Investigation of Damage Evolution, and Modeling of Residual Stress and Fracture Toughness in the Ti-Al_3Ti Metal Intermetallic Laminate (MIL) Composites

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E.A. Olevsky (SDSU)

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Outline

- Introduction
- Research Objective
- Experimental Results
- Theoretical Modeling
- Preliminary Conclusions

Introduction

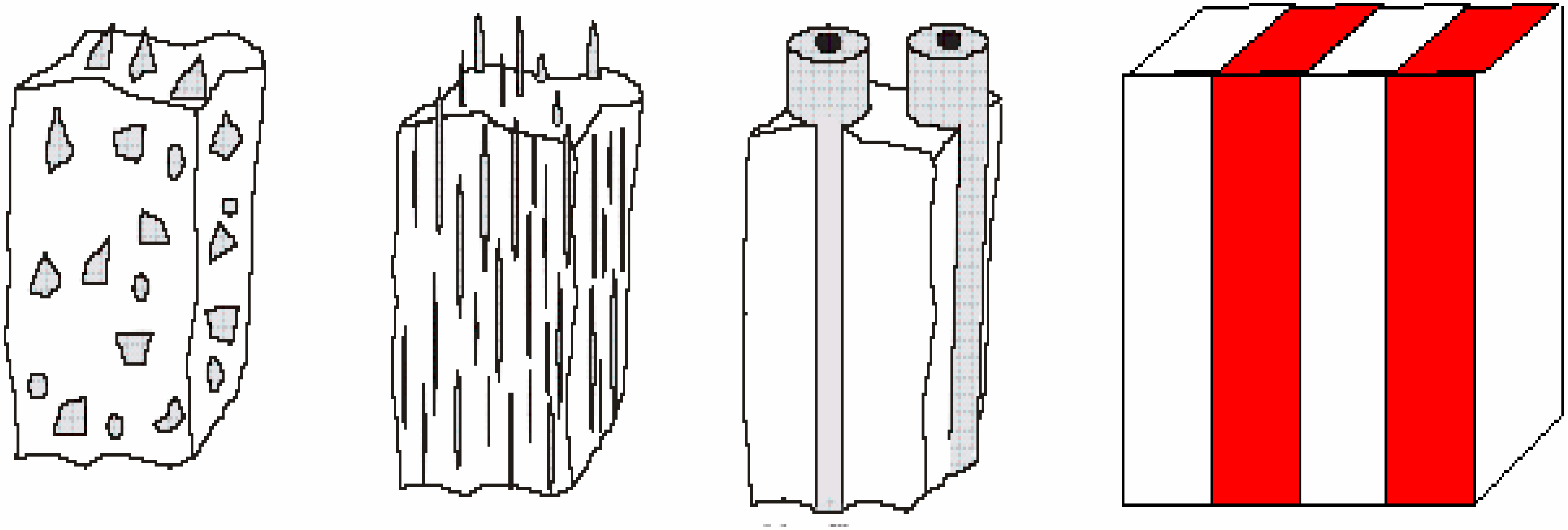
Intermetallics - Applications

- Aerospace structure
- Protective shields
- Automobile industry
- Coatings
- Armor

Intermetallics

- Advantages:
  - Good high-temperature strength
  - High stiffness
  - Good creep resistance
  - High oxidation resistance
- Disadvantages:
  - Low tensile ductility at low temperature
  - Poor fracture resistance

Toughening Intermetallics – Ductile Reinforcement



(a) Particle

(b) Short fiber/Whisker

(c) Continuous fiber

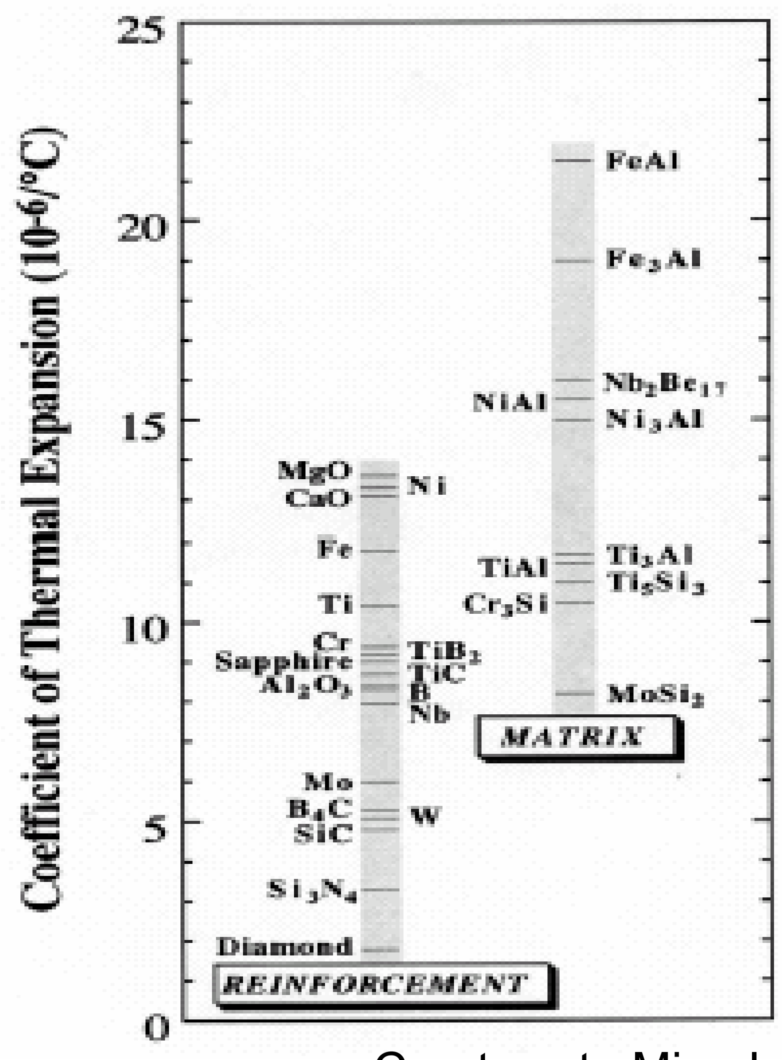
(d) Layer

Challenges in Producing Ductile Reinforced Intermetallic Composites I

- Chemical compatibility
  - To avoid undesirable microstructure and properties
- Environmental resistance
  - Subject to dynamic environment at low/intermediate temperature
- Consolidation and processing
  - Complete densification

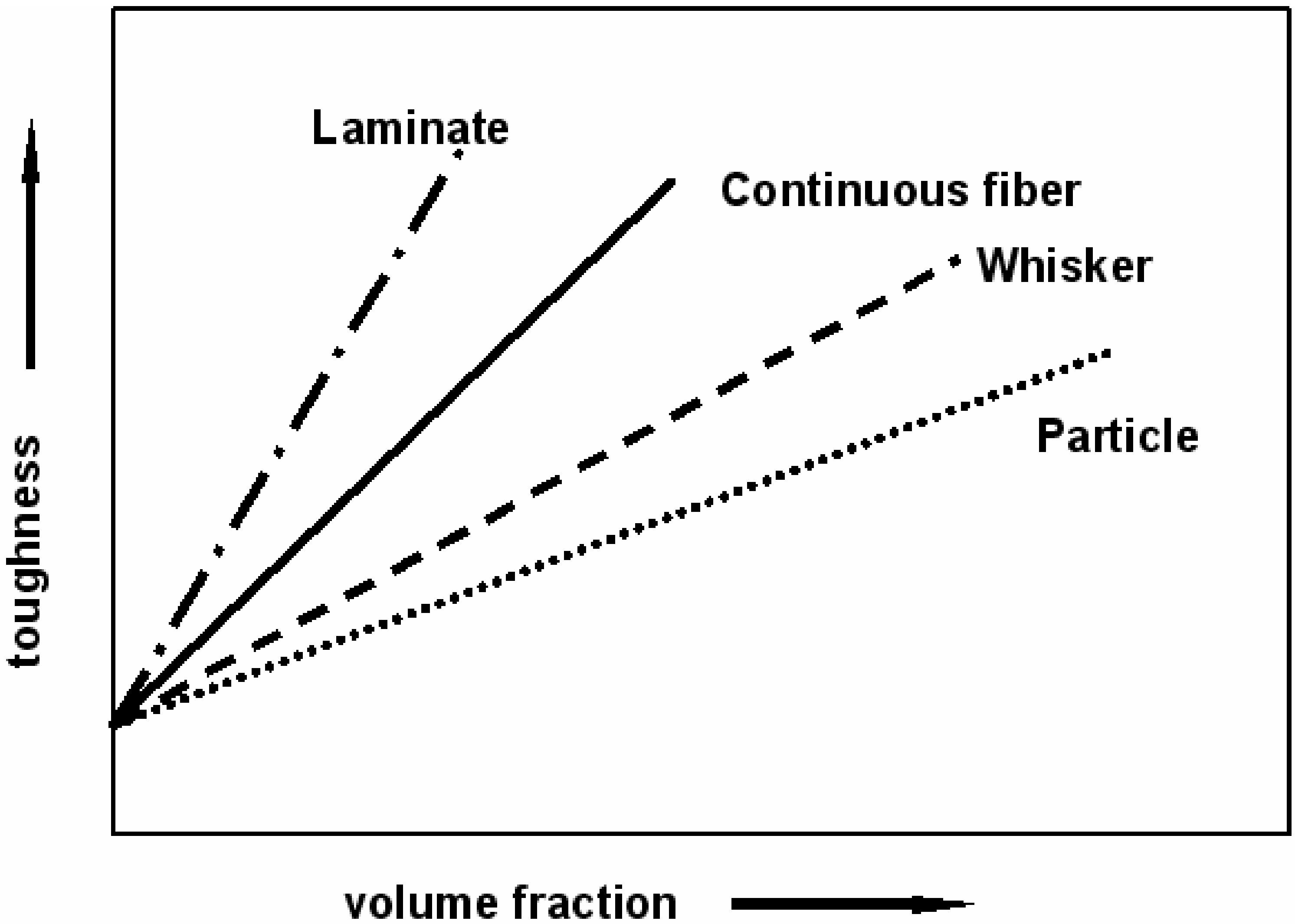
Challenges in Producing Ductile Reinforced Intermetallic Composites II

- Mismatch of thermal expansion coefficients
  - Introduce residual stress during processing and service

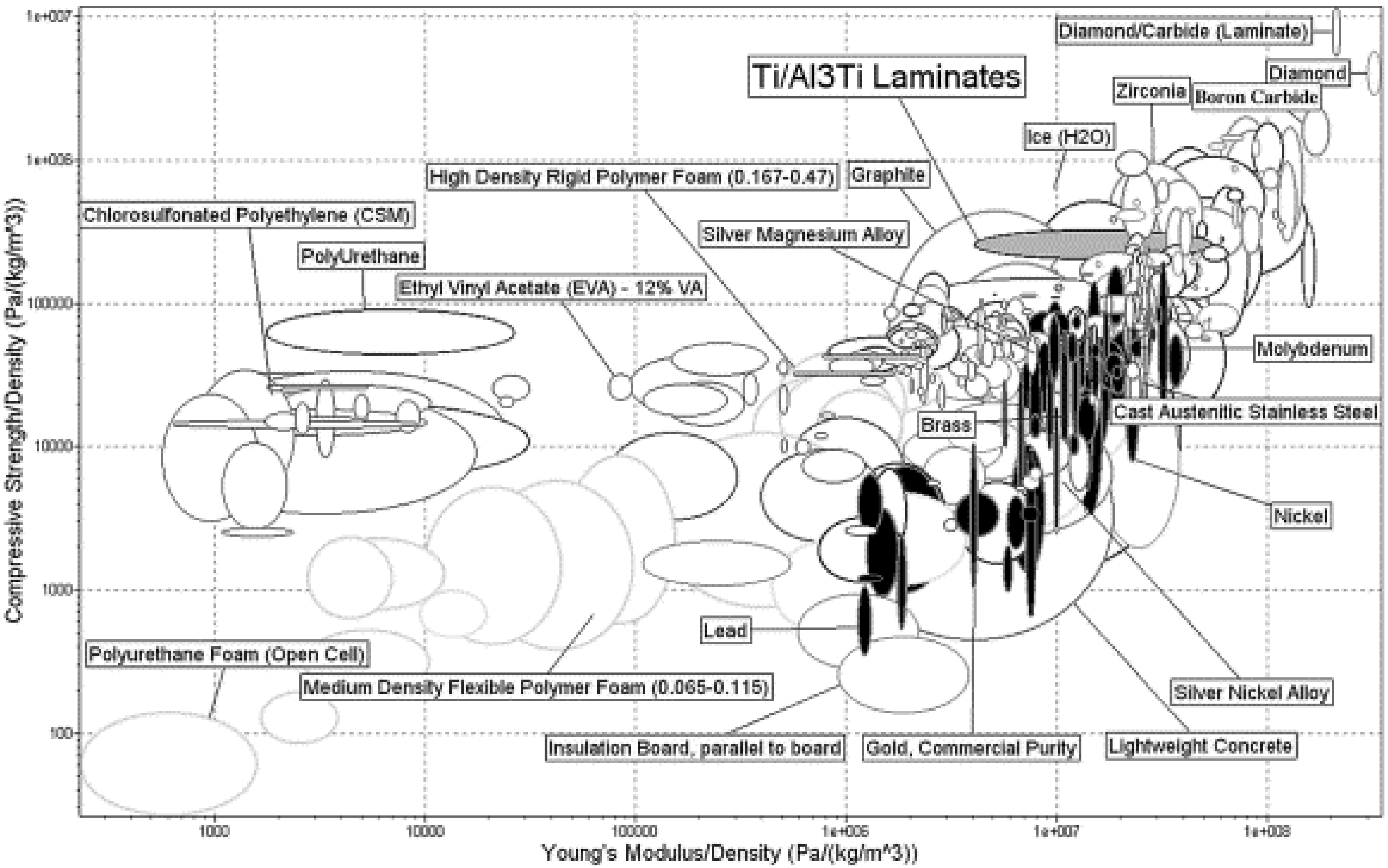


Courtesy to Miracle

Ductile Reinforced Laminate Composites

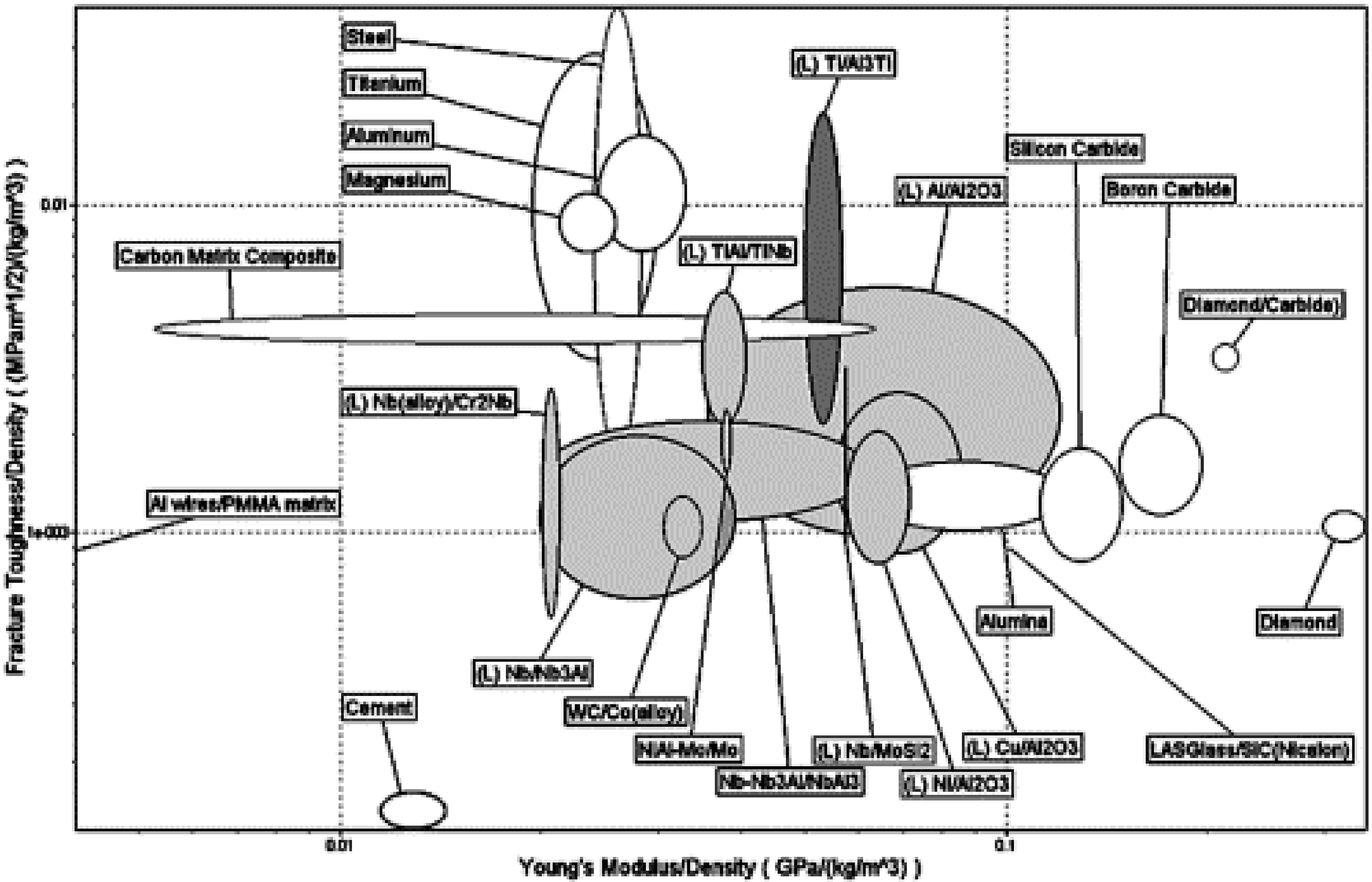


Ti-Al_3Ti MIL Composites I



Courtesy to Ashishy

Ti-Al_3Ti MIL Composites II



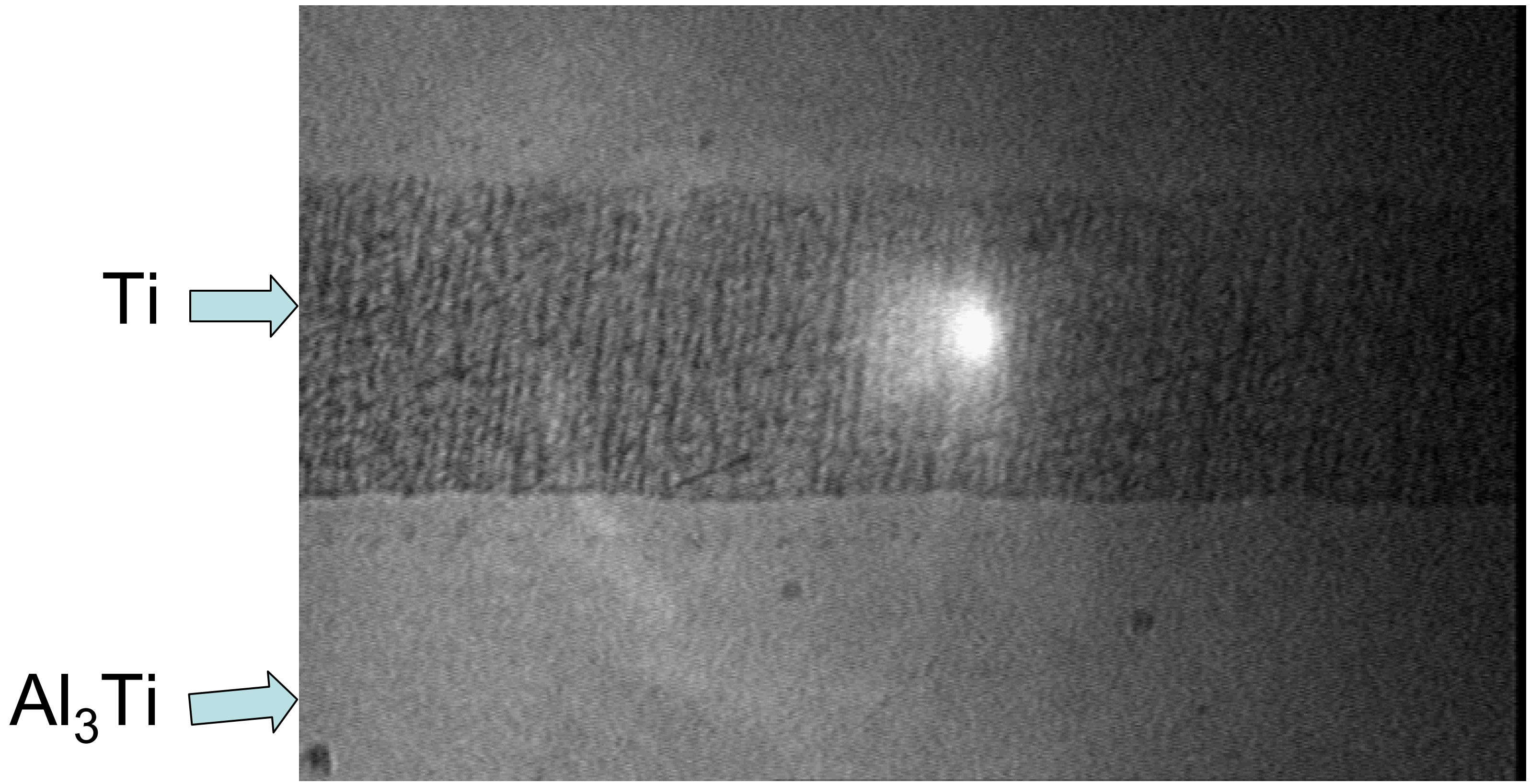
Courtesy to Ashishy

Research Objective

- Investigation of damage evolution in Ti-Al_3Ti metal intermetallic laminate (MIL) composites
- Modeling of residual stress and fracture toughness in Ti-Al_3Ti metal intermetallic laminate (MIL) composites

Experiments

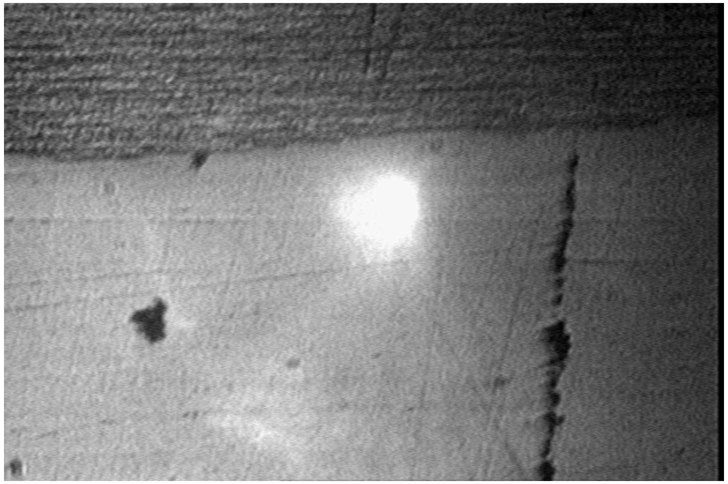
Optical Microscopy Observation on Untested Ti-Al_3Ti



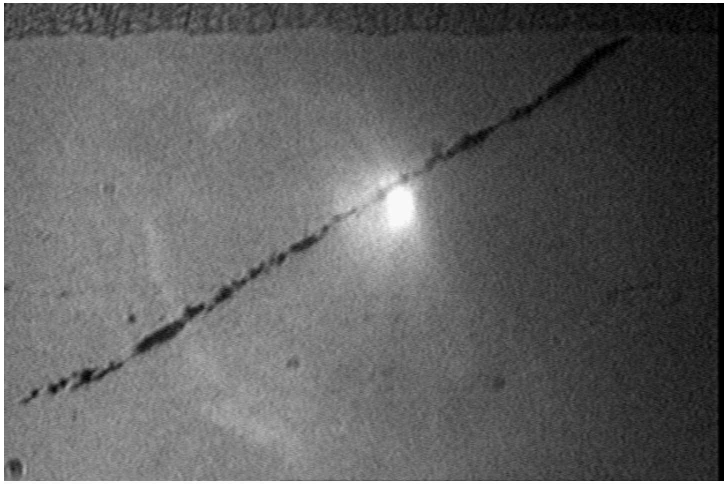
Typical untested sample

Cracks in Untested Ti-Al_3Ti

Parallel cracks

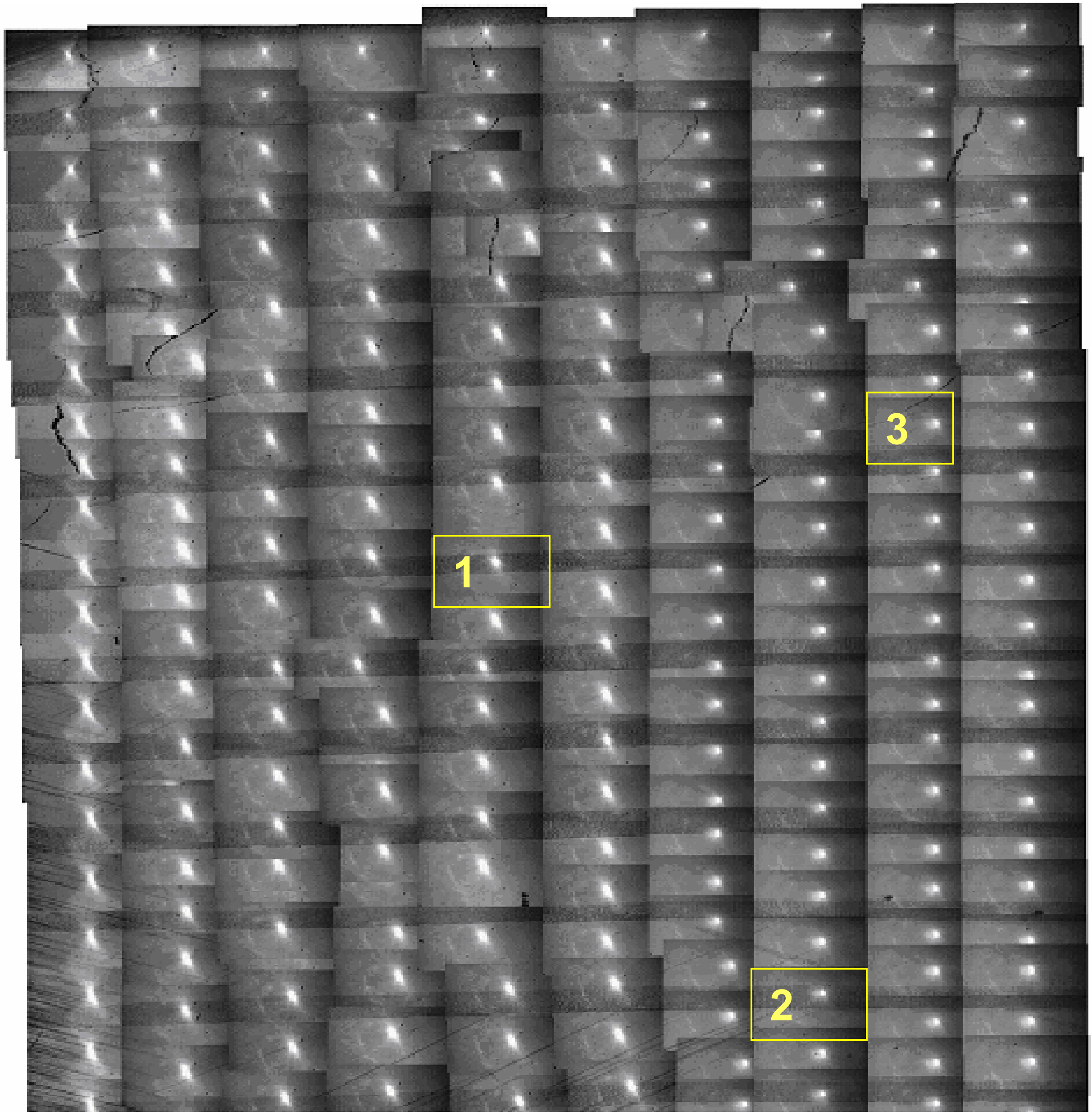


Perpendicular cracks

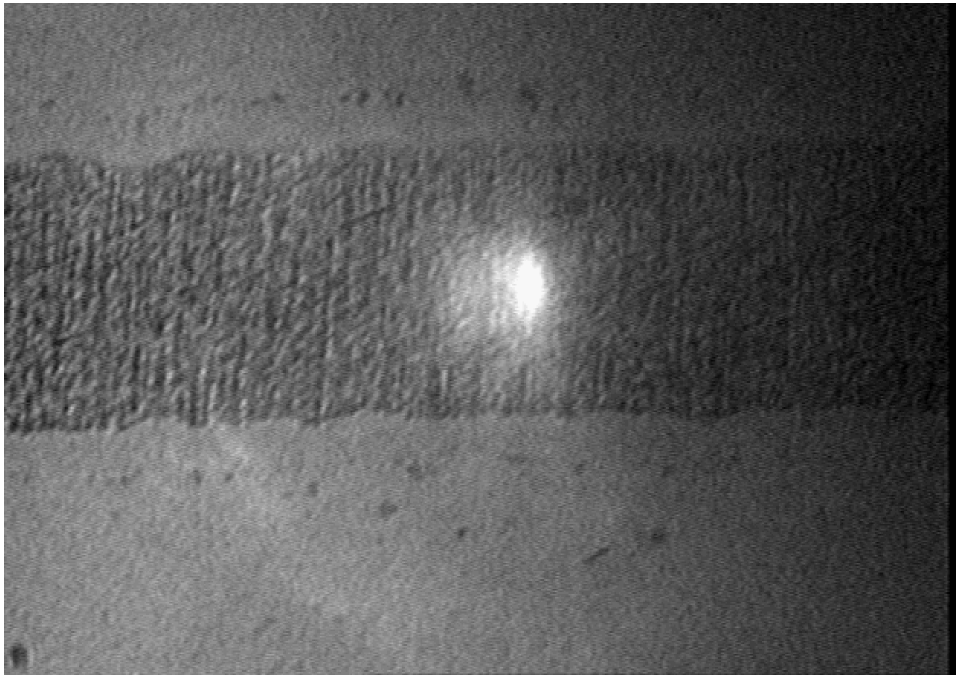


45^0 angled cracks

Optical Microscopy Observation on Untested Ti-Al_3Ti

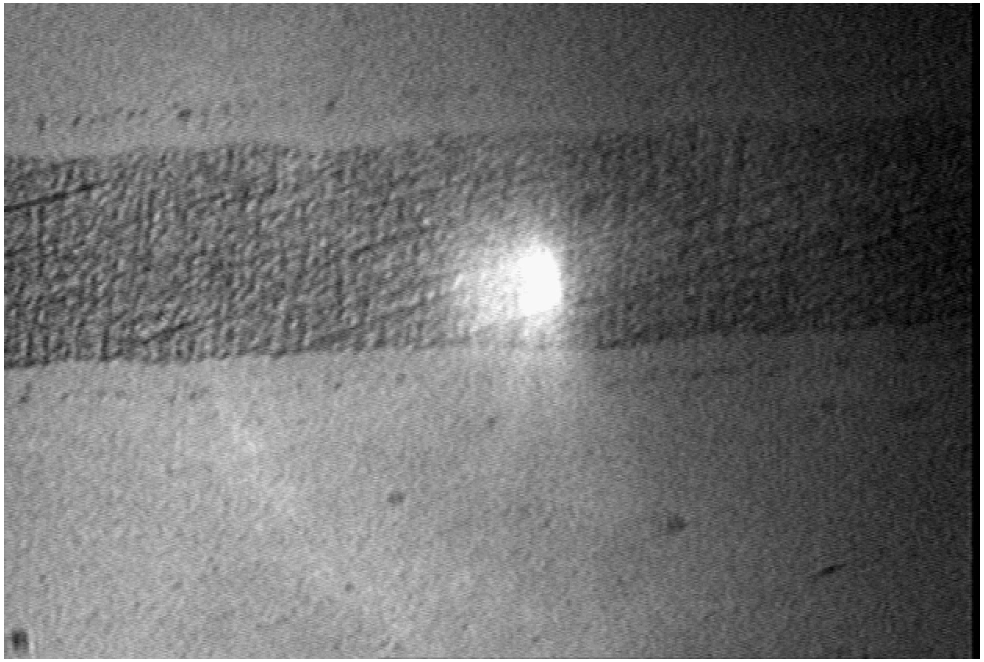


Micro-defects in Untested Ti-Al_3Ti



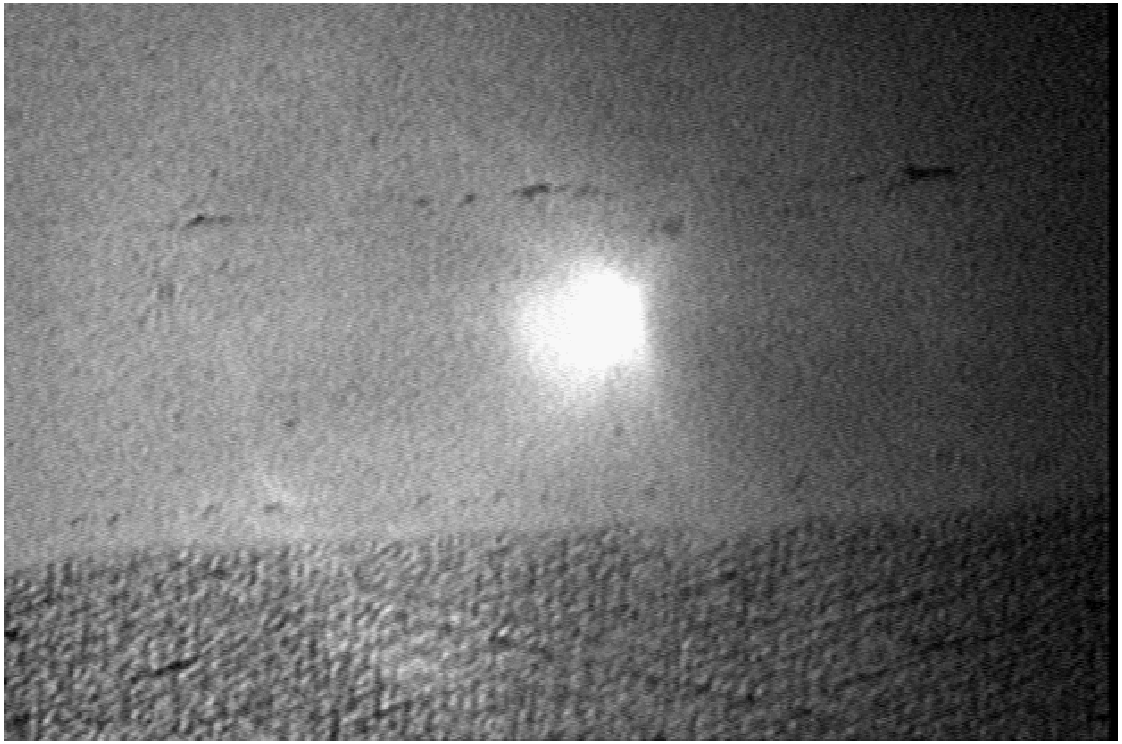
Micro-defects along the interface

Micro-defects in Untested Ti-Al_3Ti



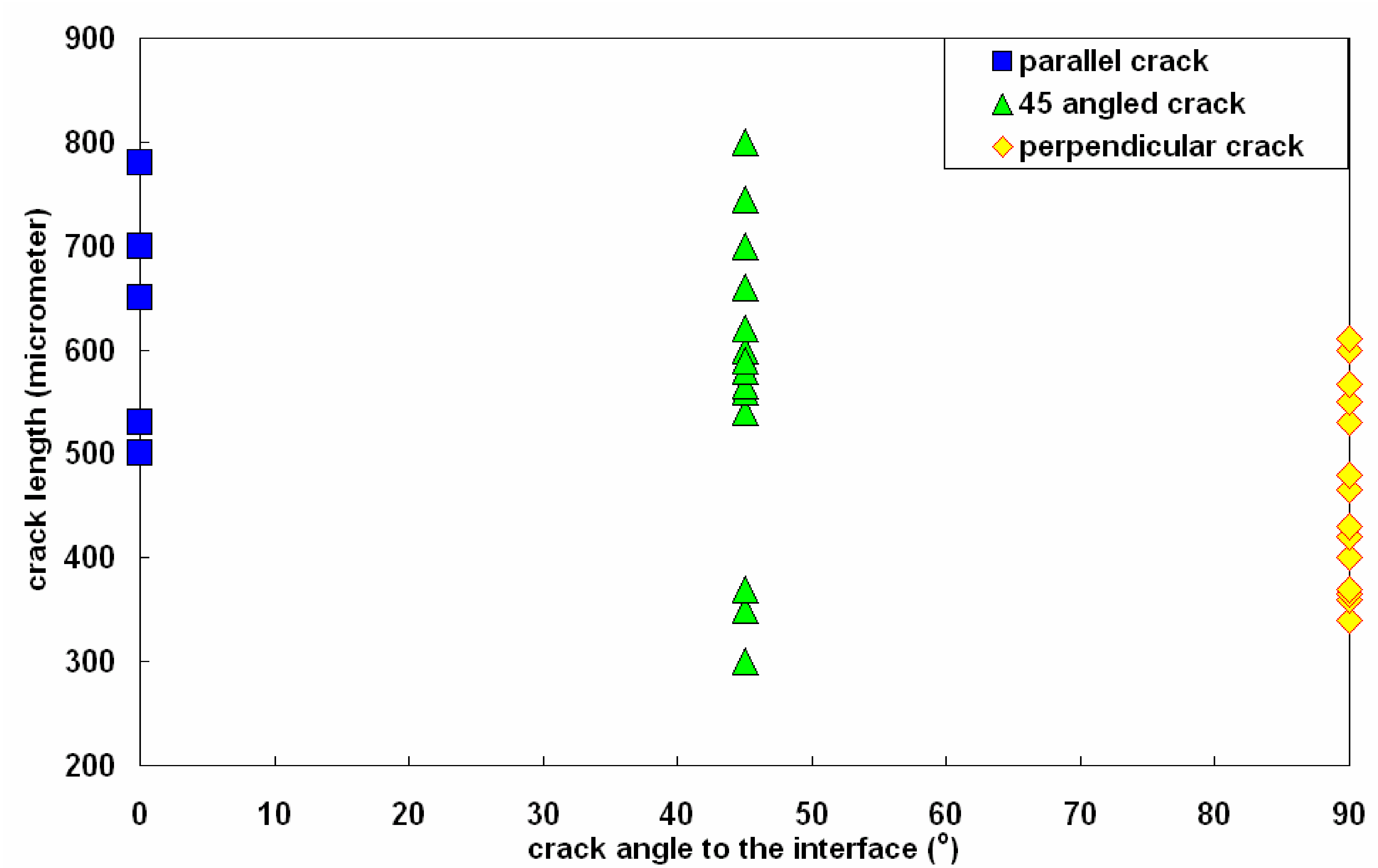
Micro-defects along the interface

Micro-defects in Untested Ti-Al_3Ti

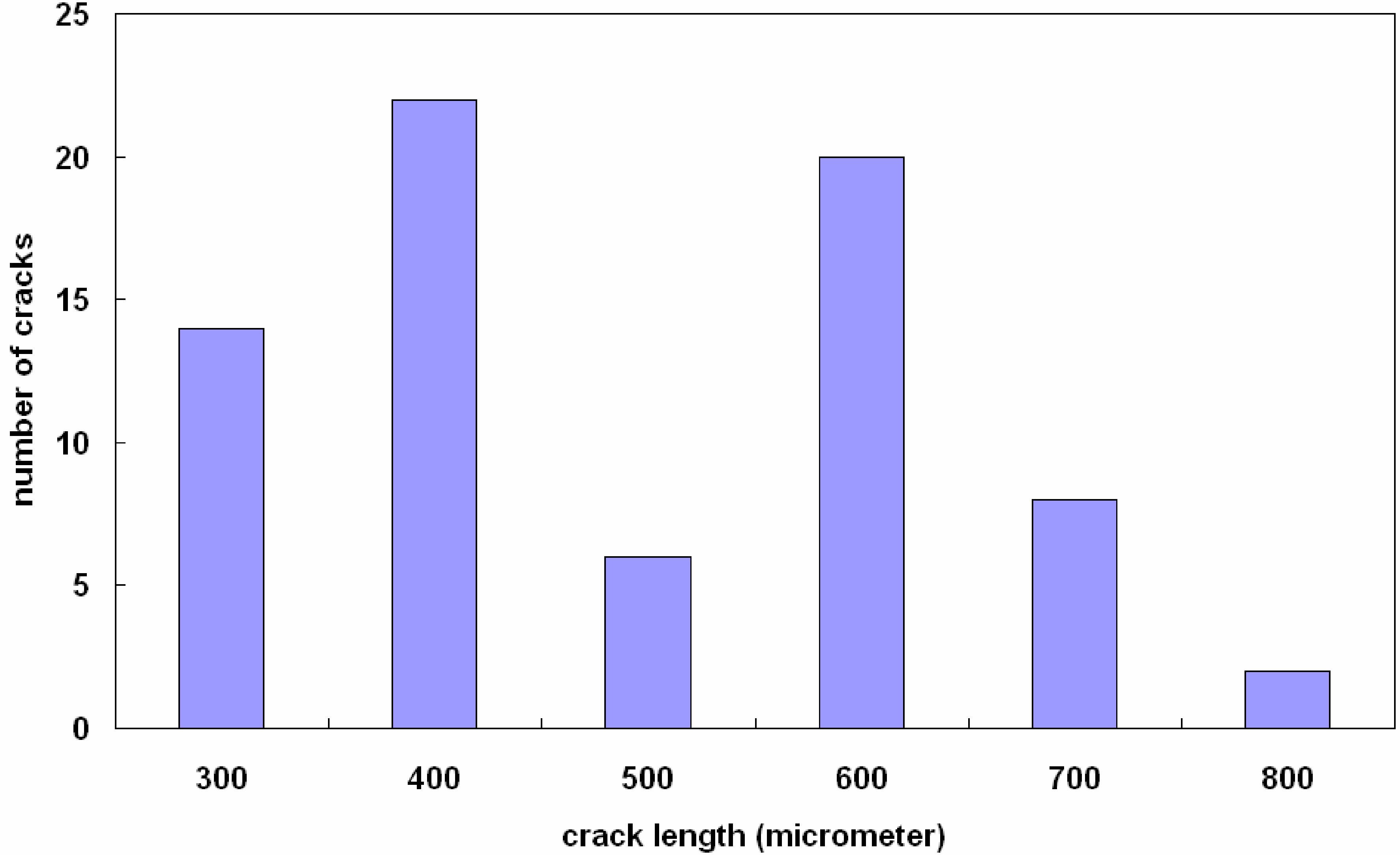


Middle line in Al_3Ti layer

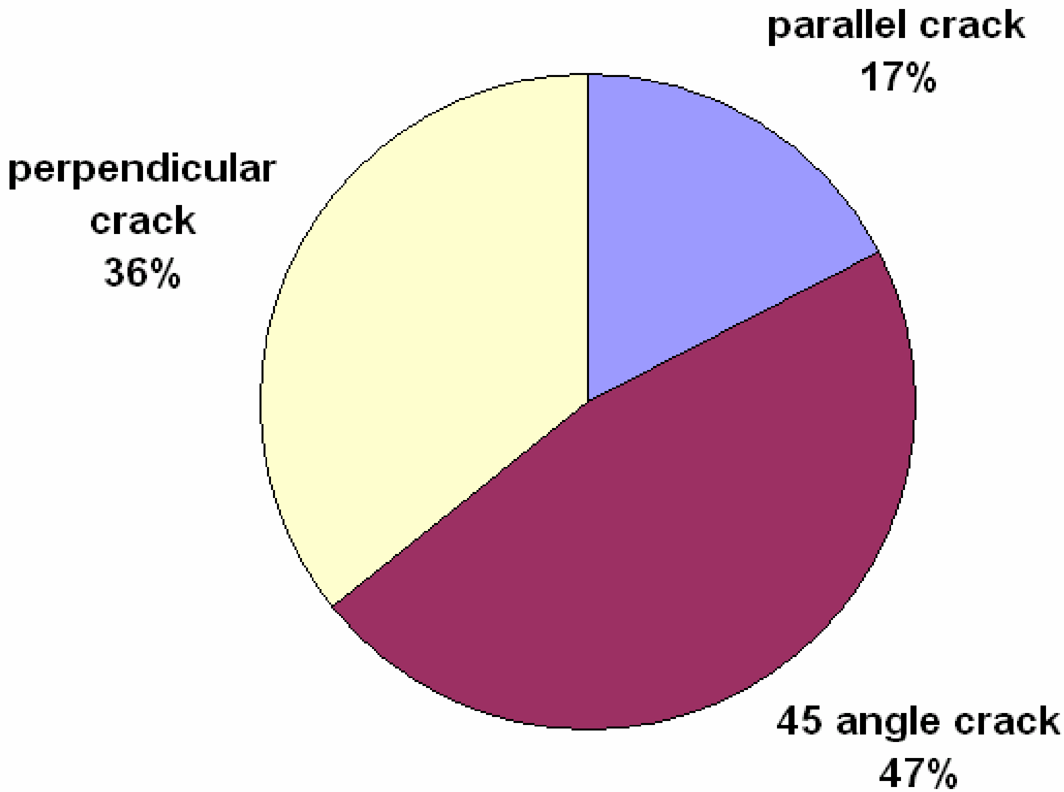
Crack Morphology in Untested Ti-Al_3Ti I



Crack Morphology in Untested Ti-Al_3Ti II



Crack Morphology in Untested Ti-Al_3Ti III

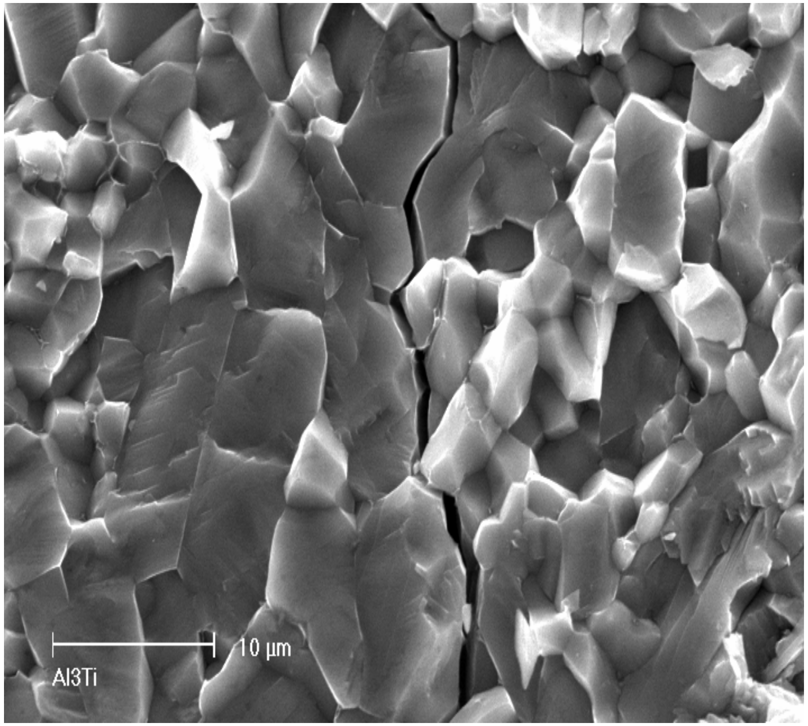


$$\rho_{crack} = \frac{\ell}{\Theta} = 1.6/cm$$

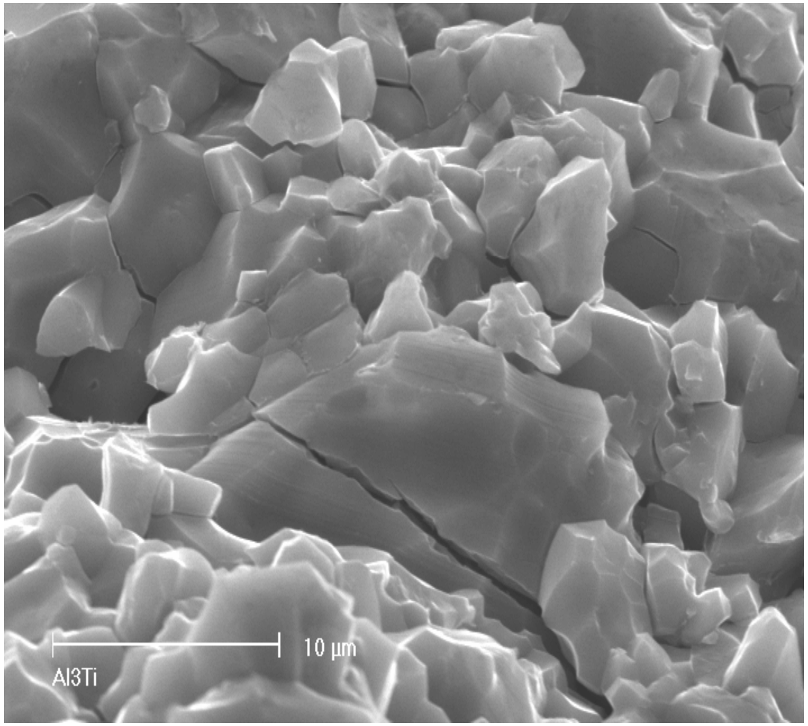
Compression Tests on Pure Al_3Ti I

	Maximum compressive stress of pure Al_3Ti (MPa)	Maximum compressive stress of Ti-Al_3Ti (35% Ti, perpendicular loading) (MPa)
Dynamic (1000/s)	1285	1300
Quasistatic (0.01/s)	921	1100
Quasistatic (0.0001/s)	890	1000

Compression Tests on Pure Al_3Ti II



Intergranular crack



Transgranular crack

Strain rate has little influences on crack modes.

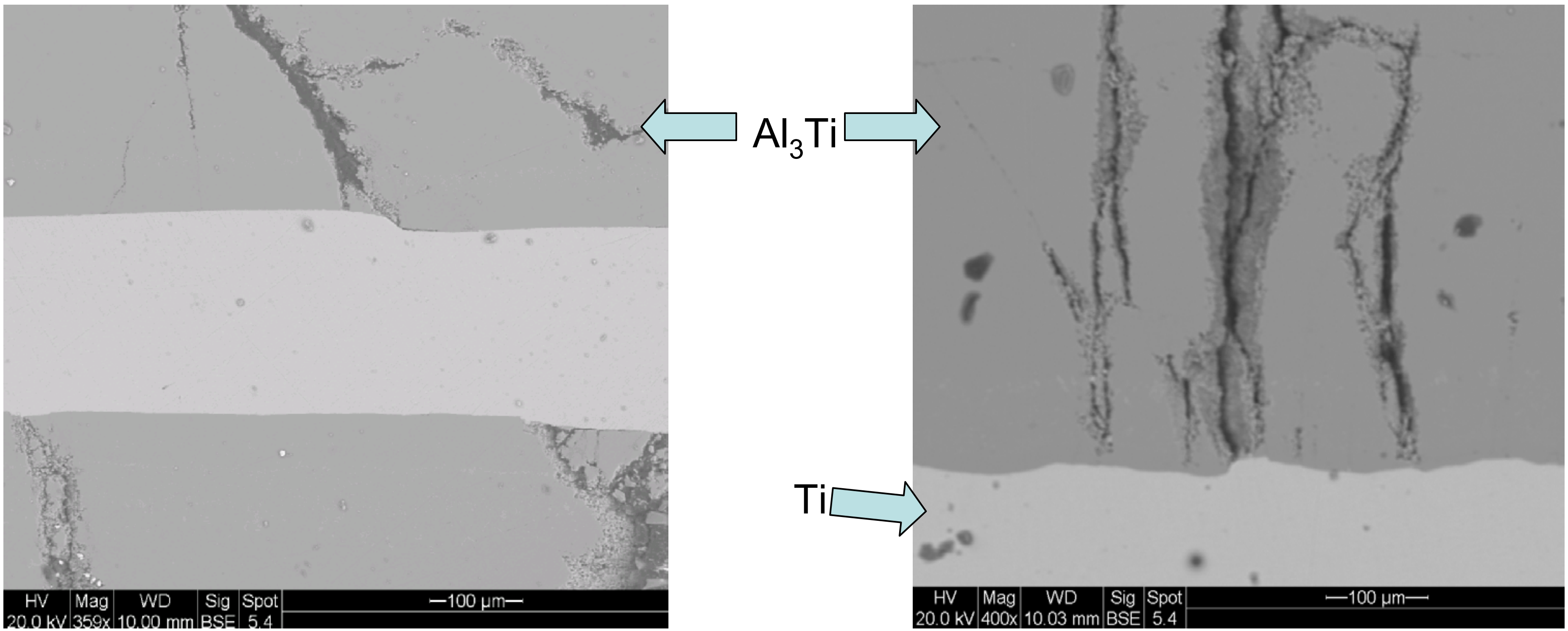
Compression Tests on Ti-Al_3Ti I

Volume Fraction of Ti-6-4	Loading Direction to the Laminate Plane	Strain Rate (/s)
14%	Perpendicular	0.0001
14%	Perpendicular	2800
14%	Parallel	0.0001
14%	Parallel	0.01
14%	Parallel	2100
50%	Perpendicular	0.0001
50%	Perpendicular	1300
50%	Perpendicular	2500
50%	Parallel	0.0001

Compression Tests on Ti-Al_3Ti II

effect of ***volume fraction*** of titanium

14% Ti *50% Ti*

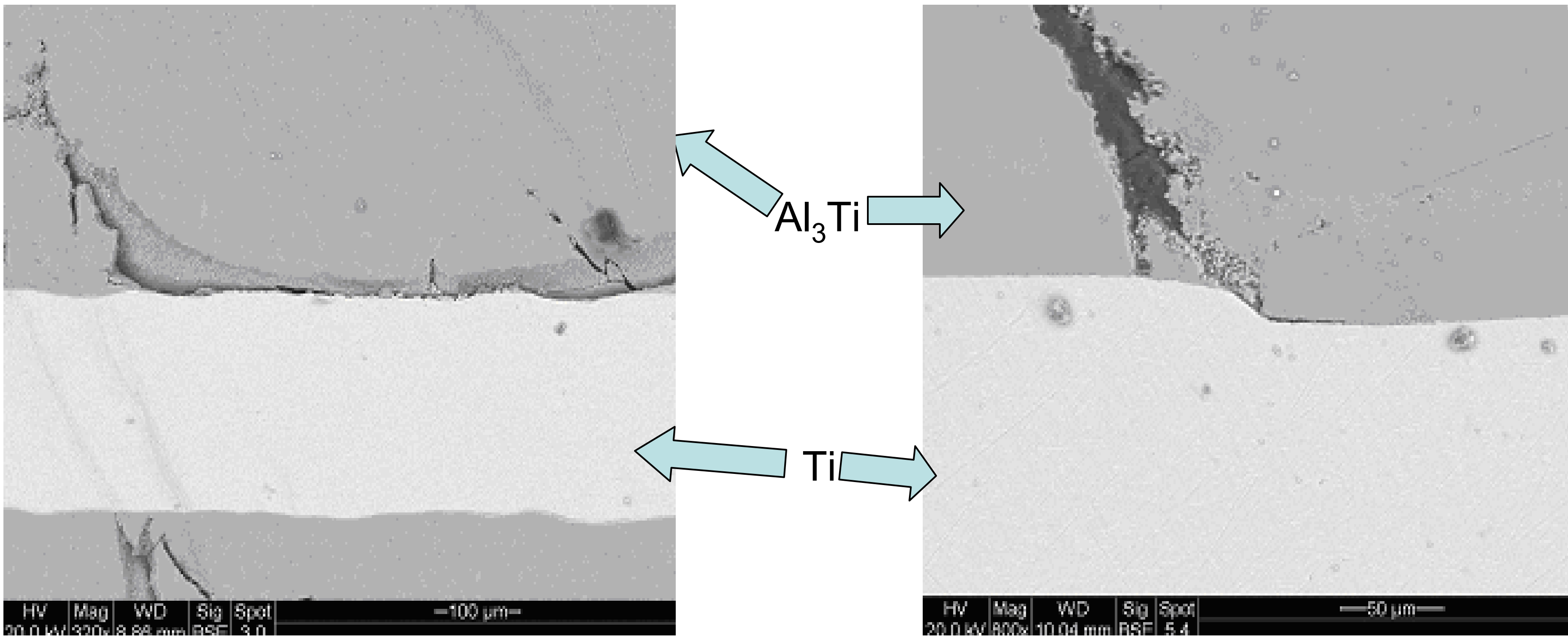


Compression Tests on Ti-Al_3Ti III

effect of the ***strain rate***

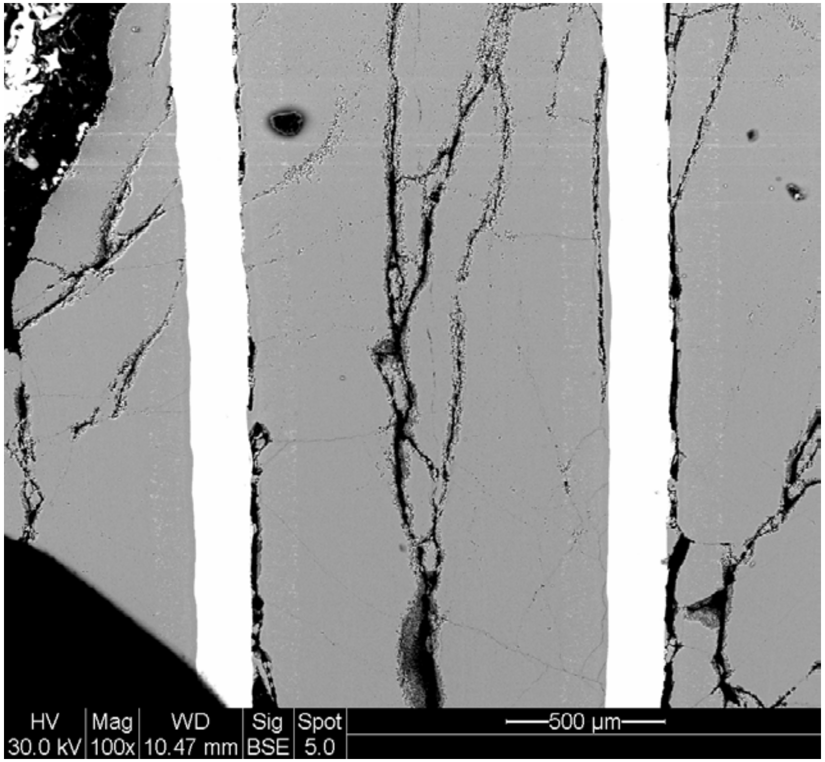
$\dot{\varepsilon} = 2800\ / s$

$\dot{\varepsilon} = 0.0001 / s$

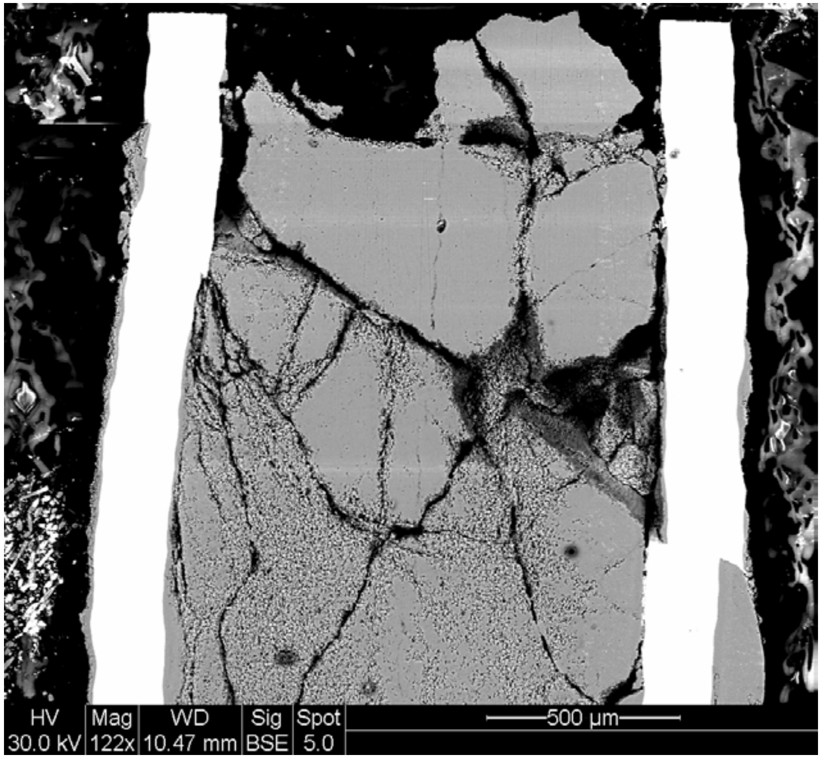


Compression Tests on Ti-Al_3Ti IV

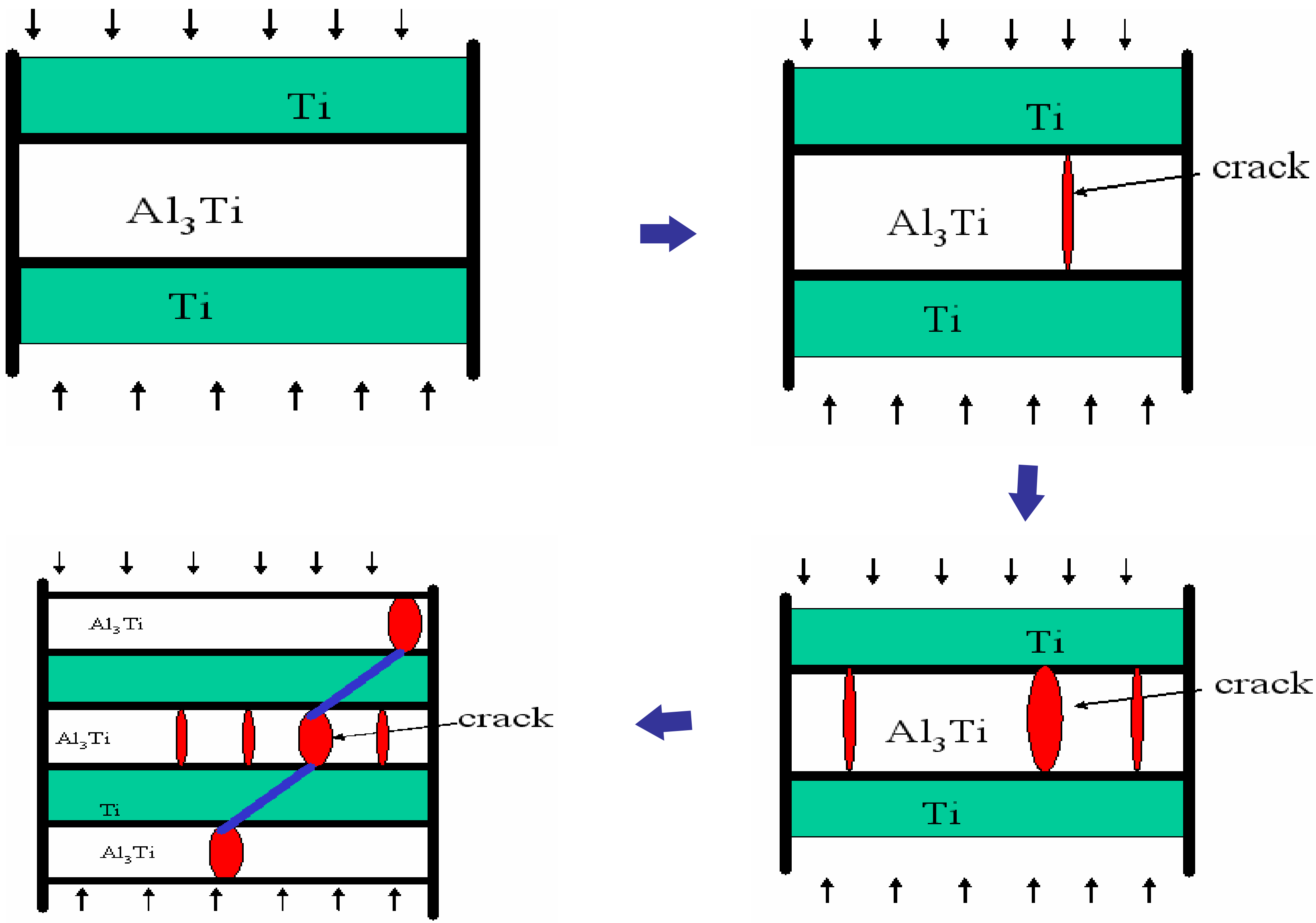
$\dot{\varepsilon} = 2100\ /s$



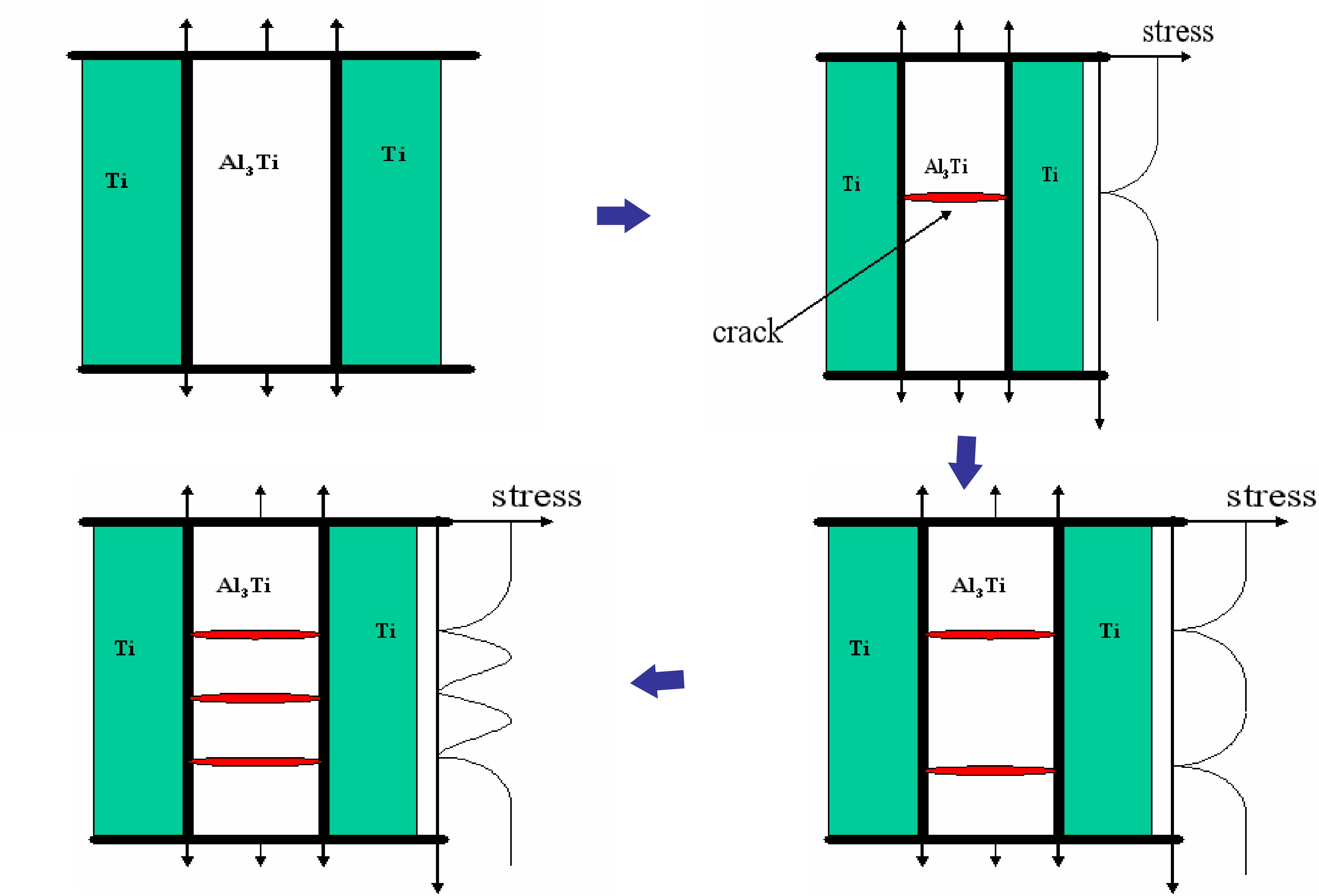
$\dot{\varepsilon} = 0.0001/s$



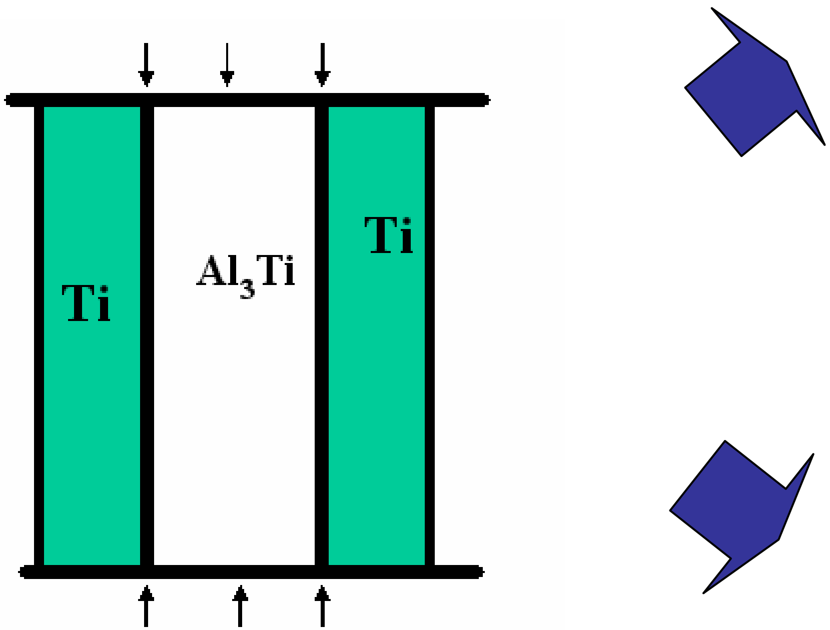
Physical Modeling: Damage Evolution I

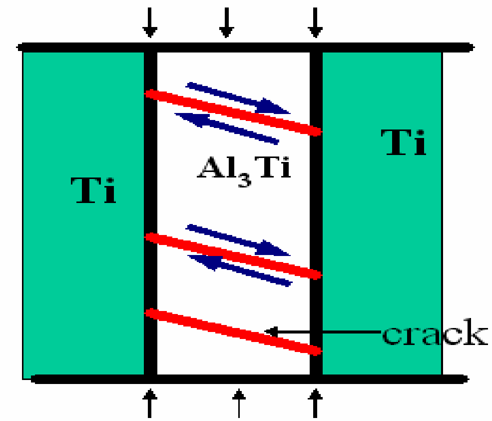


Physical Modeling: Damage Evolution II

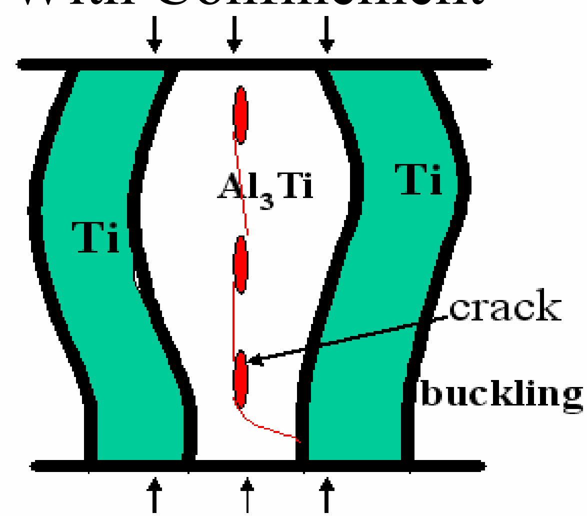


Physical Modeling: Damage Evolution III



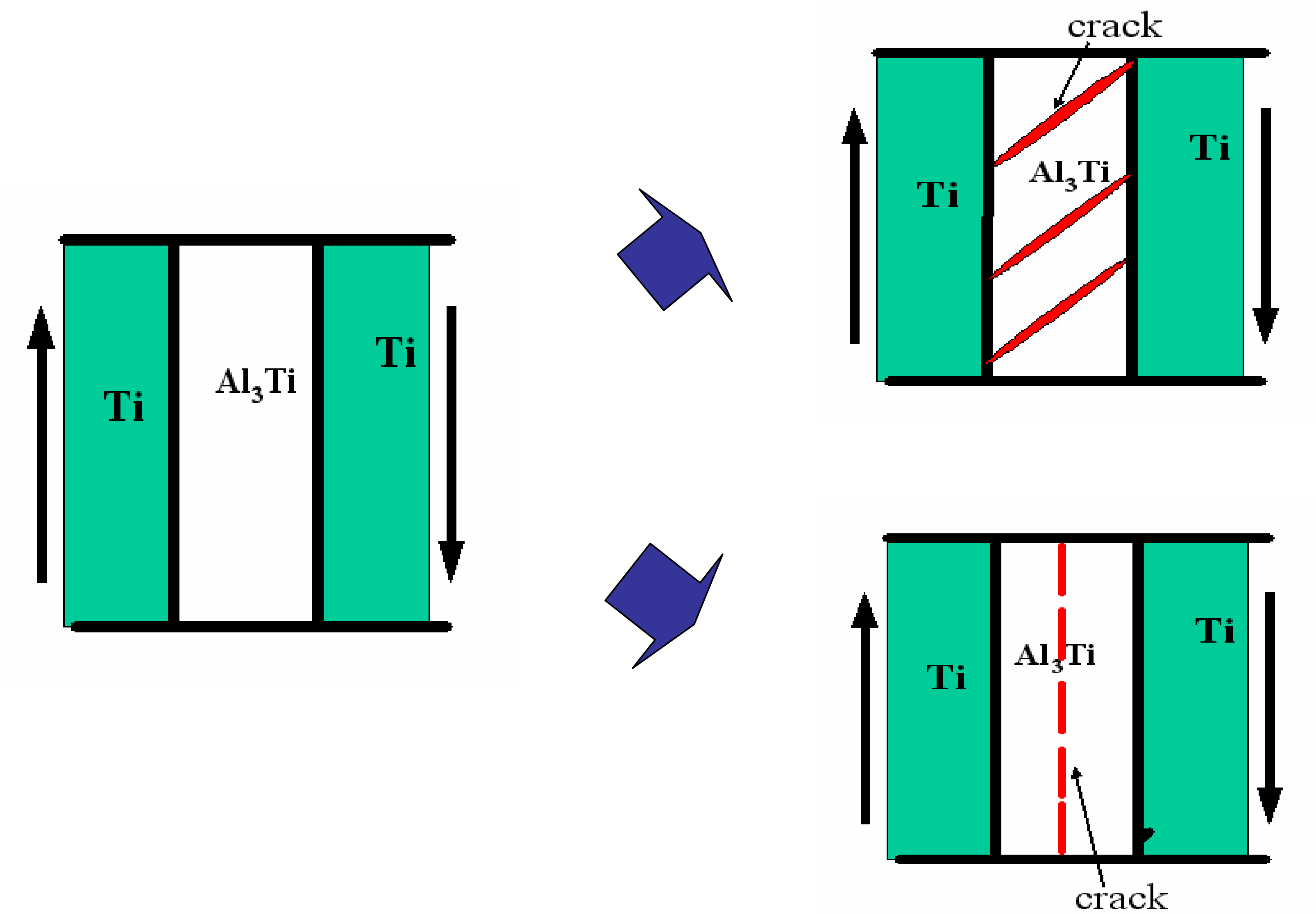


With Confinement



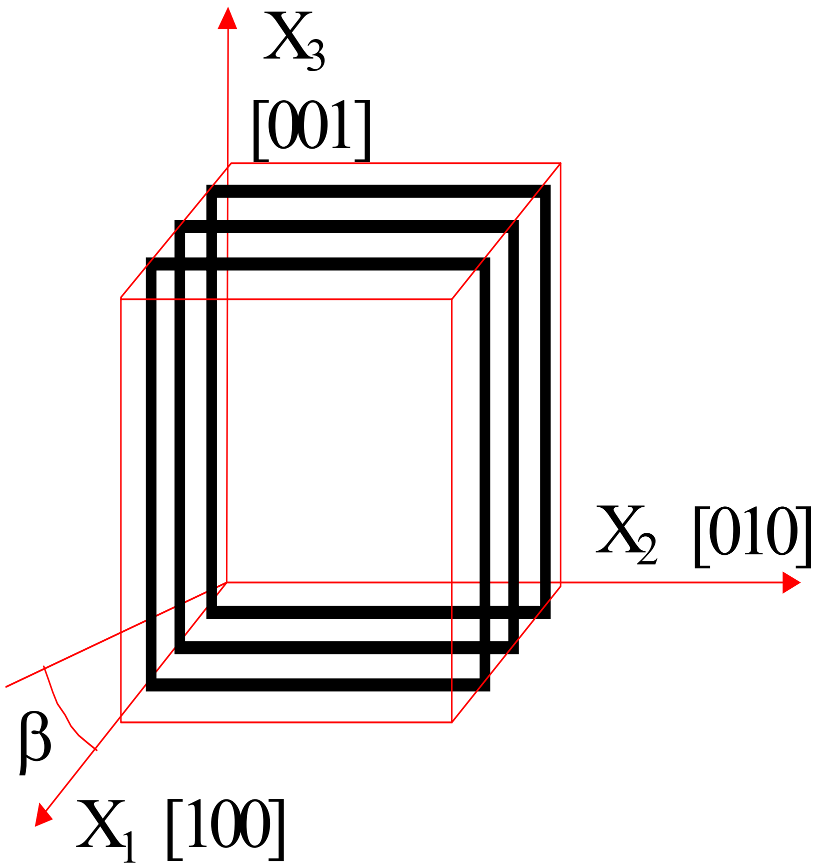
Without Confinement

Physical Modeling: Damage Evolution IV



Theoretical Modeling

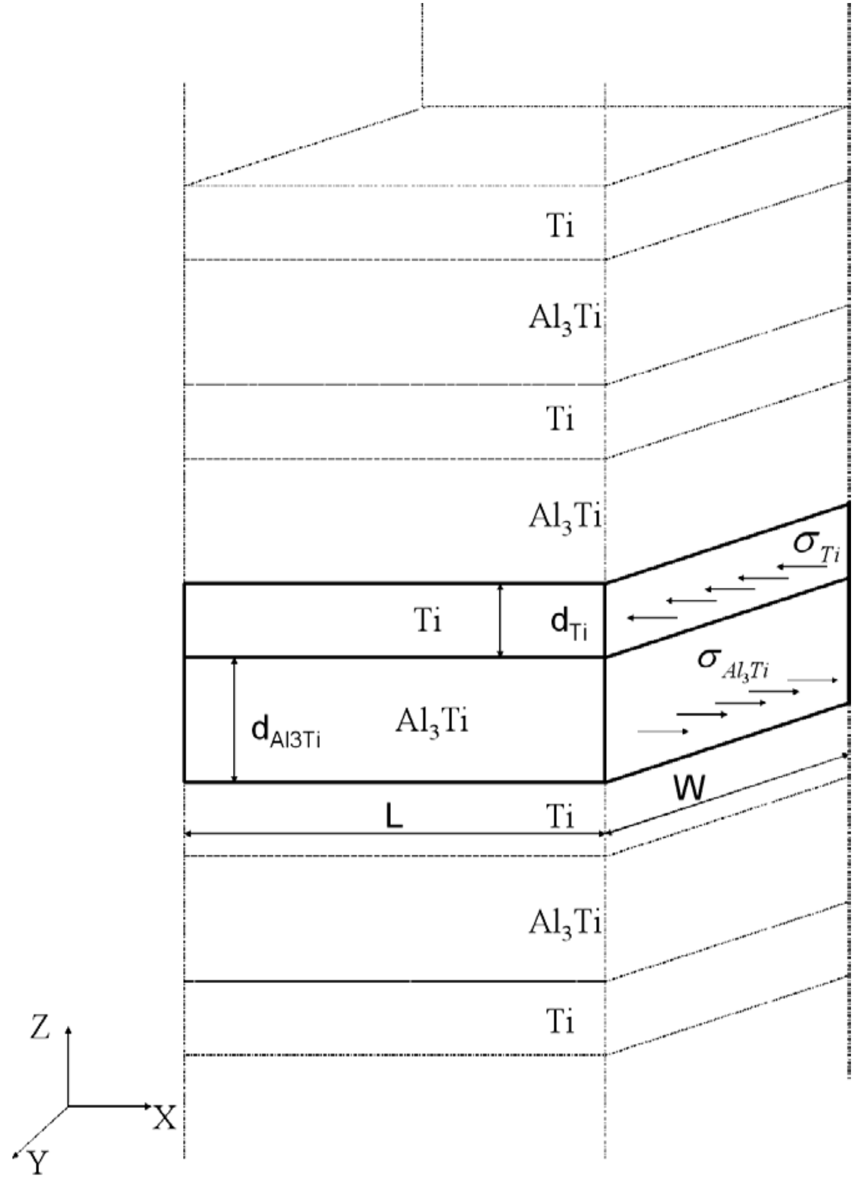
Elastic Properties of Ti-Al_3Ti



- *Volume Fraction*
- *Orientation*

Residual Stress in Ti-Al_3Ti

	Ti	Al_3Ti
α $(10^{-6}/^{o}C)$	9.5	13



Residual Stress in Ti-Al_3Ti

Calculated residual stress

$$\sigma_c = \frac{E_1(1-c)\cdot[(\alpha_2-\alpha_1)\cdot\Delta T]}{\left[1+\left(\frac{1-\gamma_2}{1-\gamma_1}\cdot\frac{E_1}{E_2}-1\right)\cdot c\right](1-\gamma_1)}$$

	14%Ti	20%Ti	35%Ti
Calculated residual stress (MPa)	345	327	282
Measured residual stress (MPa)	65.01	32.38	8.29
Measured residual stress (slow cooling) (MPa)	30.79	25.24	10.59

Residual Stress Release Mechanism I:Creep

- Creep known as time-dependent deformation is characterized by Doner-Conrad equation

$$\frac{\dot{\varepsilon}_s kT}{D \mu b} = A \left(\frac{\sigma}{\mu} \right)^n$$

$\dot{\varepsilon}_s$ is the steady-state strain rate

μ the shear modulus

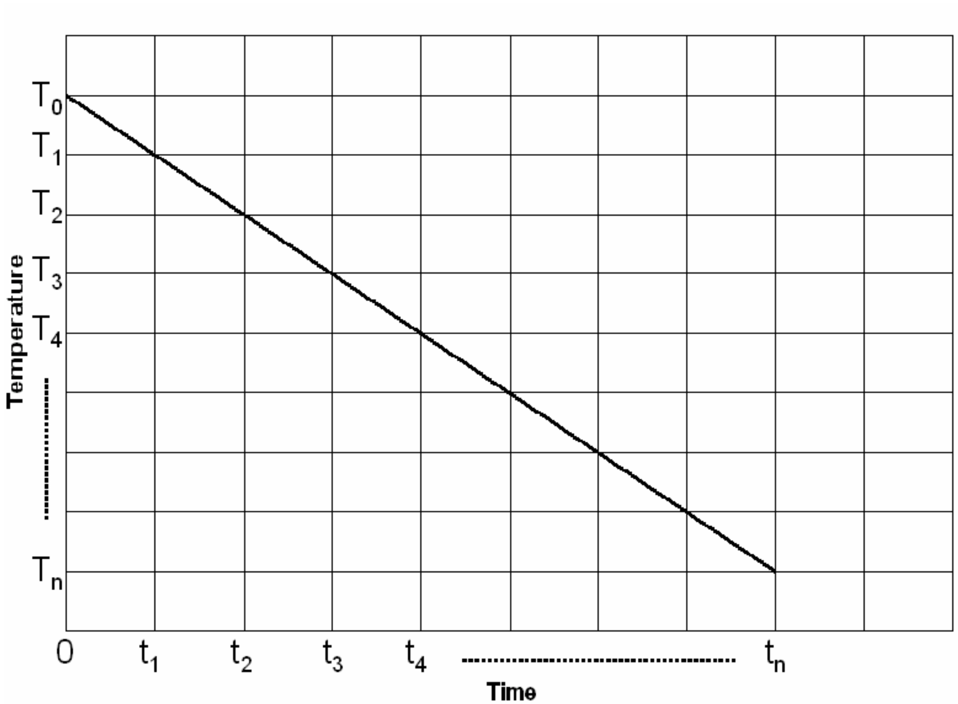
D: the diffusion coefficient

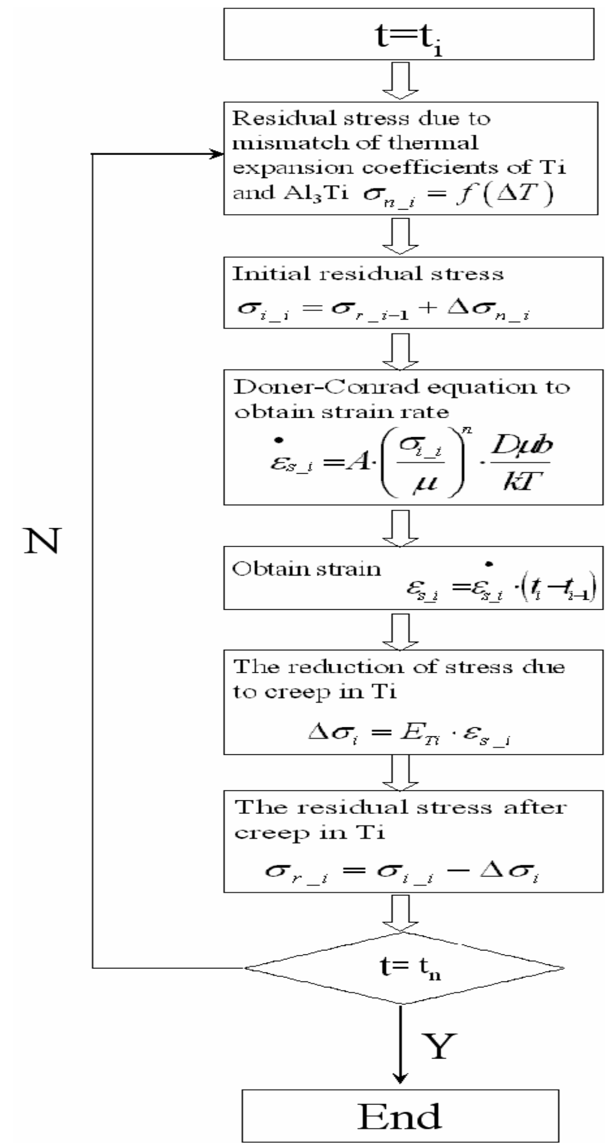
b: the Burgers vector

T: the temperature

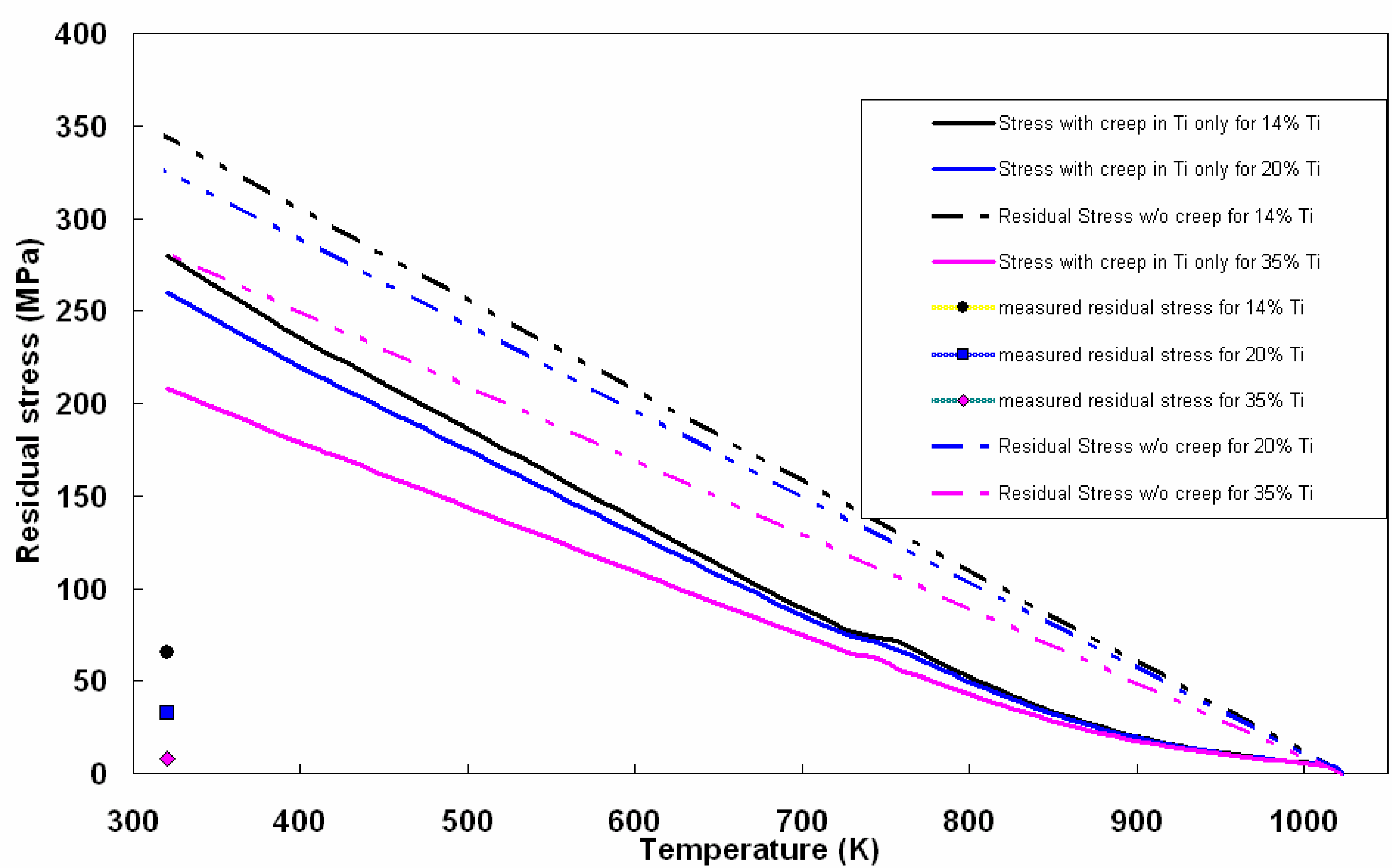
k: the Boltzmann's constant

Residual Stress Release Mechanism I:Creep

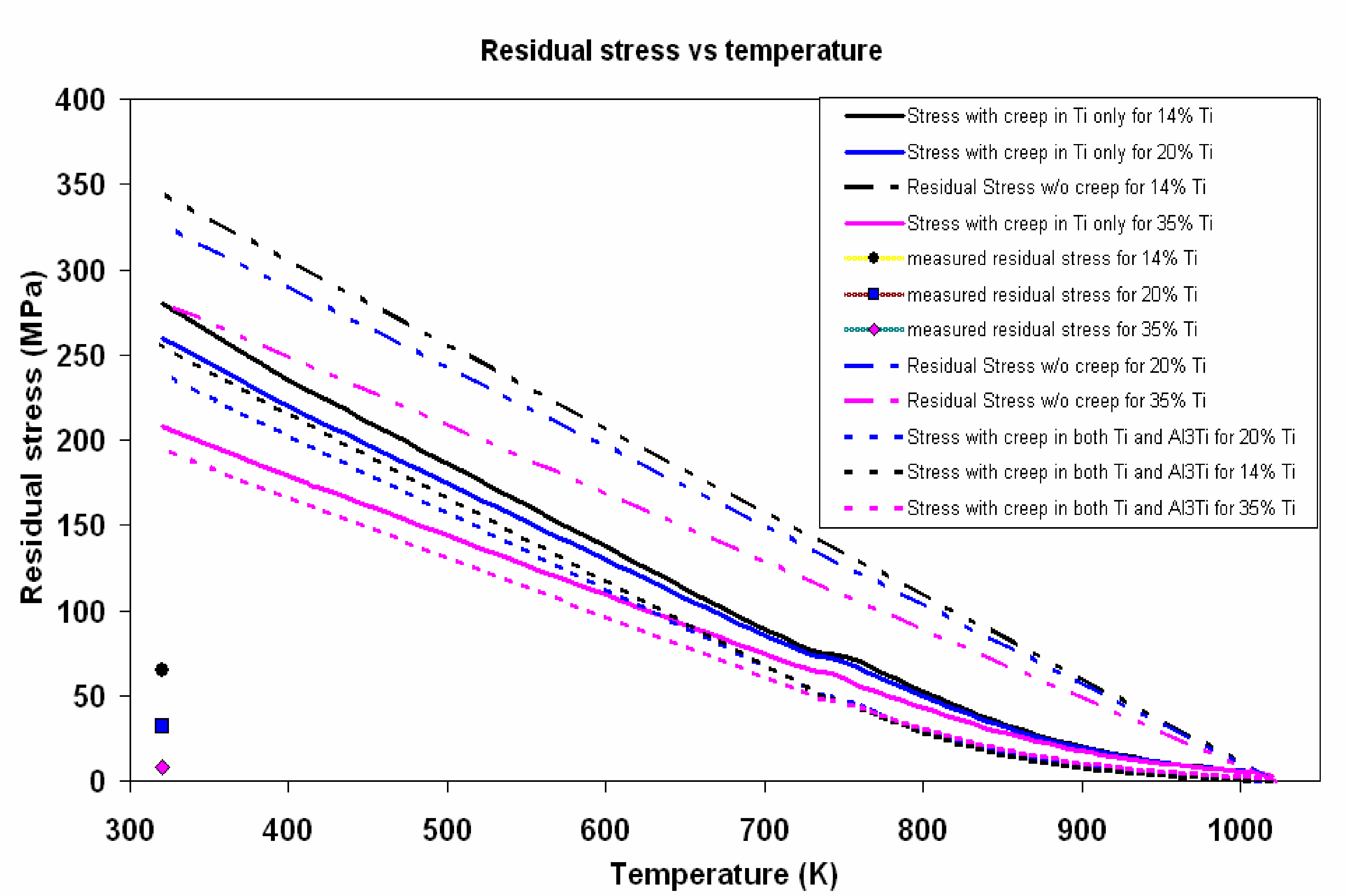




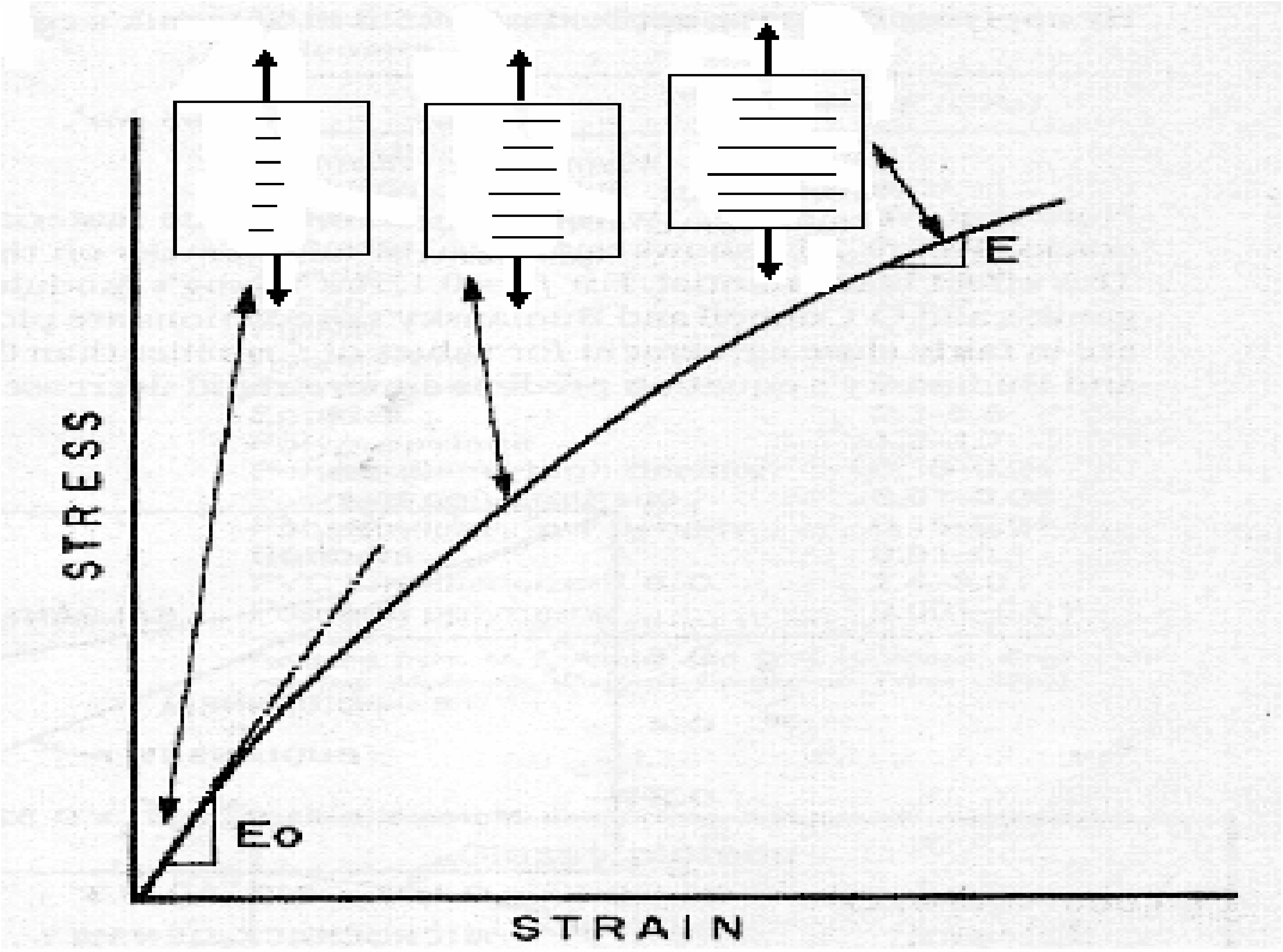
Residual Stress Release Mechanism I: Creep in Ti



Residual Stress Release Mechanism I: Creep in Both Ti and Al_3Ti



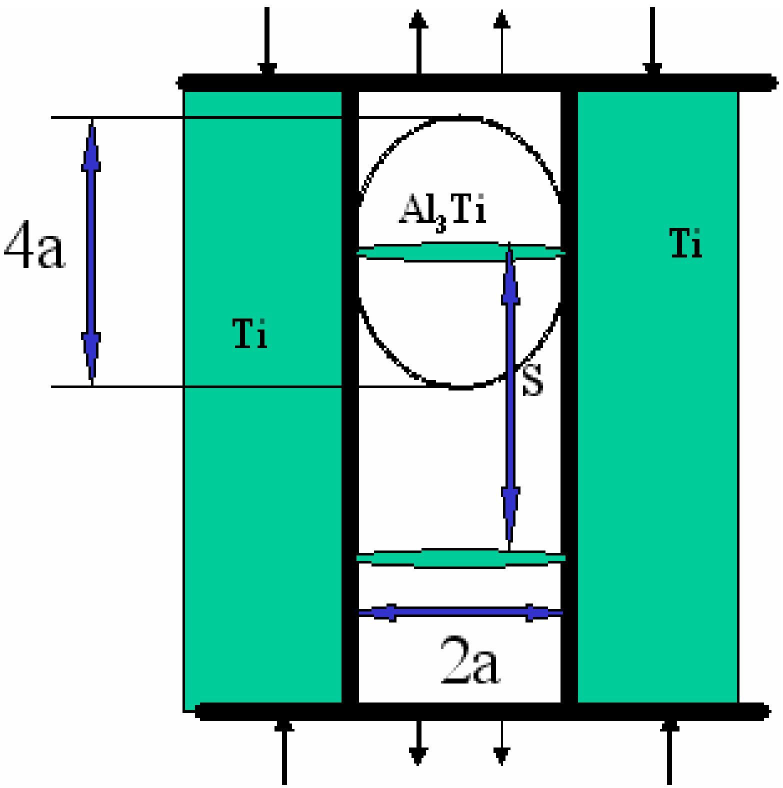
Residual Stress Release Mechanism II:Crack Propagation



Residual Stress Release Mechanism II:Crack Propagation

$$\sigma_c = \frac{E_1(1-c)\cdot[(\alpha_2-\alpha_1)\cdot\Delta T]}{\left[1+\left(\frac{1-\gamma_2}{1-\gamma_1}\cdot\frac{E_1}{E_2^e}-1\right)\cdot c\right](1-\gamma_1)}$$

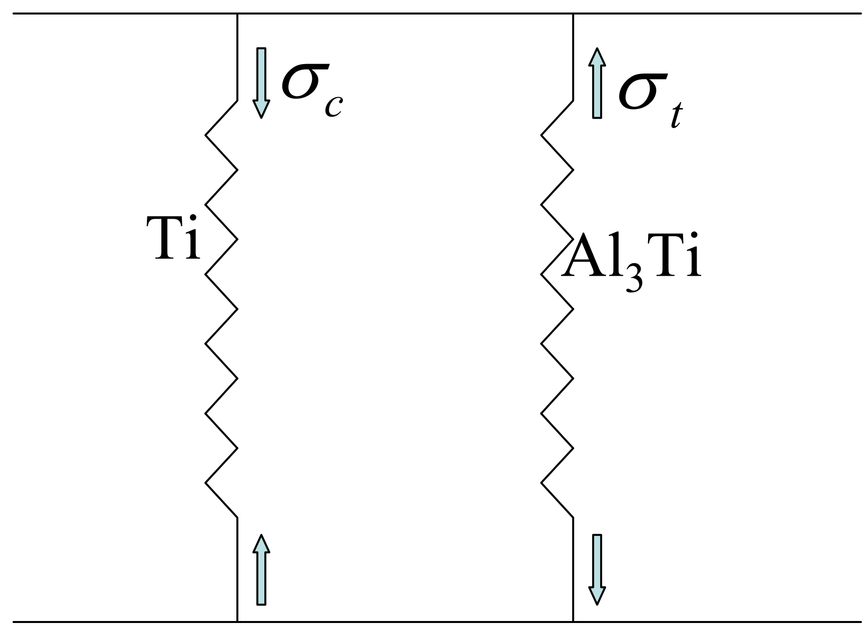
$$E_2^e = E_2\left(a,\frac{s}{a}\right)$$



(Griffith criterion)

Spring model

$$E_2^e = E_2\cdot\left(1-\frac{4a}{s}\right)$$

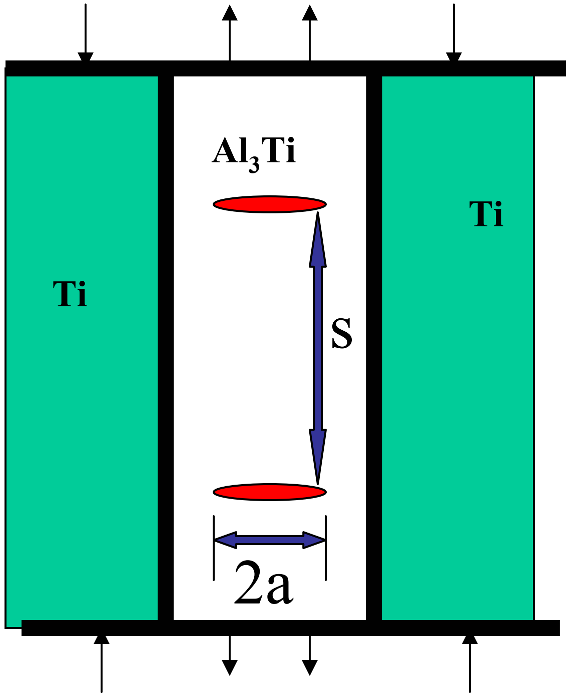


Residual Stress Release Mechanism II:Crack Propagation

$$\sigma_c = \frac{E_1(1-c)\cdot[(\alpha_2-\alpha_1)\cdot\Delta T]}{\left[1+\left(\frac{1-\gamma_2}{1-\gamma_1}\cdot\frac{E_1}{E_2^e}-1\right)\cdot c\right](1-\gamma_1)}$$

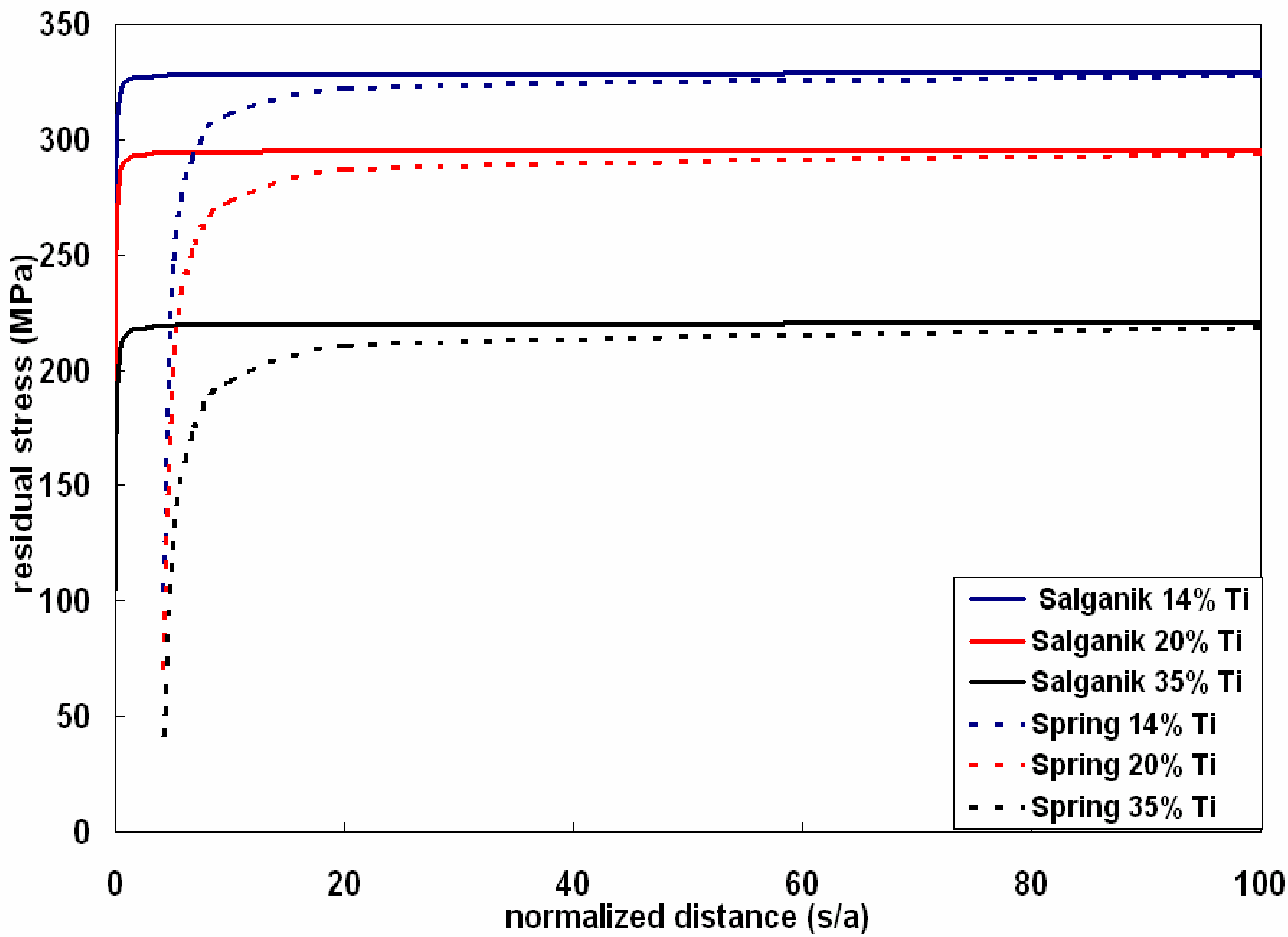
$$E_2^e = E_2\left(a,\frac{s}{a}\right)$$

Salganik model



$$E_2^e = \frac{E_2}{\left(1+\frac{16\cdot(10-3\upsilon_2)\cdot(1-\upsilon_2{}^2)}{45\cdot(2-\upsilon_2)}\cdot N\left(a,\frac{s}{a}\right)\cdot a^3\right)}$$

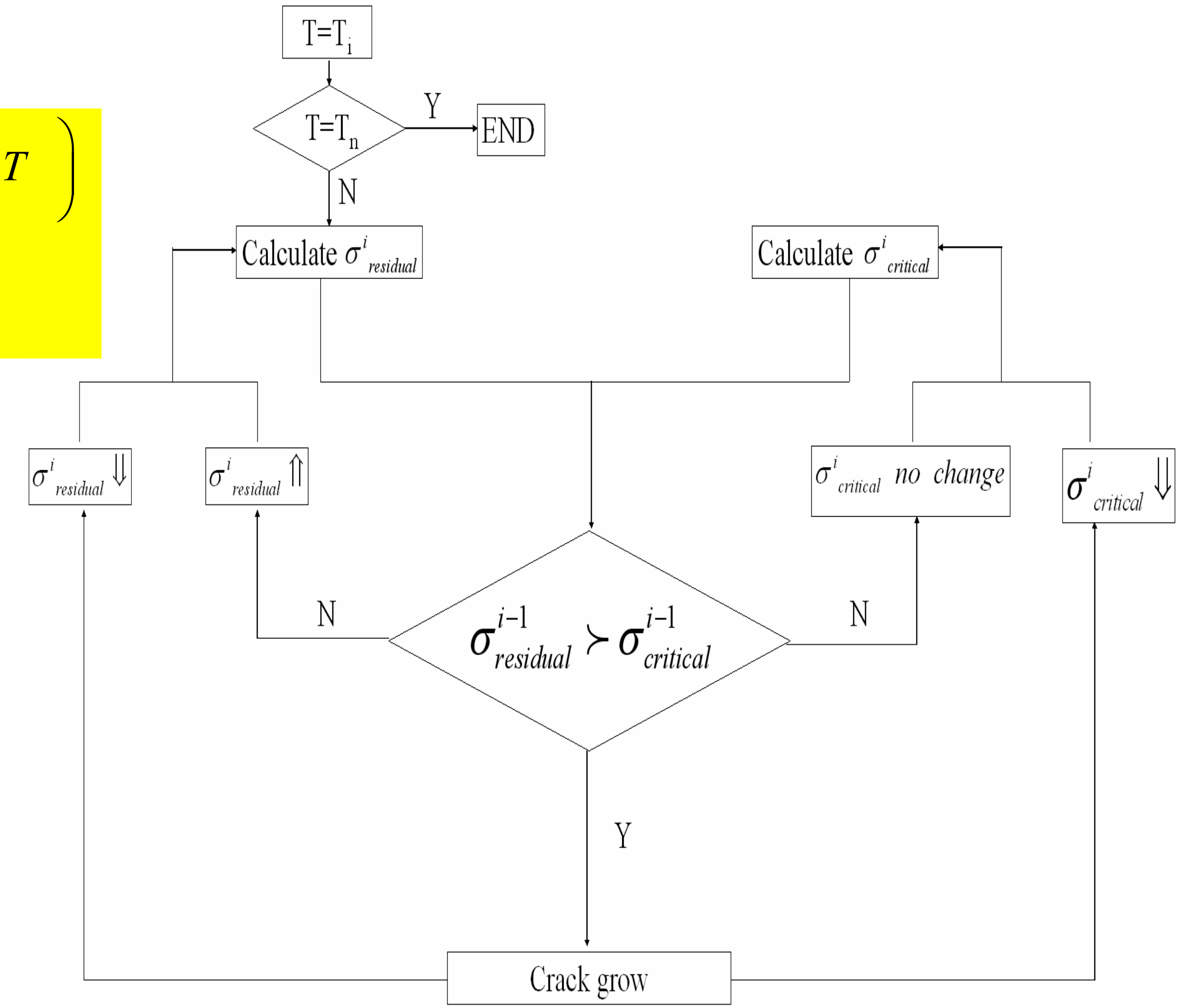
Residual Stress Release Mechanism II:Crack Propagation



Residual Stress Release Mechanism: Combining Creep and Crack Propagation

$$\sigma_{residual} = \sigma\left(a, \frac{s}{a}, T\right)$$

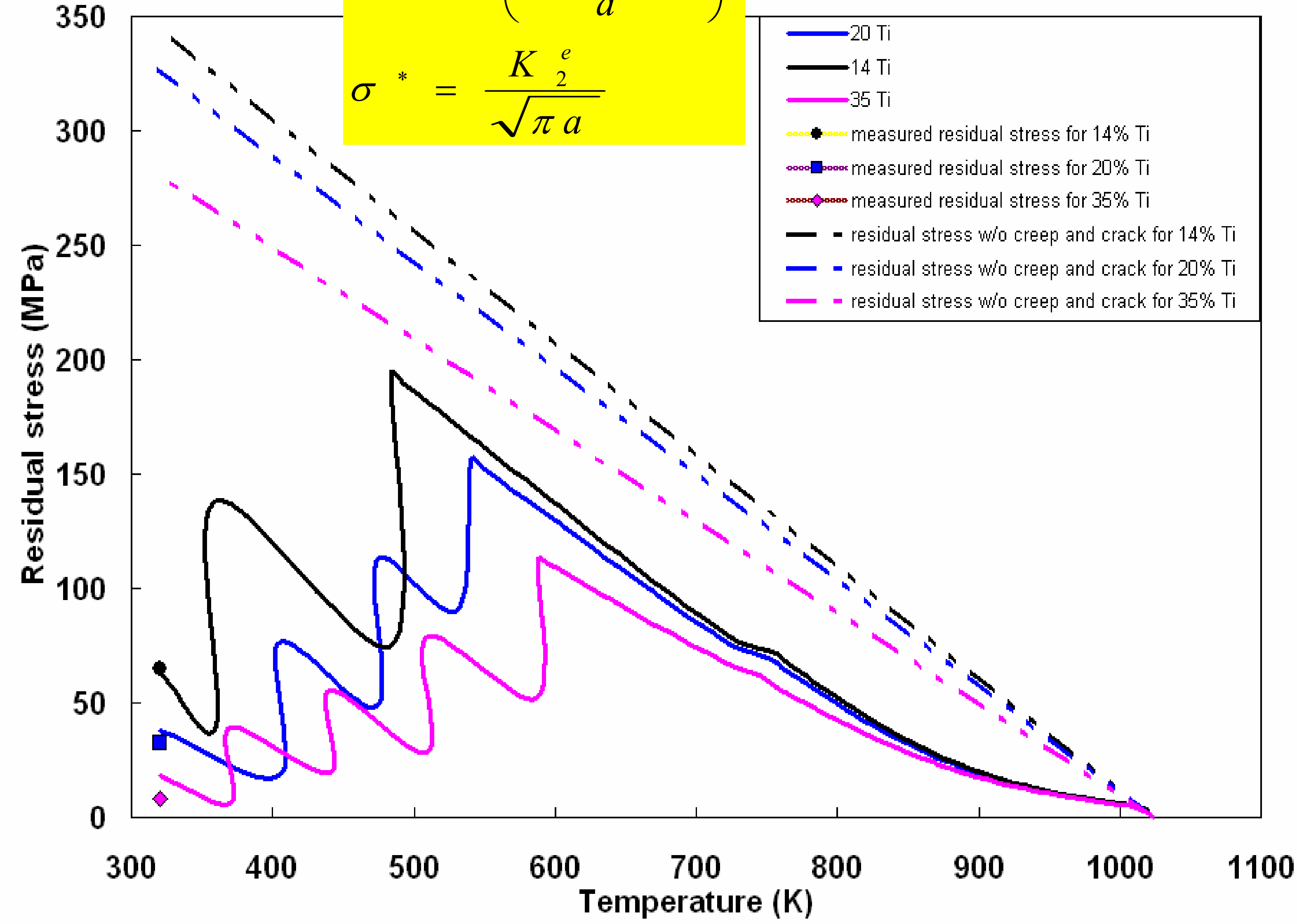
$$\sigma^{*}_{critical} = \frac{K_2^e}{\sqrt{\pi a}}$$



Residual Stress Release Mechanism

$$\sigma = \sigma\left(a, \frac{s}{a}, T\right)$$

$$\sigma^{*} = \frac{K_2^e}{\sqrt{\pi a}}$$

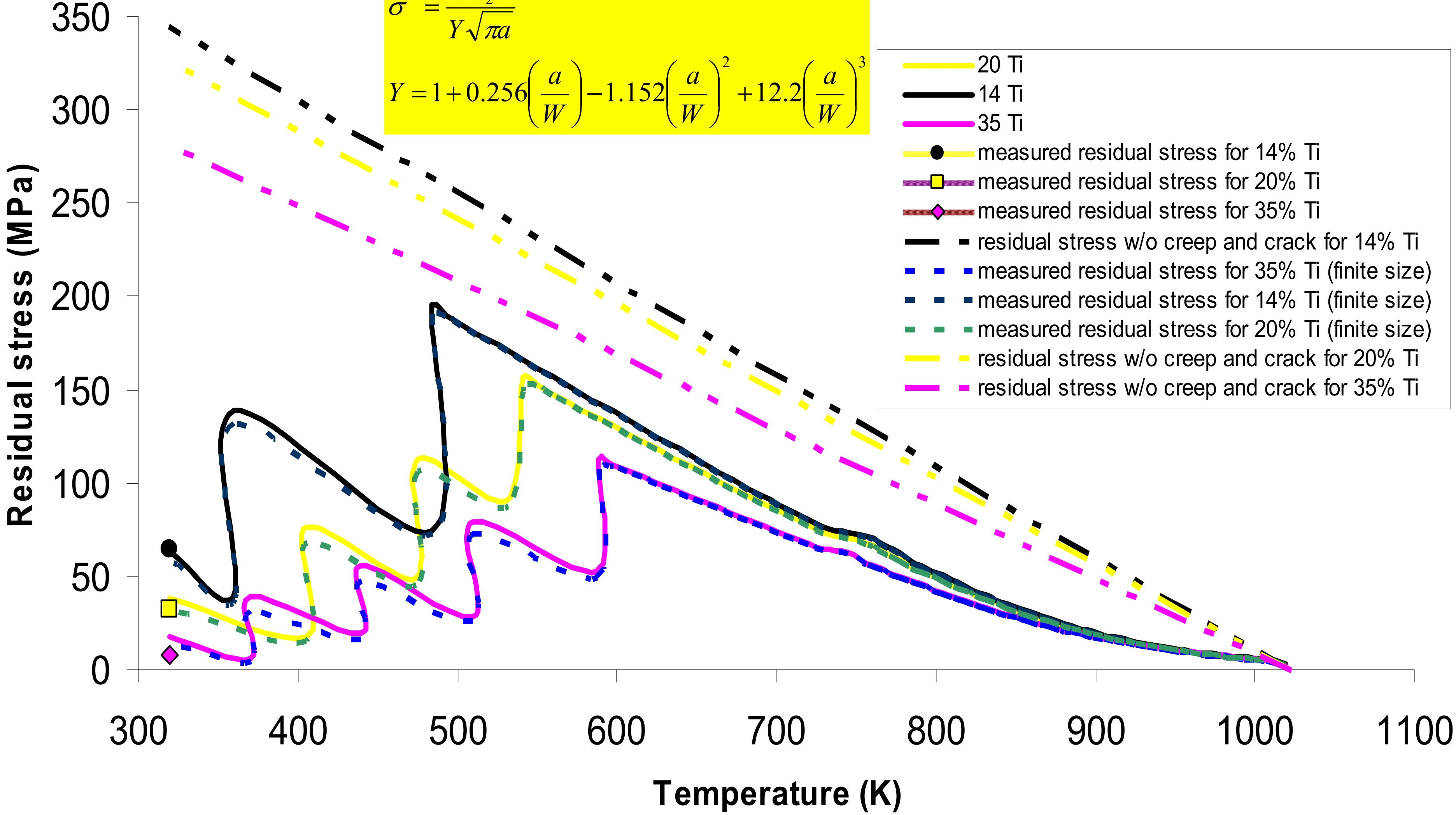


Residual Stress Release Mechanism (cont'd)

$$\sigma = \sigma\left(a, \frac{s}{a}, T\right)$$

$$\sigma^* = \frac{K_2^e}{Y\sqrt{\pi a}}$$

$$Y = 1 + 0.256\left(\frac{a}{W}\right) - 1.152\left(\frac{a}{W}\right)^2 + 12.2\left(\frac{a}{W}\right)^3$$



Fracture Toughness

Apparent fracture toughness of Ti-Al_3Ti MIL composite can be calculated from

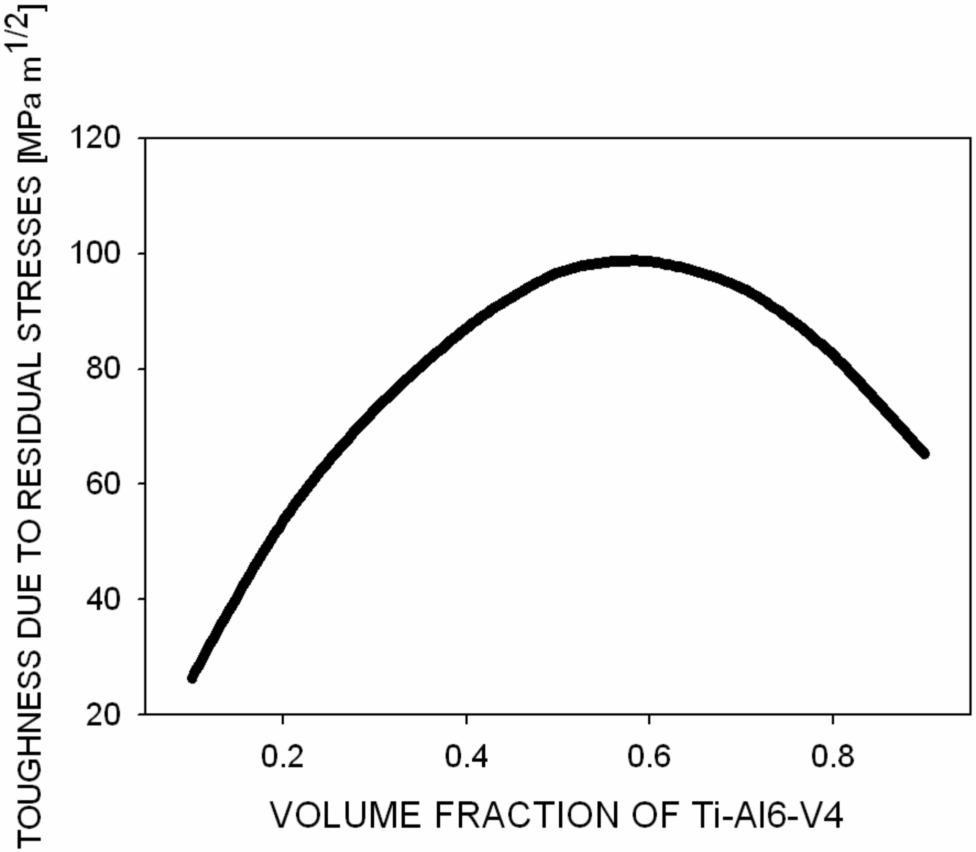
$$K_{c,\,app} = K_T + K_0$$

stress intensity due to the designed residual stresses

crack-initiation toughness of MIL

$$K_T = \int_0^a h\left(x/a, \alpha\right) \cdot \sigma_r(x)\, dx$$

Stress intensity was evaluated as a function of volume fraction of Ti:



Preliminary Conclusions

Preliminary Conclusions (Experiments)

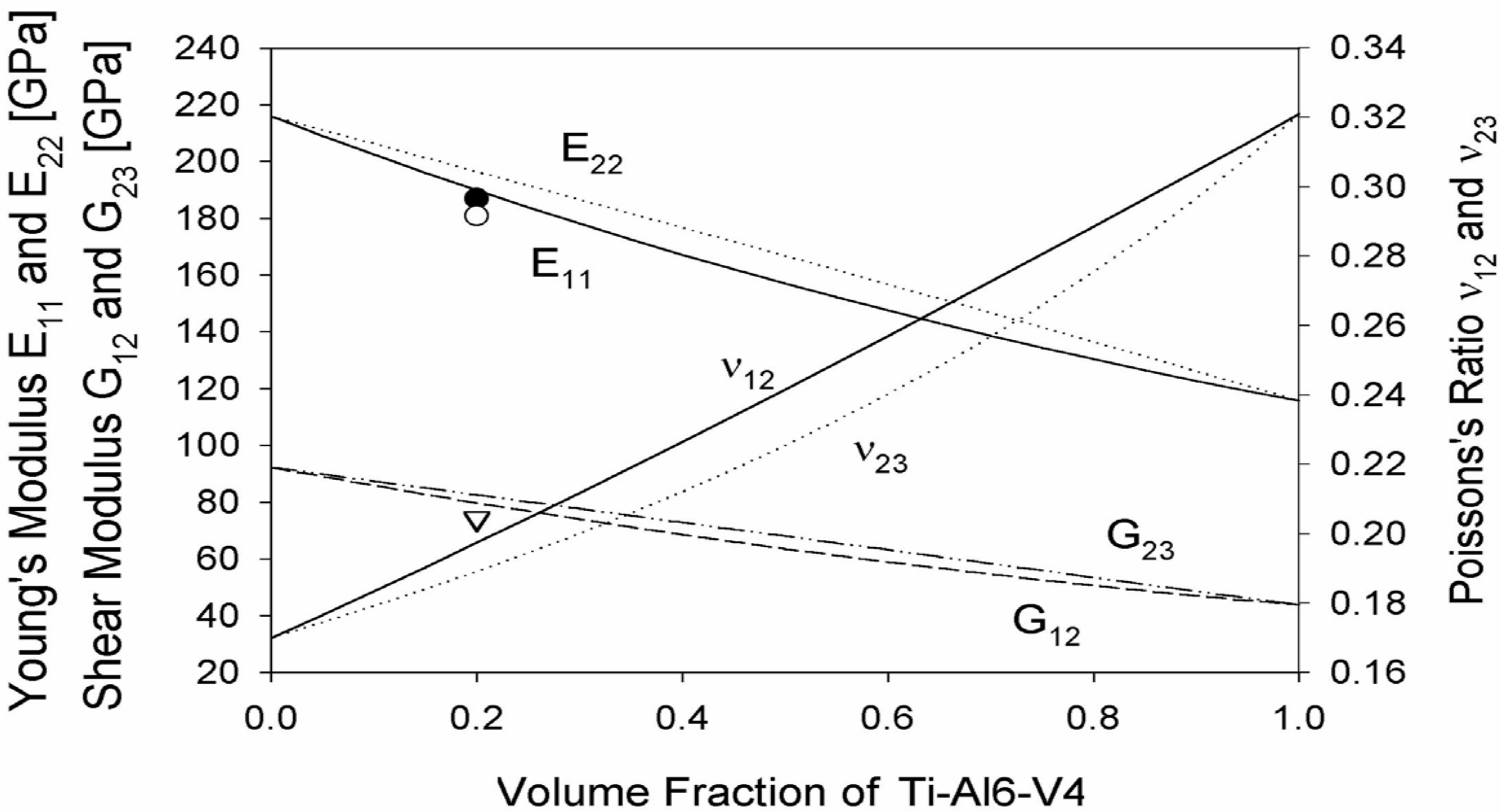
- Optical microscopy observations have showed the crack morphology of untested Ti-Al_3Ti MIL composites.
- Quasi-static and dynamic compression tests were conducted on pure Al_3Ti. Transgranular and intergranular cracks were found under SEM. The experiments show the strain rate has little effects on the formation of the two different crack morphologies.
- Compression tests were conducted on the Ti-Al_3Ti MIL composites, and the effects of different loading directions, different strain rates and different volume fraction of titanium on the damage evolution have been assessed.
- Four different damage evolution mechanisms have been identified, including axial splitting, shear localization in Ti layers, crack propagation along the central plane of weakness in Al_3Ti, and delamination at Al_3Ti-Ti interface.

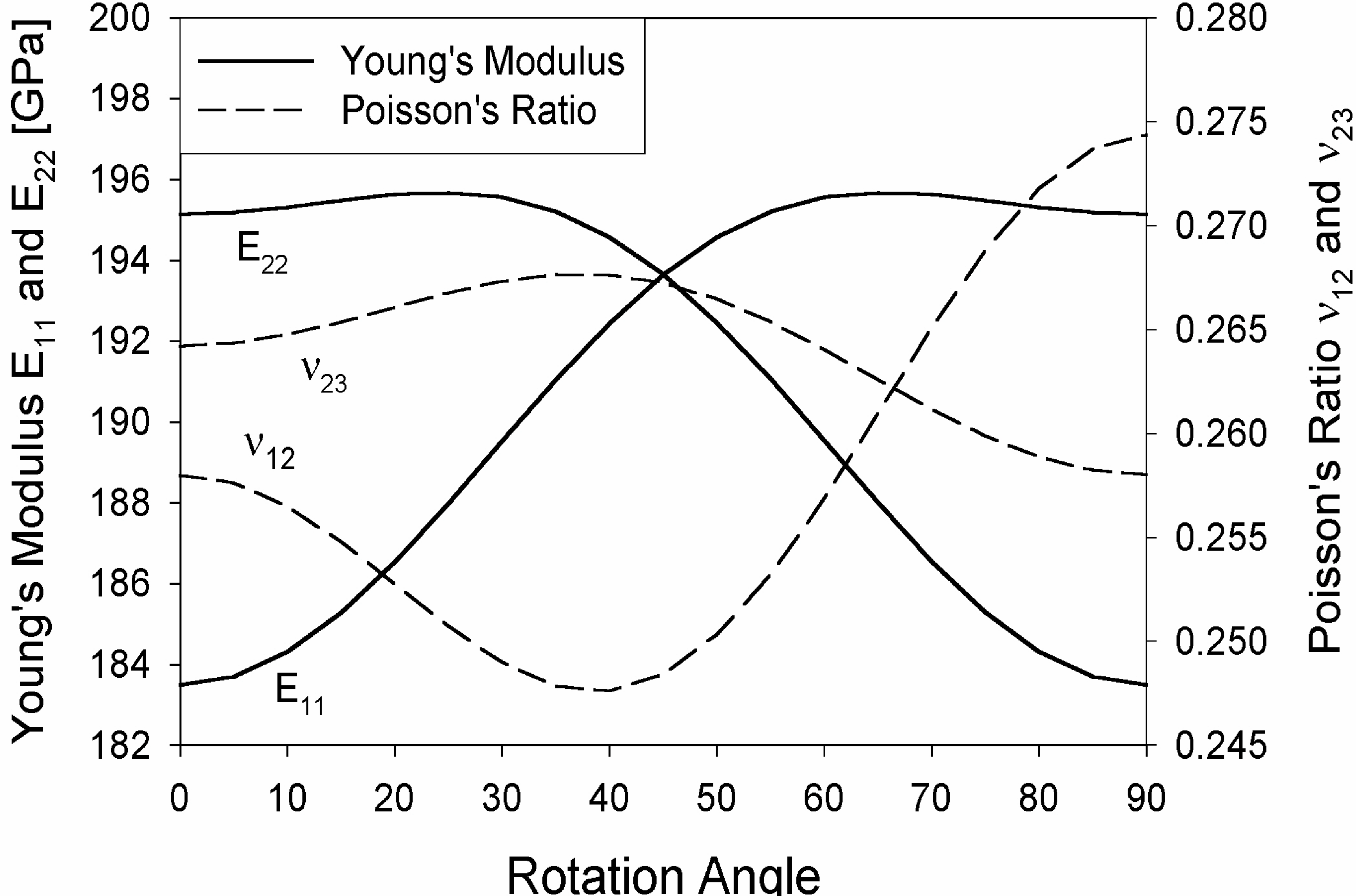
Preliminary Conclusions (Theoretical Modeling)

- The effect of orientation and volume fraction of Ti on the elastic properties of Ti-Al_3Ti has been investigated.
- Residual stress in Ti-Al_3Ti has been evaluated by elastic analysis and two stress relaxation mechanisms.
- The apparent fracture toughness of Ti-Al_3Ti has been evaluated using a weight function method.

Thank you.

Calculations (Lines) and Data from RUS-Measurements (Dots)
Elastic Constants for MIL




Young's Modulus
Poisson's Ratio
Young's Modulus E_{11} and E_{22} [GPa]
Poisson's Ratio ν_{12} and ν_{23}
Rotation Angle
E_{22}
E_{11}
ν_{23}
ν_{12}
182
184
186
188
190
192
194
196
198
200
0.245
0.250
0.255
0.260
0.265
0.270
0.275
0.280
0
10
20
30
40
50
60
70
80
90