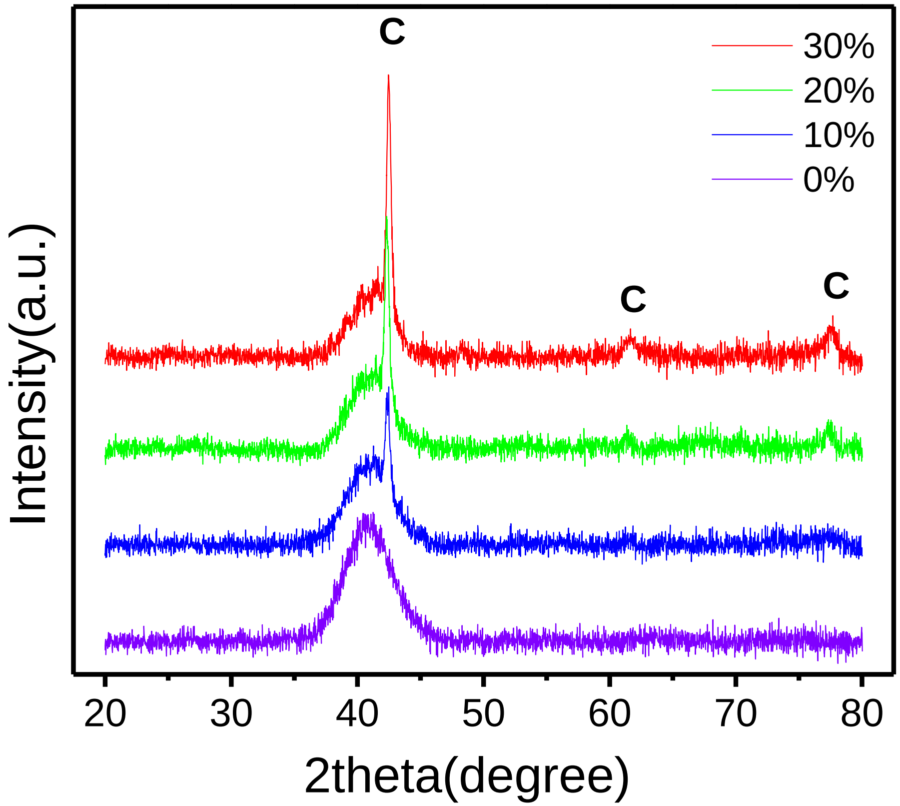
Pressing at Supercooled Liquid Region of mixed powders with high pressure (600MPa) to consolidate the sample through viscous flow of metallic glass matrix.

Fabrication : Spark plasma sintering

SEM image



XRD pattern

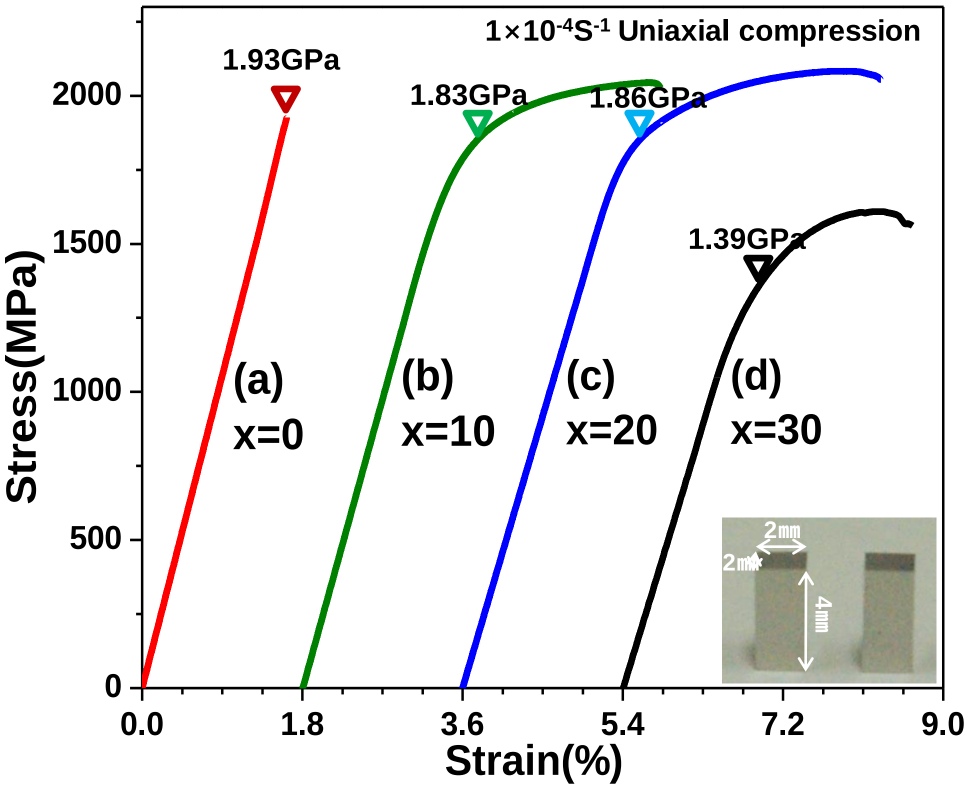


Ultrasonic measurement

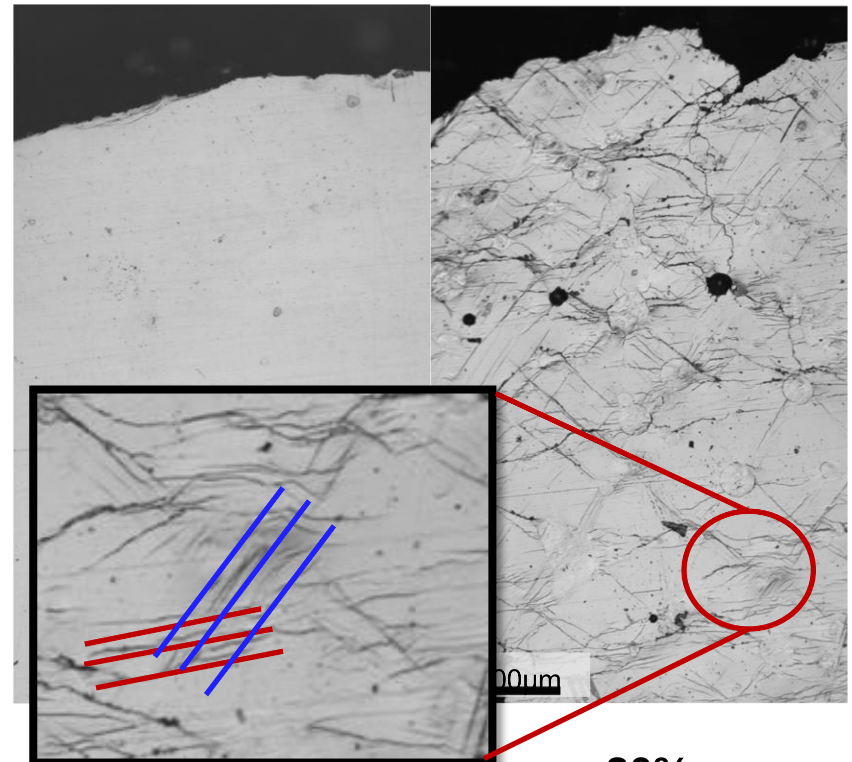
	Density(g/cm)	*v*	E(GPa)	G(GPa)	G/K
0%	7.90	0.360	80.6	29.6	0.21
10%	7.77	0.369	74.2	27.1	0.19
20%	7.67	0.374	70.6	25.7	0.18
30%	7.58	0.378	68.4	24.8	0.17

Compression test: Large plasticity and work-hardening behavior

Cu-based BMG + x% TiNiCu



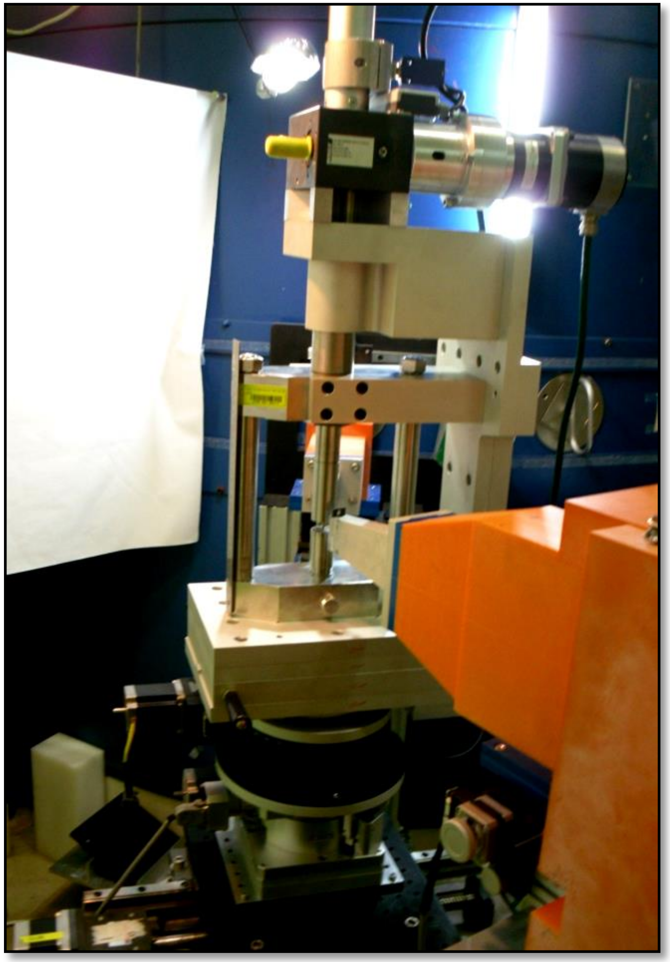
Cu-based BMGC with 20% TiNiCu



1. Large plasticity and Work hardening behavior
2. Fracture crack – propagate through interface of the 2nd phase and matrix
3. Multiple shear bands: initiation & propagation

Deformation Mechanism of BMGC with transformable 2nd phase

- **Neutron source diffractometer, wave length=1.46Å**
- **Gauge volume: 2 x 2 x 2 mm³ (along the radial direction)**
- **Deep penetration depth (several centimeters in most materials)**

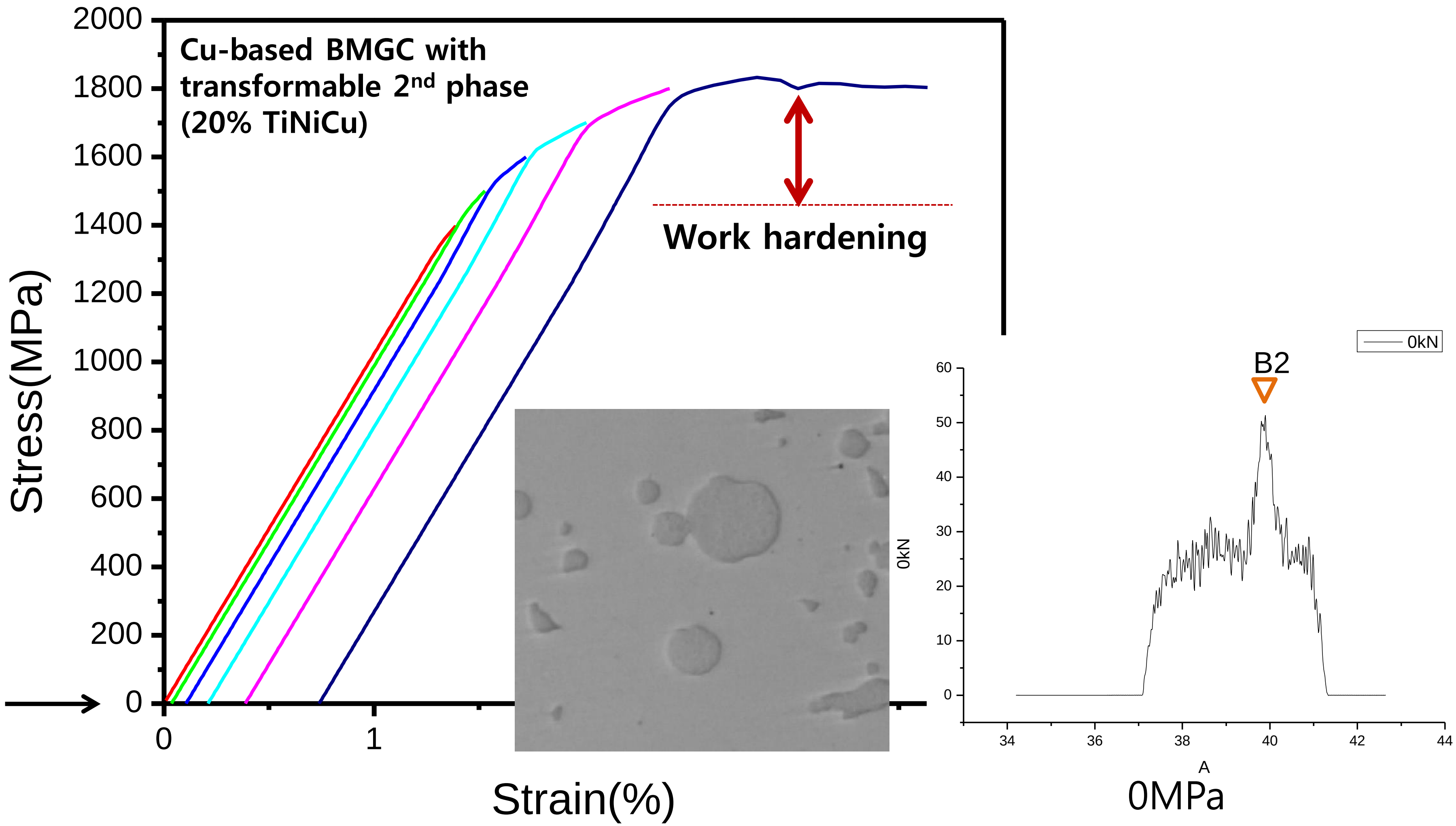


Neutron diffraction

➡ **Powerful tool for analyzing internal strain/phase in bulk samples during deformation**

KAERI

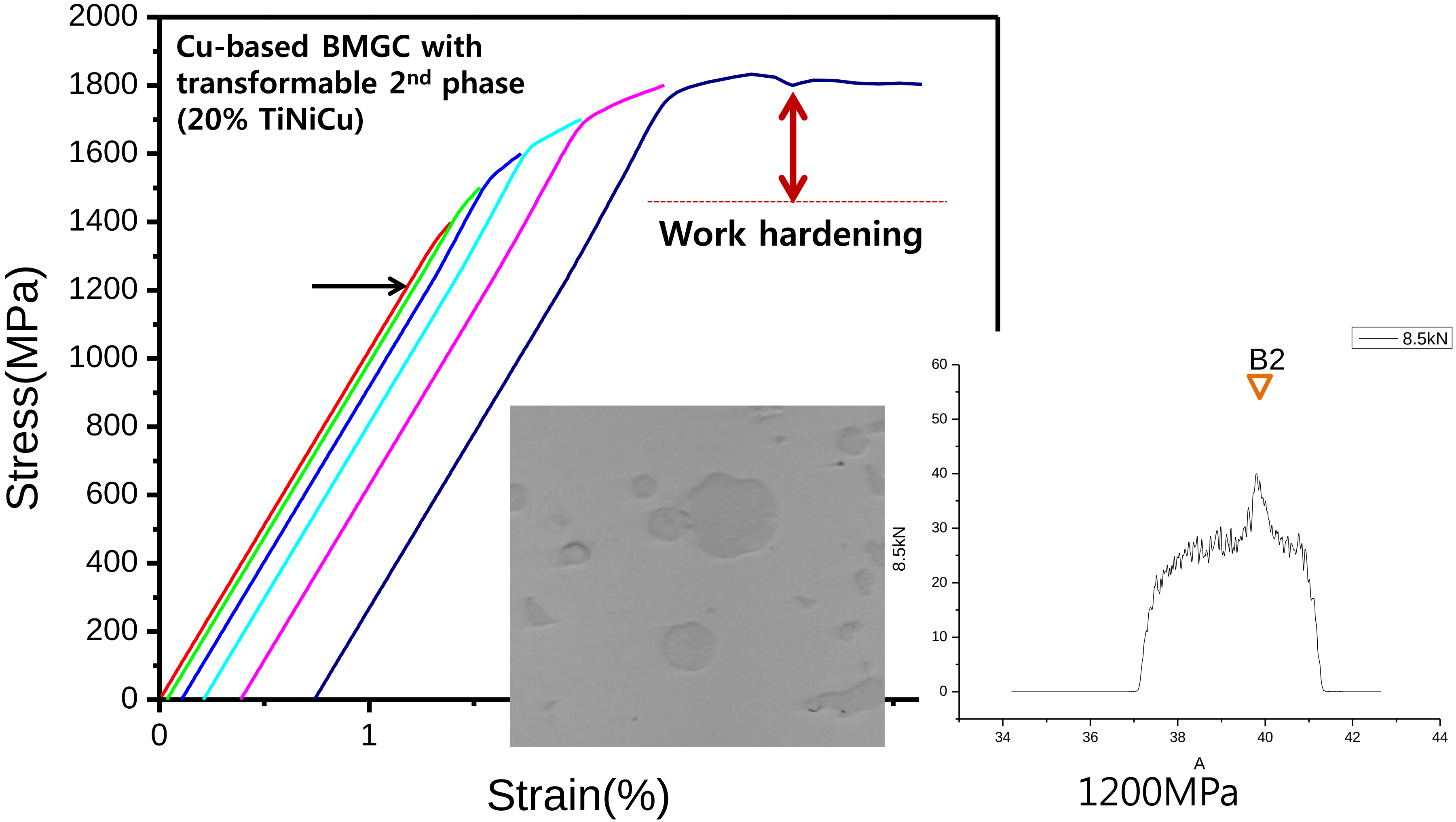
In-situ neutron diffraction measurement under compression



Work hardening of BMGCs

1. M.T. is constrained by horizontal frame of MG matrix because of the imbalance of Poisson’s ratio during M.T.(~0.5) with elastic loading of MG matrix(~0.33).

In-situ neutron diffraction measurement under compression



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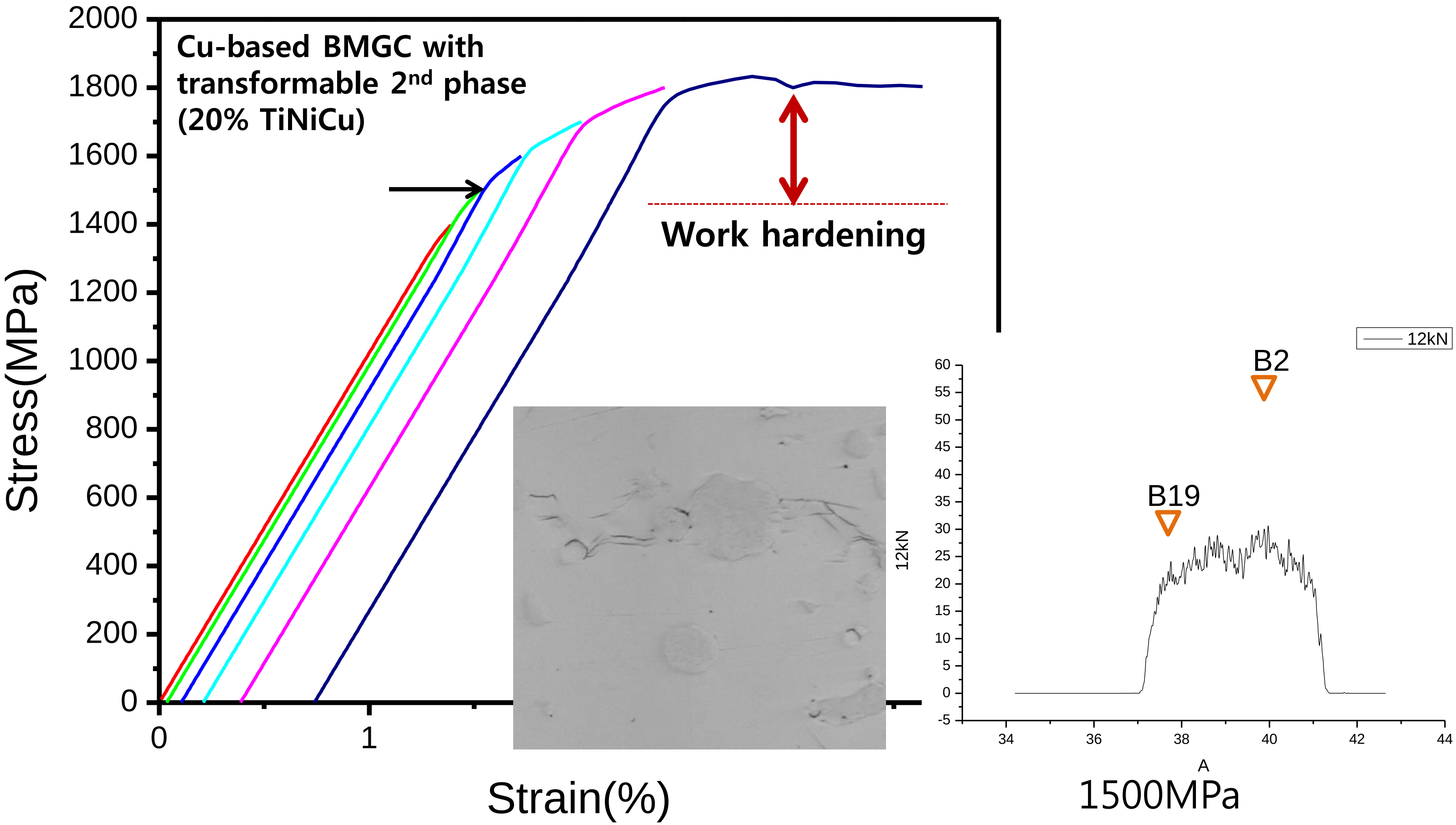
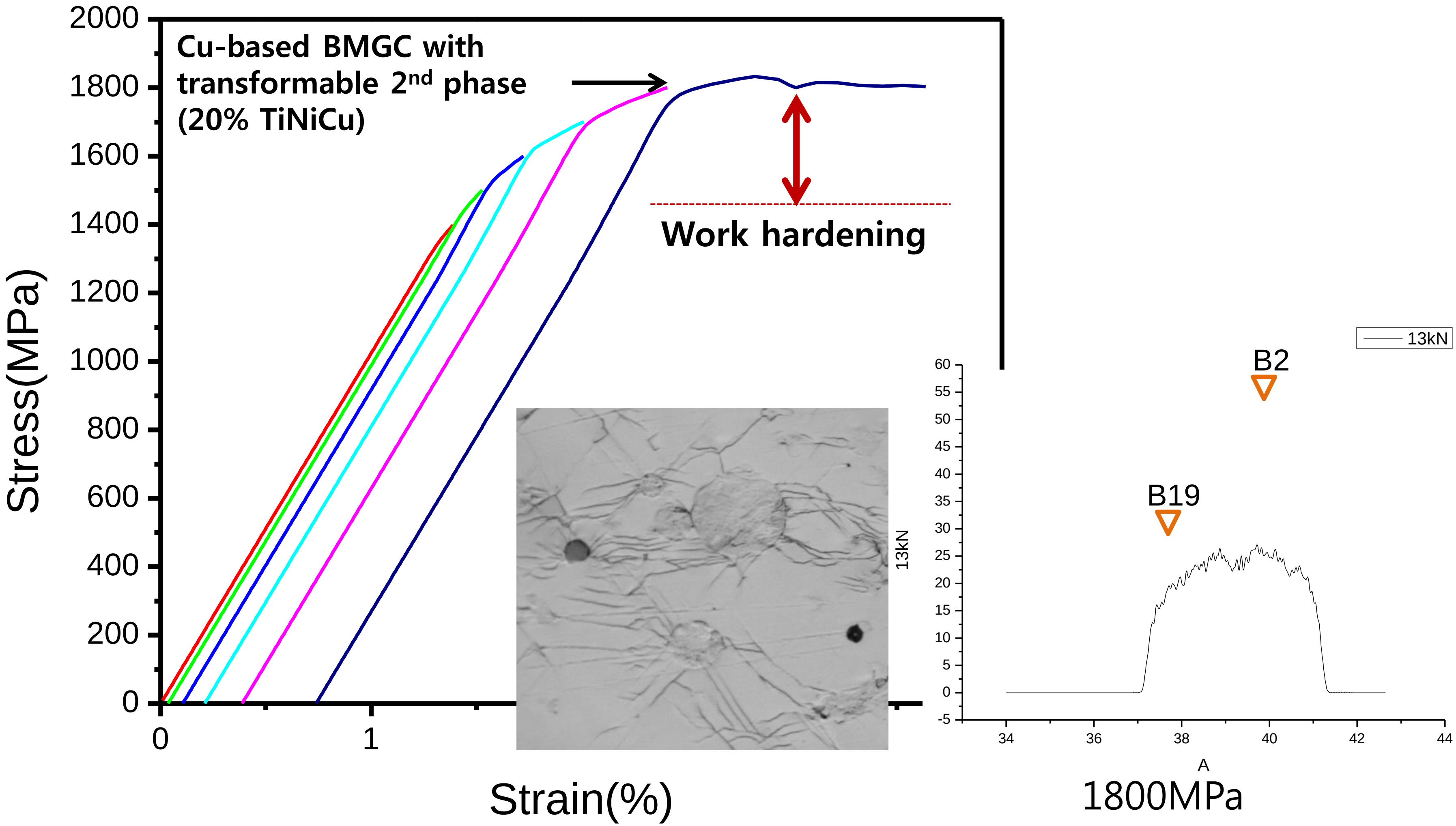


Work hardening of BMGCs

2. M.T./slip deformation of 2^{nd} phase are allowed to proceed with formation of shear bands in the metallic glass matrix near yield strength.



Work hardening of BMGCs

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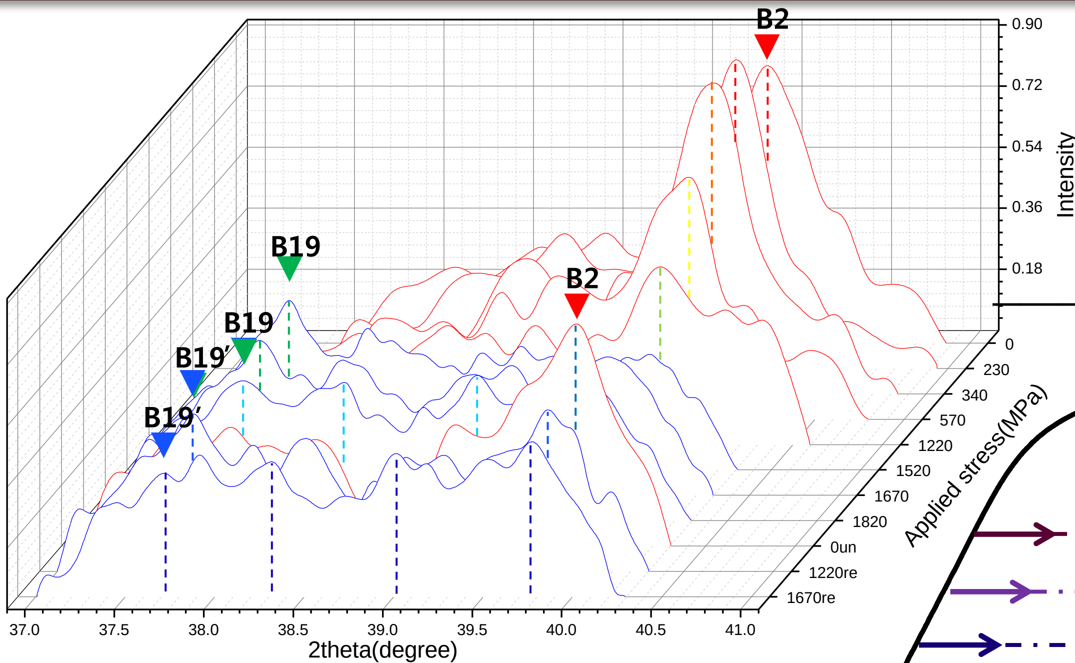
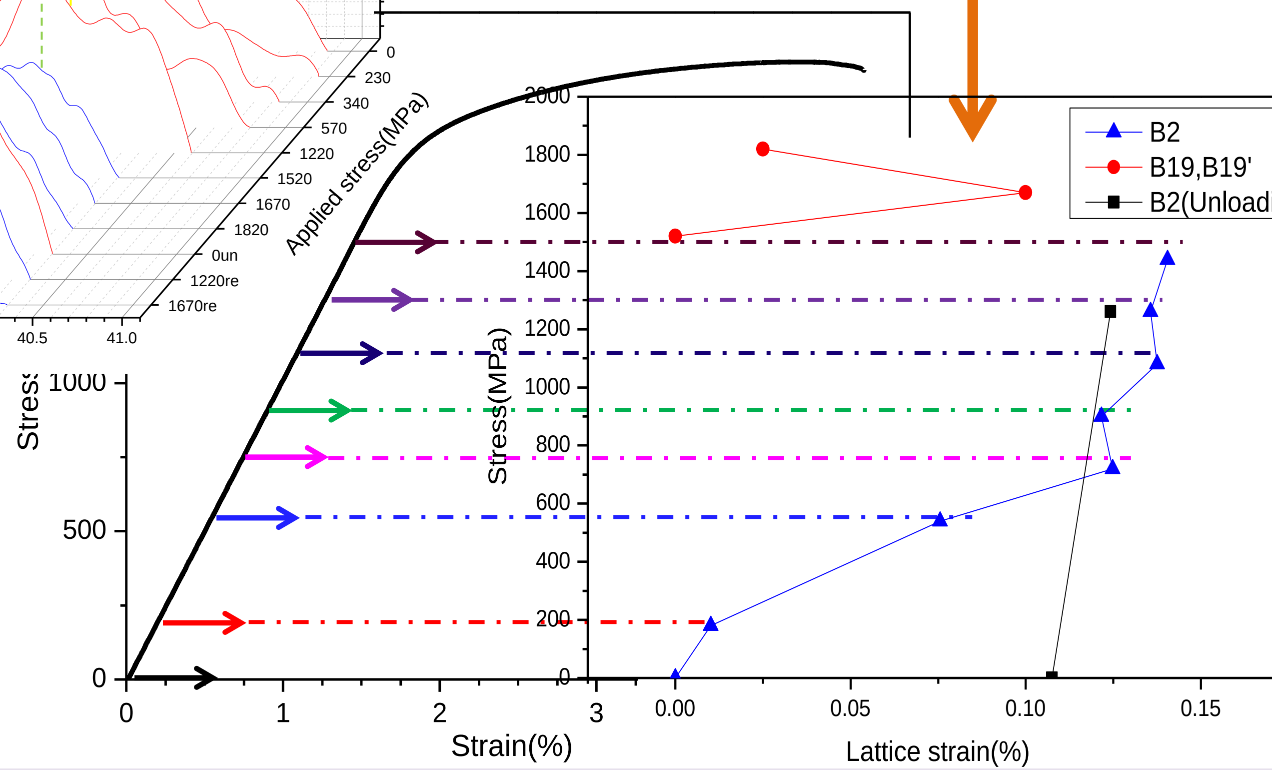


$$\lambda = 2d\sin\theta \quad , \varepsilon = \frac{d}{d - d_0}$$



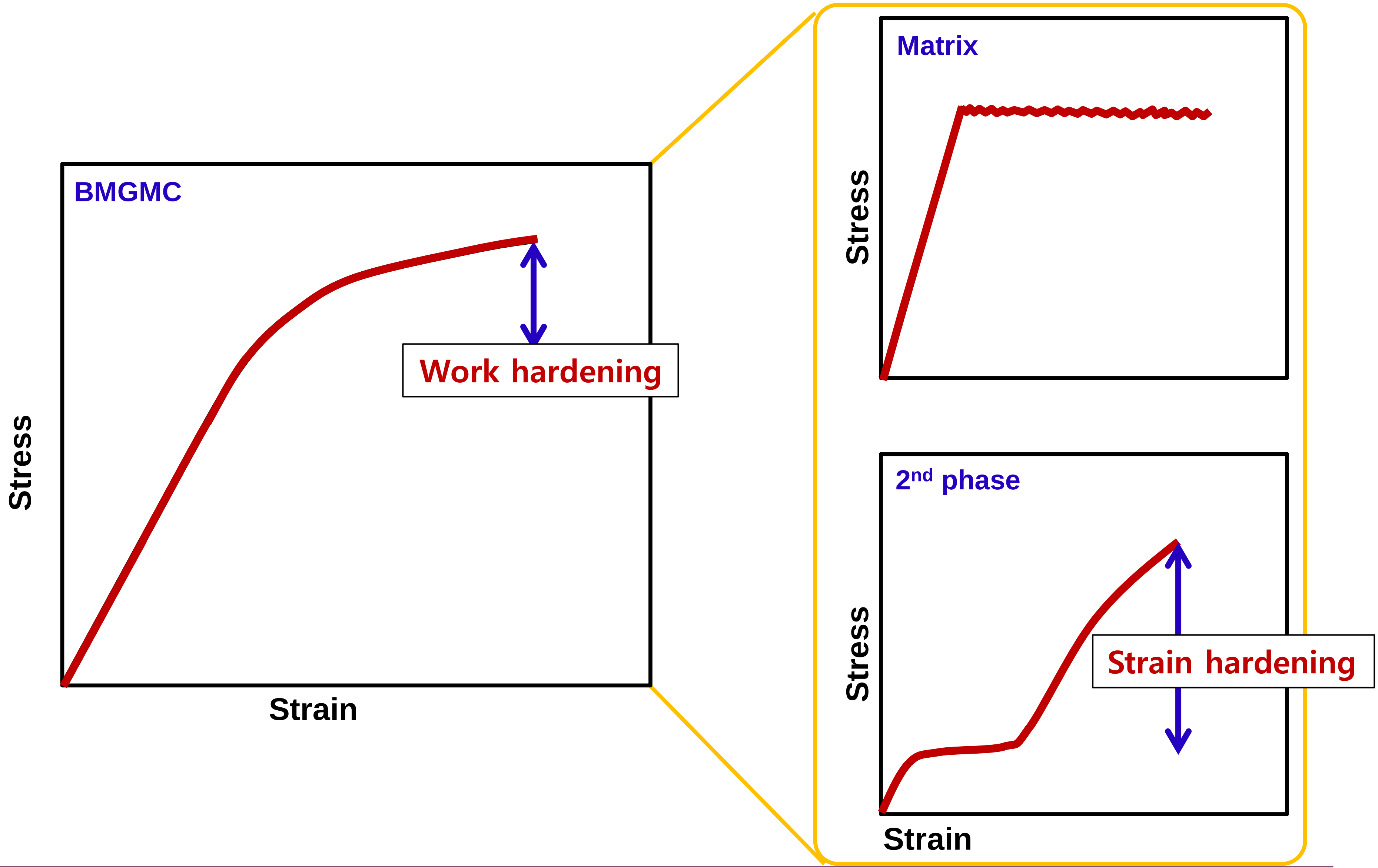
- Martensitic transformation didn't occur during elastic loading of the composites.
- Lattice strain stopped increasing at certain stress level.

Work-hardening of BMGCs with transformable 2nd phases

1. M.T. is constrained by horizontal frame of MG matrix because of the imbalance of Poisson's ratio during M.T.(~0.5) with elastic loading of MG matrix (~0.33).

Mechanism of Work-hardening in BMGC with transformable 2nd phase

"Strain hardening of 2nd phase contributes to work hardening behavior of BMGC."



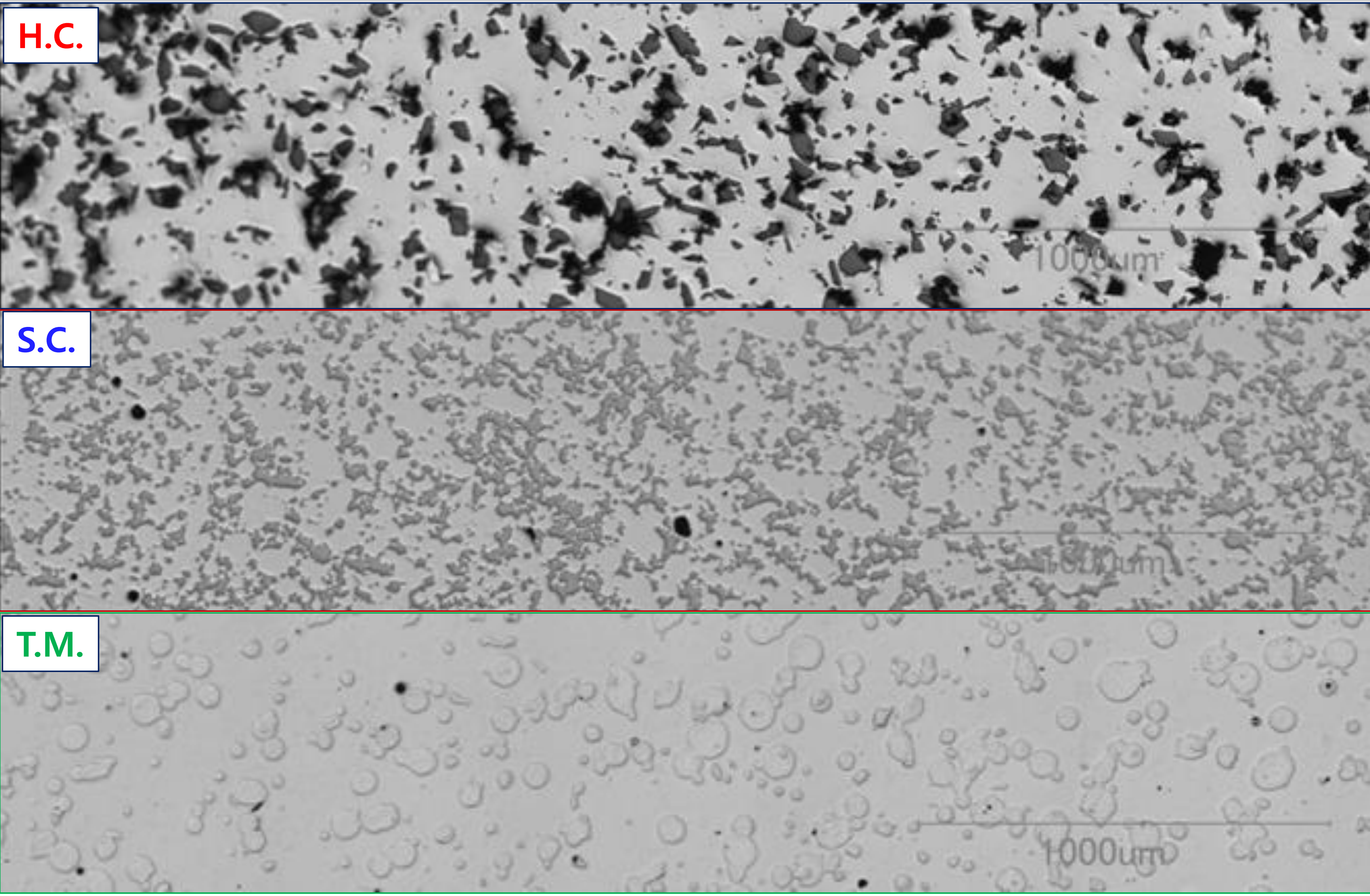
Bulk metallic glass composite

- Comparison of Work-hardenability depending on 2nd Phases

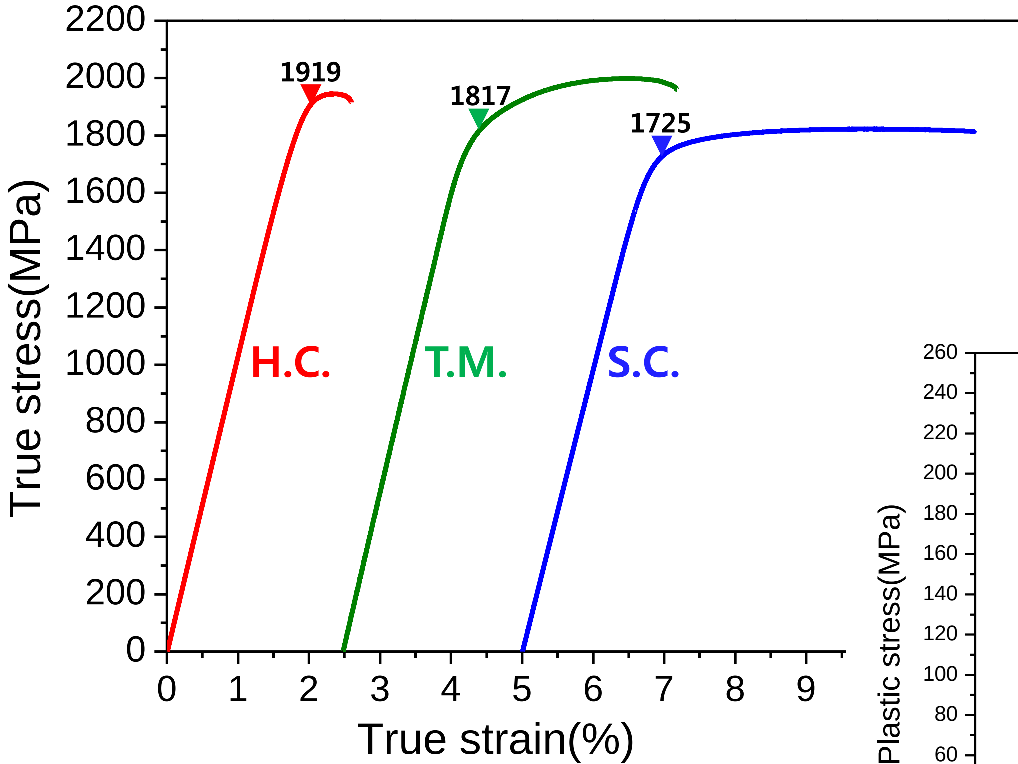
Hard ceramic, Soft crystalline, Transformation mediated
→ Applying deformation mechanisms to serrated flow

Different martensitic transformation temperature

Comparison of Work-hardenability depending on 2nd Phases

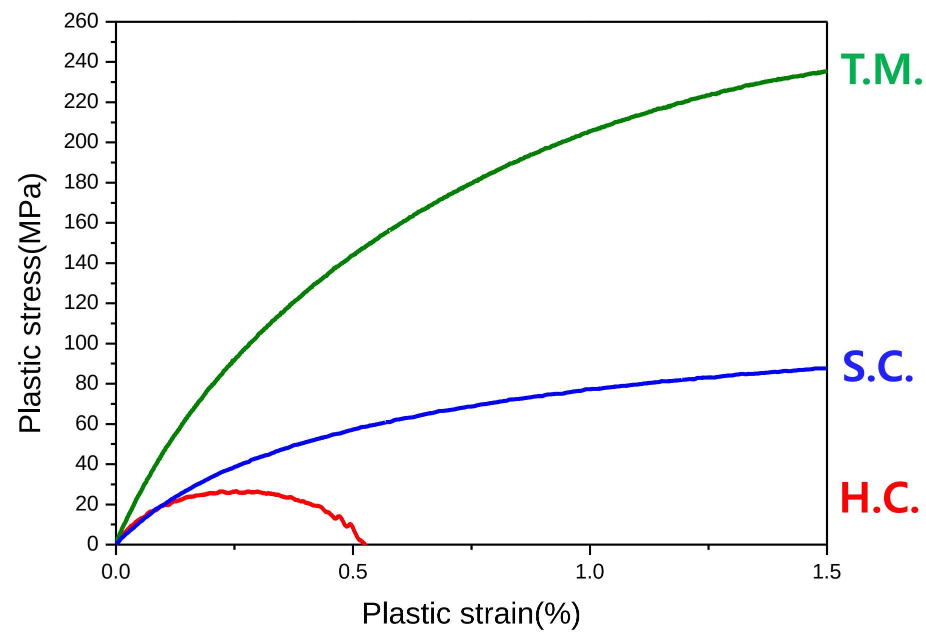


Comparison of Work-hardenability depending on 2nd Phases



$$\sigma_p = \sigma - \sigma_y$$

$$\varepsilon_p = \varepsilon - \varepsilon_y - \frac{\sigma_p}{E}$$



- **T.M. : Strain hardening**
- **H.C., S.C. : Strain softening**

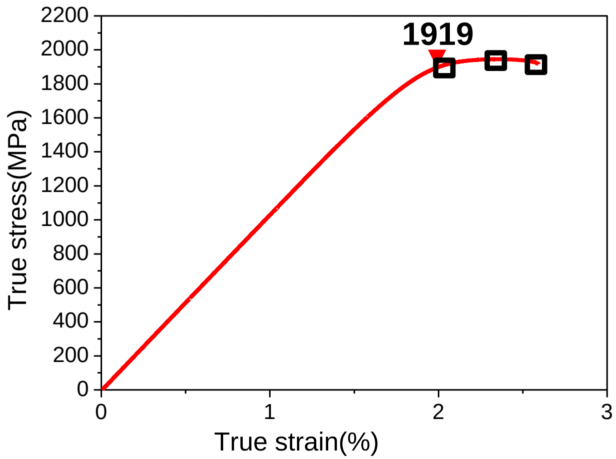
Higher strain hardening of T.M., then larger work hardenability of BMGMCs

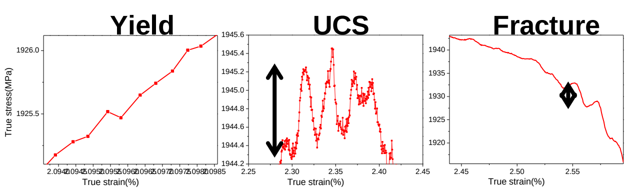
Strain hardening(2nd) **Work hardening**

(T.M. > S.C. > H.C.) **(T.M. > S.C. > H.C.)**

Serrated flow

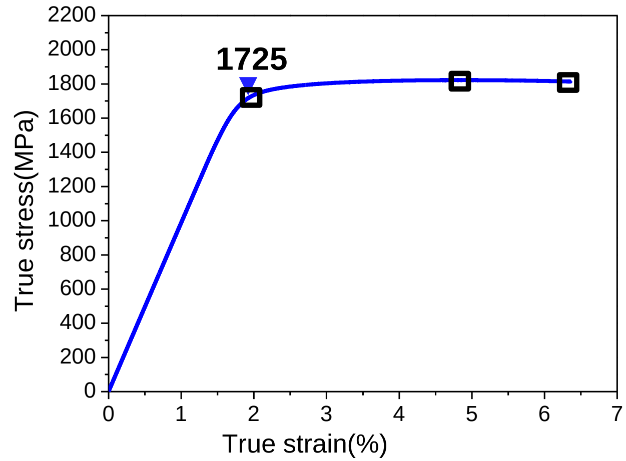
H.C.

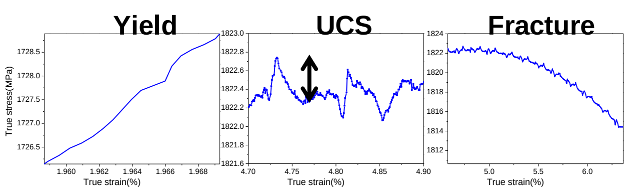




Δσ~0 Δσ~0.8 Δσ~10

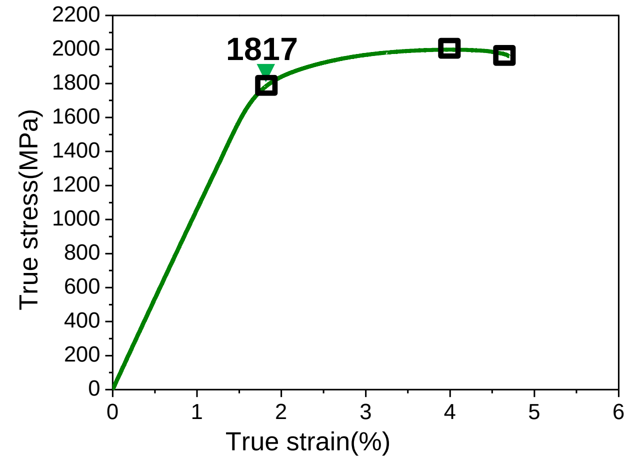
S.C.

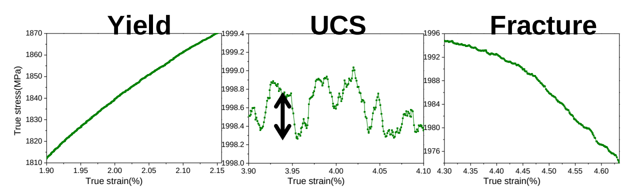




Δσ~0 Δσ~0.5 Δσ~0.5

T.M.



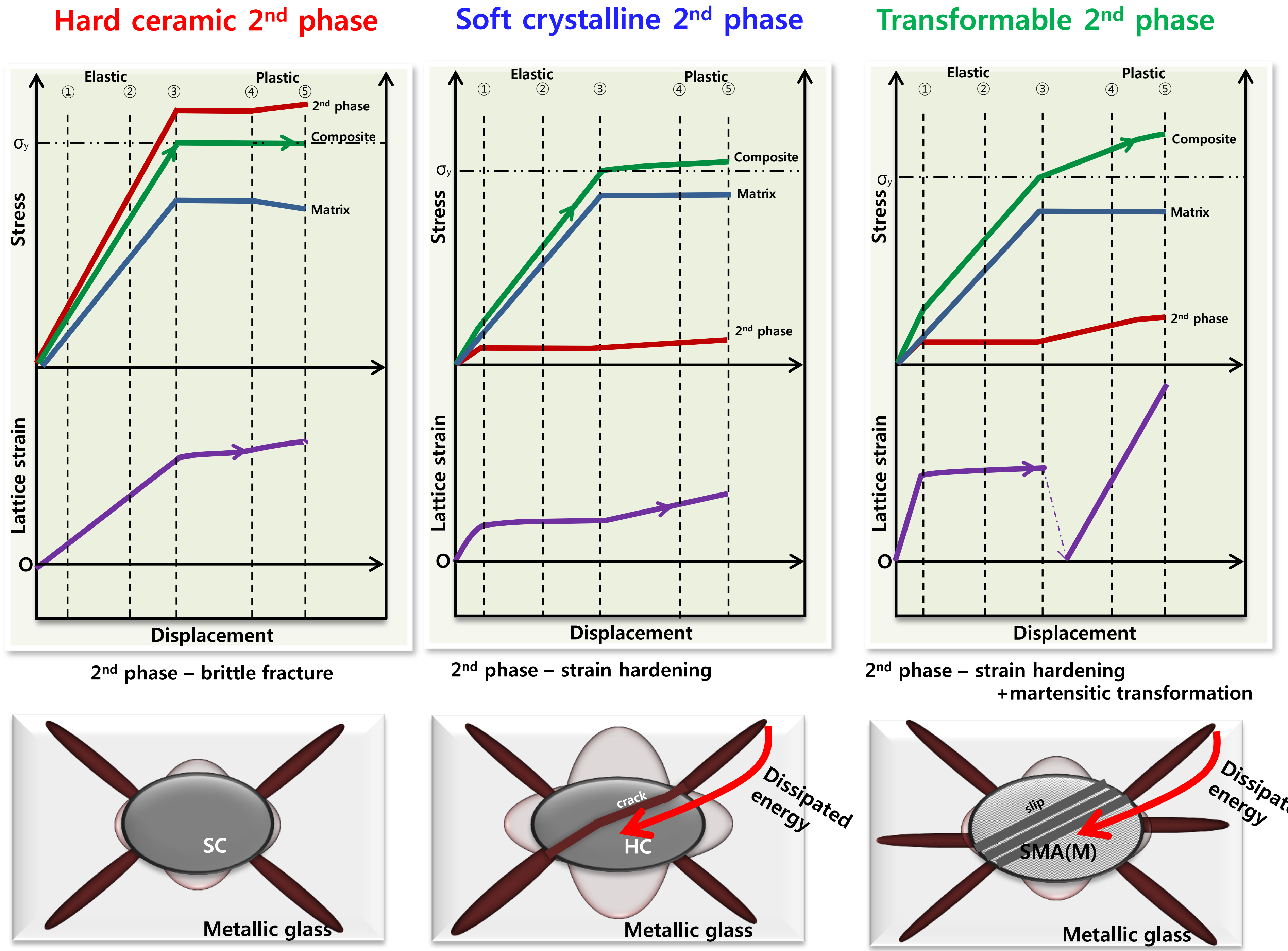


Δσ~0 Δσ~0.3 Δσ~0.5

H.C. Δσ increases continuously

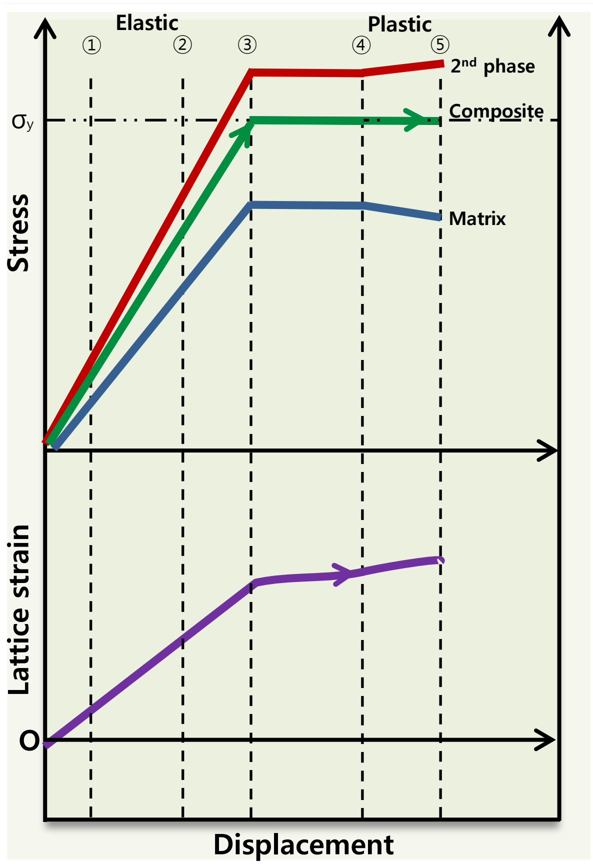
S.C. & **T.M.** Δσ increases from 0 to 0.3~0.8 MPa and becomes saturated

Ability of absorbing dissipated energy : T.M. > S.C. > H.C. Why?



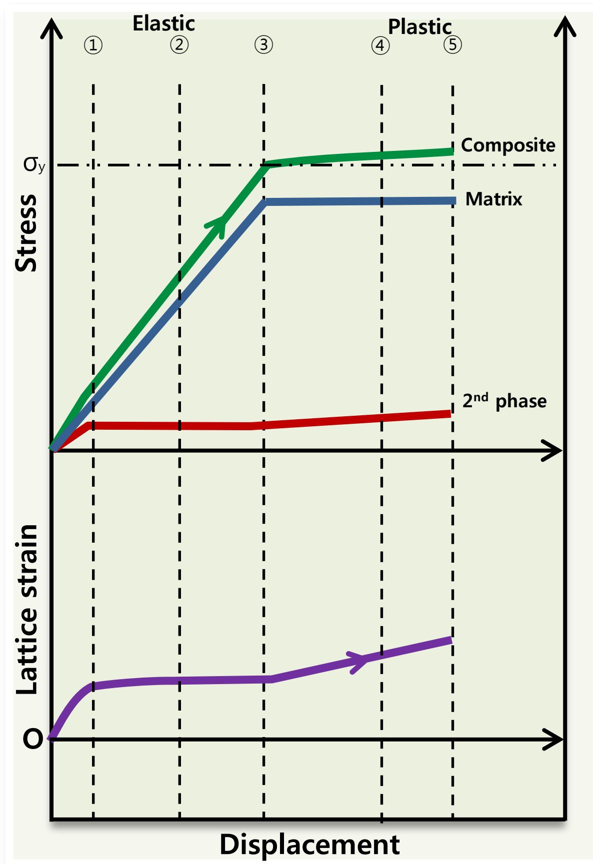
Hard ceramic 2nd phase
Soft crystalline 2nd phase
Transformable 2nd phase
Elastic
Plastic
① ② ③ ④ ⑤
2nd phase
Composite
Matrix
σy
Stress
Lattice strain
O
Displacement
2nd phase – brittle fracture
2nd phase – strain hardening
2nd phase – strain hardening +martensitic transformation
SC
crack
HC
slip
SMA(M)
Dissipated energy
Metallic glass

Hard ceramic 2nd phase



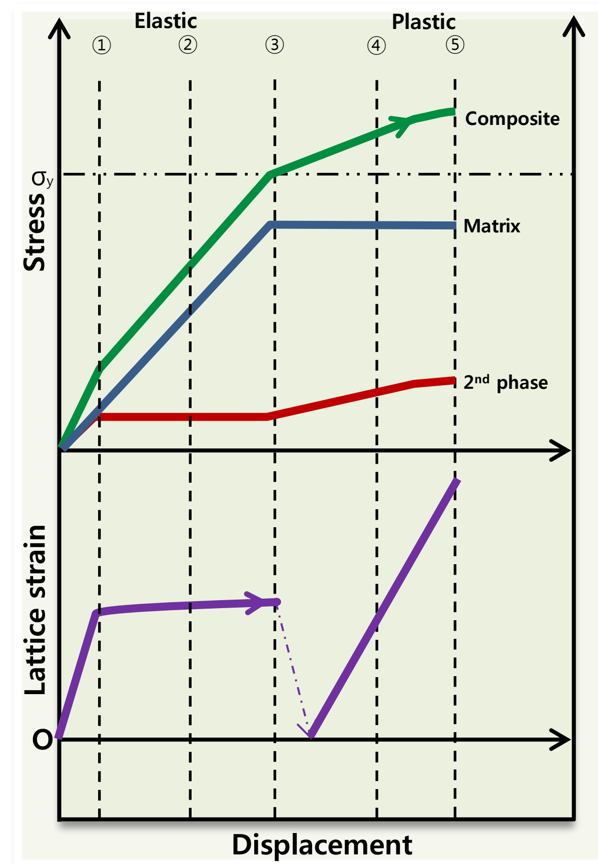
2nd phase – brittle fracture

Soft crystalline 2nd phase



2nd phase – strain hardening

Transformable 2nd phase



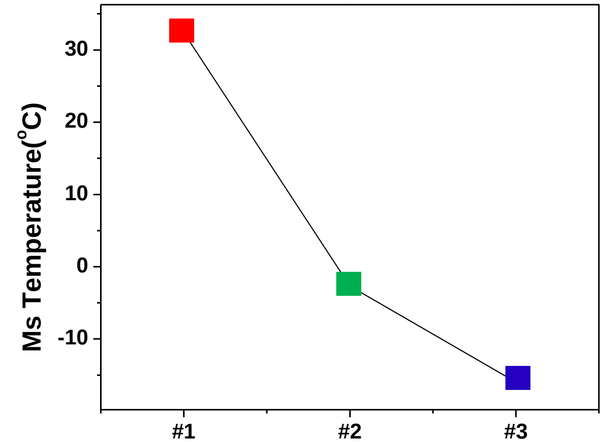
2nd phase – strain hardening
+martensitic transformation

Absorption mechanism of dissipated energy during shear banding	
Hard ceramic	None
Soft crystalline	Strain hardening
Transformation mediated	Martensitic transformation, Strain hardening

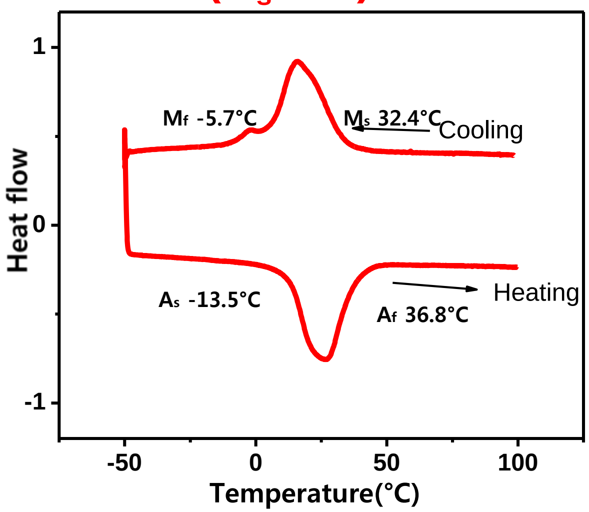
Manipulation of Work-hardenability by Controlling 2nd Phases

Yielding : Martensitic transformation

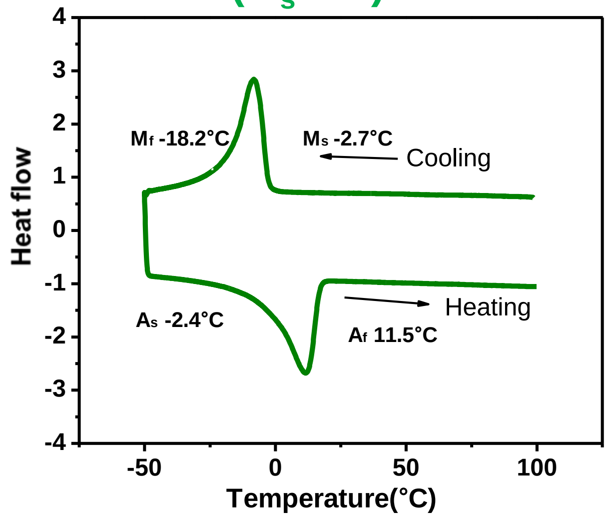
A (M_s= 32) B (M_s= -3) C (M_s= -16)



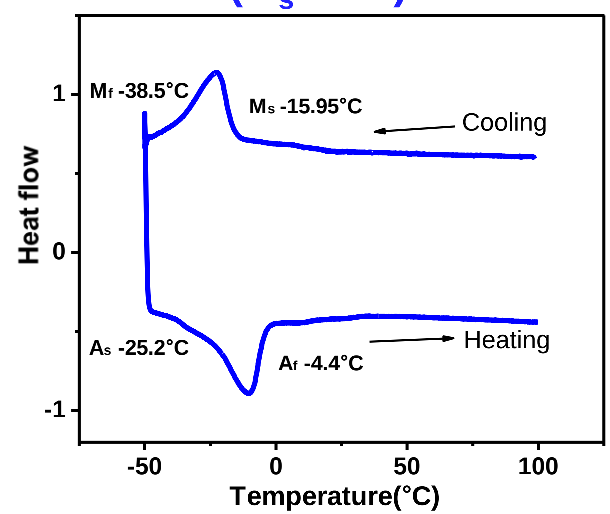
A (M_s= 32)



B (M_s= -3)



C (M_s= -16)

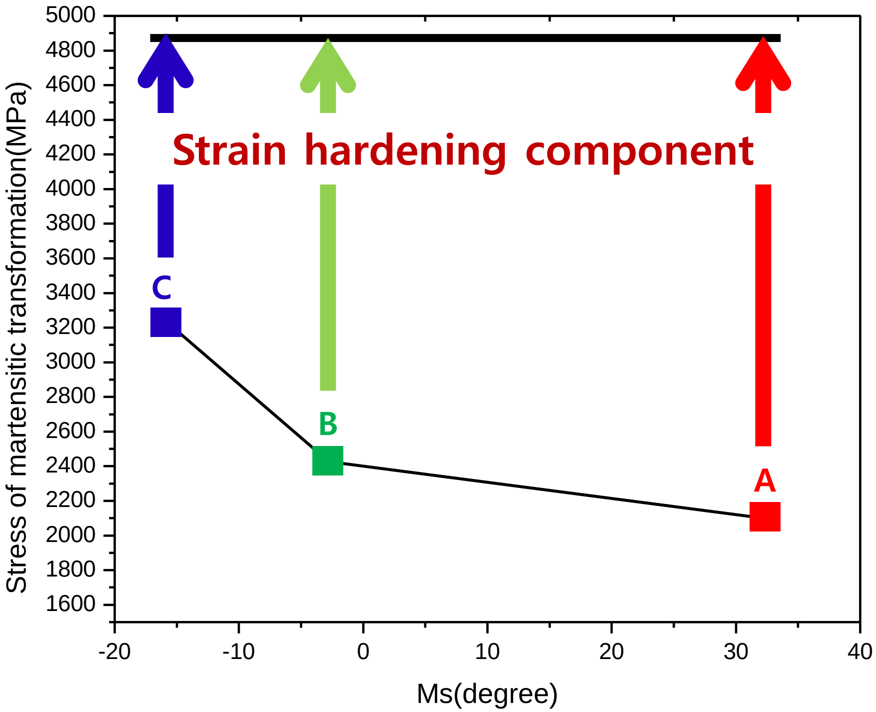


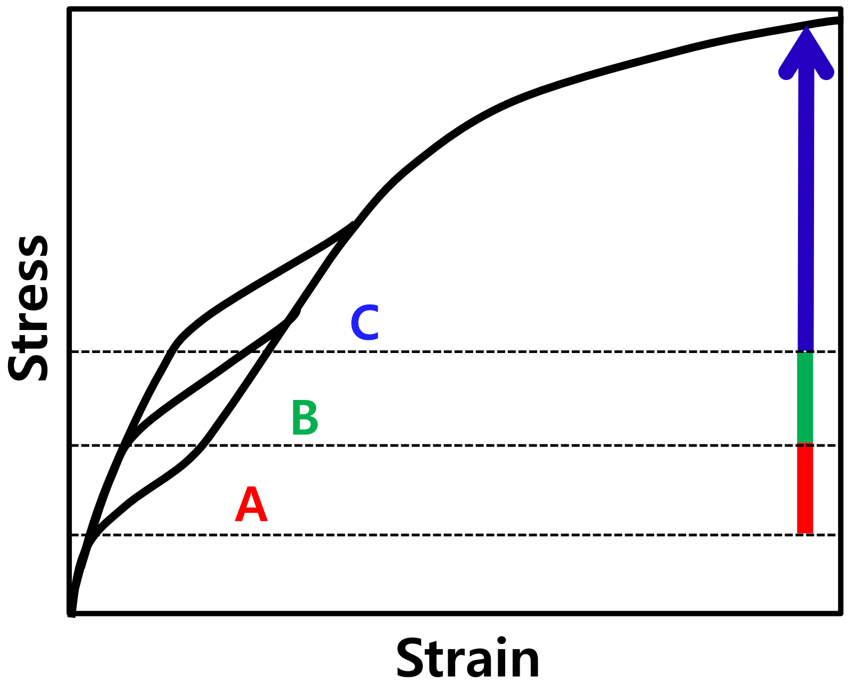
Change the characteristics of 2nd phase

1. Different characteristic of Martensitic Transformation (A, B, C)
2. Same weight fraction (~volume fraction) of 2nd phase (20%)

Manipulation of Work-hardenability by Controlling 2nd Phases

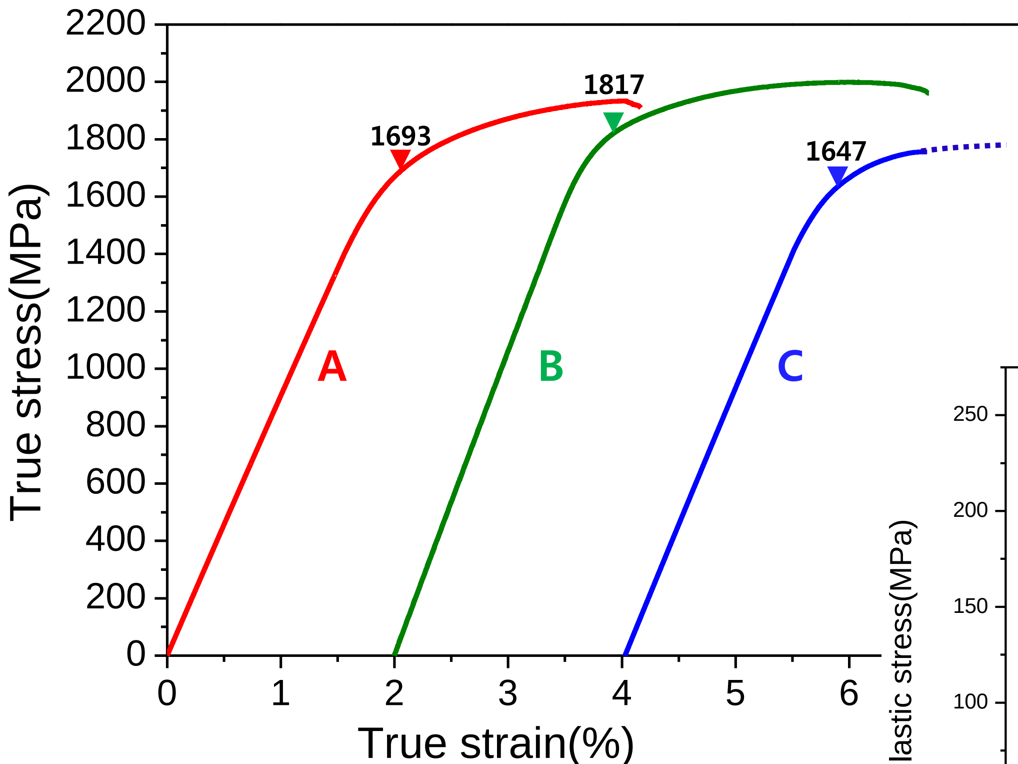
Measurement of martensitic transformation stress : Nano-indentation





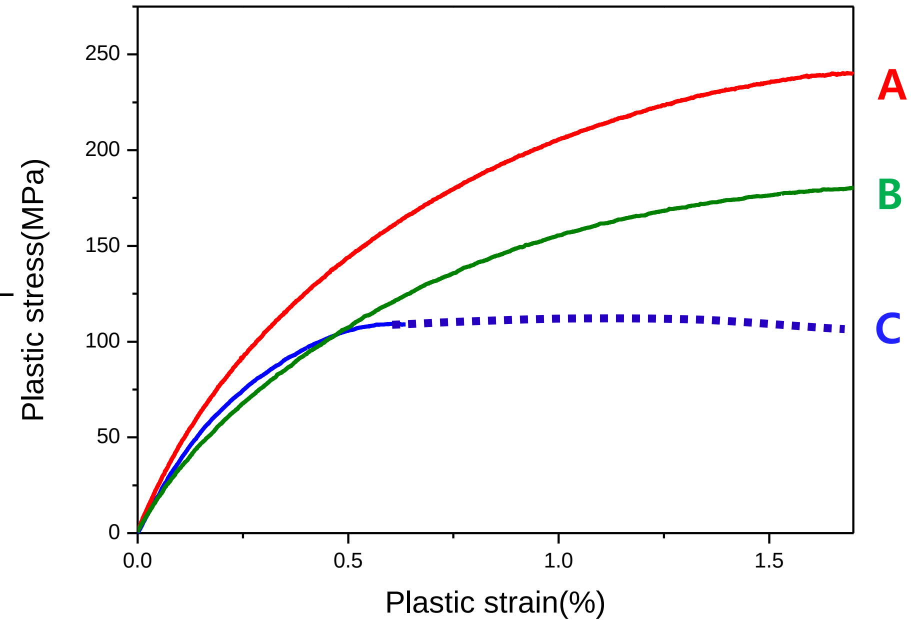
	Er(GPa)	H(GPa)	MT stress(GPa)	Strain hardening
A	61.2±3.1	4.88±0.26	2.10±0.19	
B	58.4±3.4	3.92±0.23	2.43±0.56	
C	57.1±2.3	3.99±0.29	3.24±0.22	

Manipulation of Work-hardenability by Controlling 2^{nd} Phases



$$\sigma_p = \sigma - \sigma_y$$

$$\varepsilon_p = \varepsilon - \varepsilon_y - \frac{\sigma_p}{E}$$



*** "Work hardenability" ∝ "Strain hardenability after M.T."**

Higher M_s & Easier M.T. of 2^{nd} phase, then larger work hardenability of BMGMCs

Ms(below R.T.)	M.T. stress	Strain hardening(2^{nd})	Work hardening
(A > B > C // D)	(A < B < C // D)	(A > B > C // D)	(A > B > C // D)

Conclusions

1. Newly developed ex-situ BMGCs with transformable TiNiCu 2nd phase exhibit large plasticity and superior work-hardening behavior.

2. Work hardening of BMGCs with transformable 2nd phase is from delayed strain hardening of 2nd phase after matrix yielding, which can be evaluated by in-situ neutron diffraction measurement under compression test.

3. The reason of superior work hardenability of BMGMCs with transformation mediated 2nd phase is supposed to come from higher performance of absorbing dissipated energy of shear band by strain hardening and martensitic transformation.

4. We can optimize work-hardenability of BMGCs by controlling the fraction & martensitic transformability of 2nd phase in BMGC.

   → "Work hardenability" ∝ "Strain hardenability after M.T."

Thank you for your kind attention