Research Activity of Arai Laboratory in Gas Turbine
Tokyo University of Science

Solid Mechanics

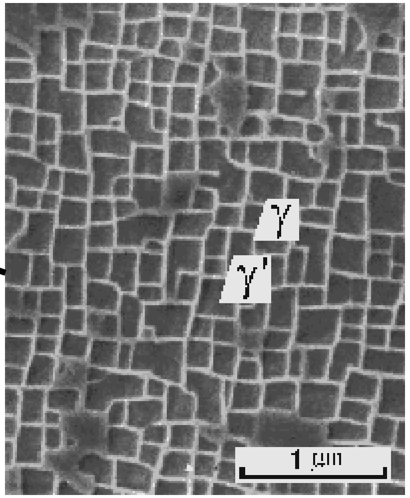
Solid Mechanics, Damage Mechanics & Interface Mechanics Lab.
Dept. of Mechanical Engineering, Faculty of Engineering
Tokyo University of Science

Research Projects

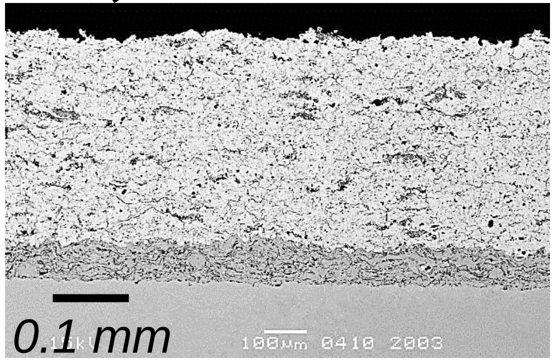
1) Nonlinear structural analysis of gas turbine blade and thermal barrier coating
2) Development of λ-controlled environmental coating for a high-temperature components
3) Maintenance system based upon controlling crack propagation
4) Development of life management system for aged structures
5) Damage mechanics for structural components attacked by natural disaster
6) Improvement of fracture toughness of high-temperature materials based upon bio-mimetics concept

Nonlinear structural analysis of gas turbine blade and thermal barrier coating

Turbine blade

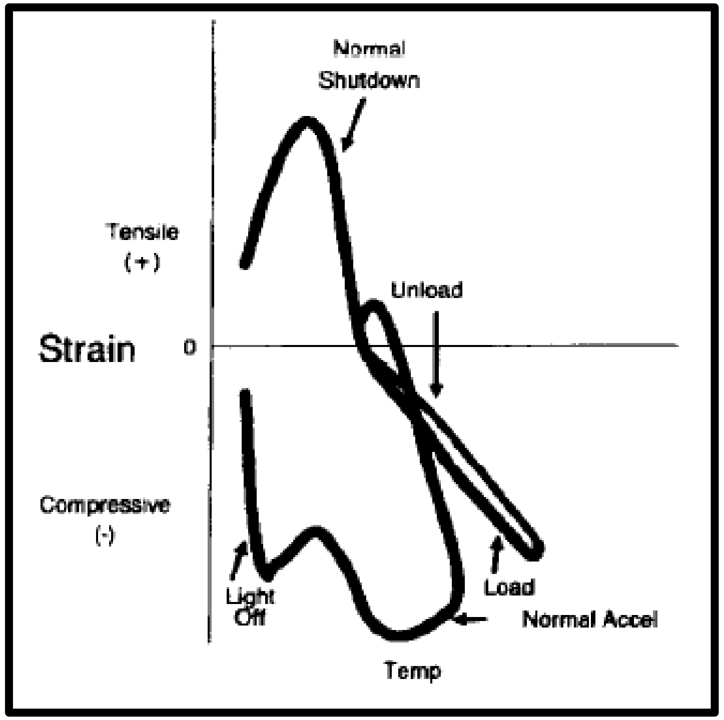


Ni-based superalloy

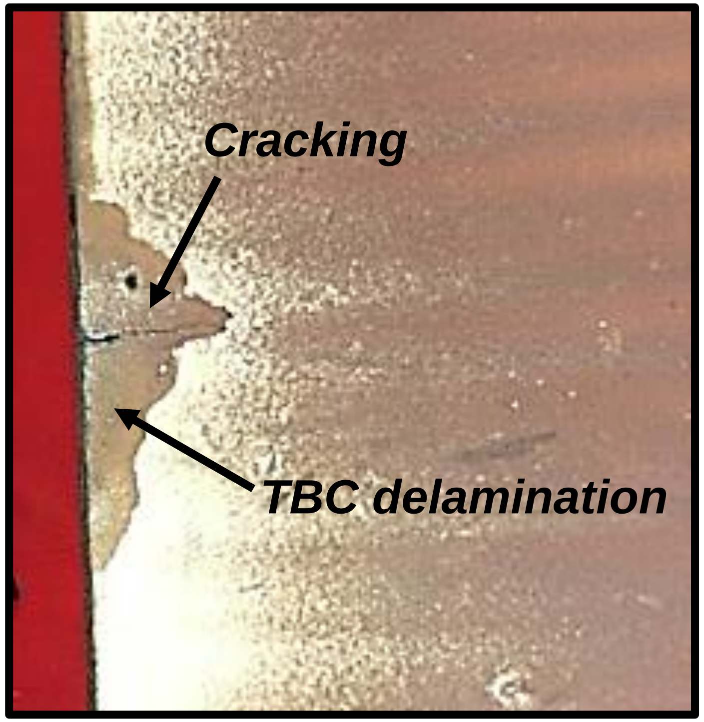


Thermal barrier coatings

Complex stress-temperature exposure and related damages



First stage bucket leading edge strain/temperature variation (Ref:GE gas turbine philosophy, GER3434-D)



Cracking and TBC delamination in leading edge (Courtesy by Chugoku electric company)

This project is supported by TEPCO, TOCALO and JSPS KAKENHI Grant Number JP 18K03847.

Nonlinear structural analysis of gas turbine blade and thermal barrier coating

Ni-based superalloy IN738LC

Viscoplastic constitutive equation:

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} + \varepsilon_{ij}^{T}$$

where

$$\varepsilon_{ij}^{e} = \frac{1+\nu}{E}\sigma_{ij} - \frac{\nu}{E}\sigma_{kk}\delta_{ij}$$

$$\dot{\varepsilon}_{ij}^{p} = \frac{3}{2}\dot{p}\frac{\sigma'_{ij} - X'_{ij}}{J(\sigma - X)}$$

$$\dot{p} = \left\{\frac{J(\sigma - X)}{K}\right\}^{n}$$

$$\dot{X}_{ij} = C\left\{\frac{2}{3}a\dot{\varepsilon}_{ij}^{p} - \left(X_{ij} - Y_{ij}\right)\dot{p}\right\} - \gamma J(X)^{m-1} + \frac{X_{ij}}{Ca}\frac{\partial(Ca)}{\partial T}\dot{T}$$

$$\dot{Y}_{ij} = -\alpha\left(Y_{st}\frac{X_{ij}}{J(X)} + Y_{ij}\right)\gamma J(X)^{m}$$

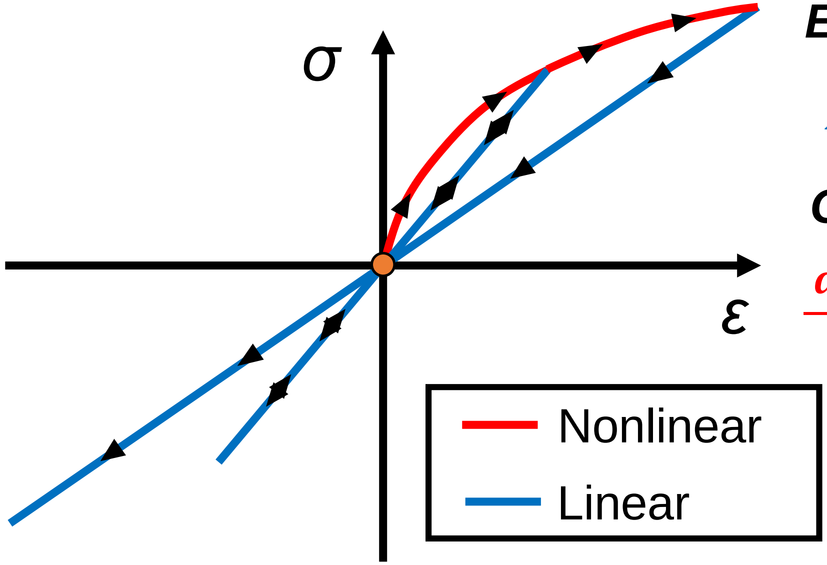
Bond coat CoNiCrAlY

Bilinear model:

$$E = E(T)$$

$$\sigma_{p}\left(\varepsilon_{p}, T\right) = \sigma_{Y}(T) + H(T)\varepsilon_{p}$$

Top coat PS-YSZ



Damage-coupled inelastic constitutive equation:

$$\varepsilon_{ij} = \left[S_{ijkl}^{0} + \frac{8}{3}D\left(\frac{1-\nu^{2}}{\pi E}\right)K_{ijkl}\right]\sigma_{kl}$$

Damage parameter D

$$\dot{D} = \dot{D}_{e}\langle\dot{D}_{e}\rangle\langle\sigma_{m}\rangle + \dot{D}_{c}\langle\dot{D}_{c}\rangle\langle\sigma_{m}\rangle + \dot{D}_{f}$$

Elastic term

$$D_{e} = \frac{1}{2}D_{0}A\left\{\left(\frac{p\langle p\rangle}{p_{0}}\right)^{n1} + \left(\frac{|q|}{q_{0}}\right)^{m1}\right\}$$

Creep term

$$\frac{dD_{c}}{dt} = \frac{1}{2}D_{0}B\left\{\left(\frac{p\langle p\rangle}{p_{0}}\right)^{n2} + \left(\frac{|q|}{q_{0}}\right)^{m2}\right\}$$

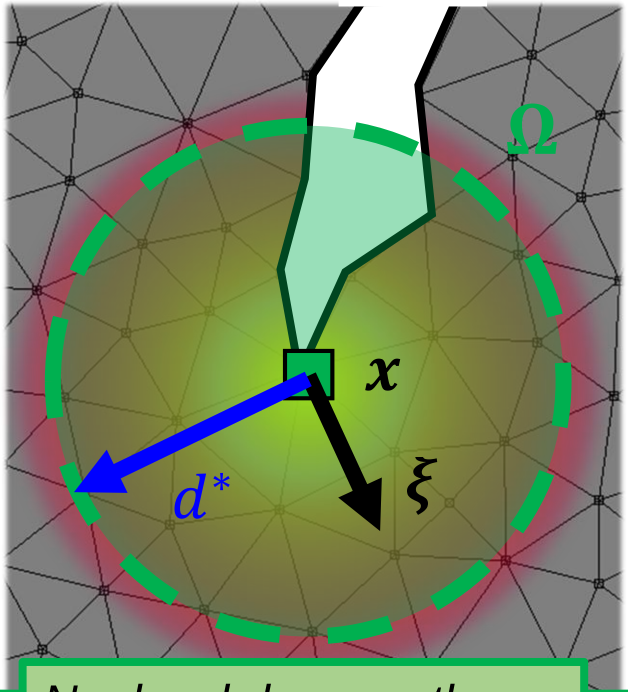
Fatigue term

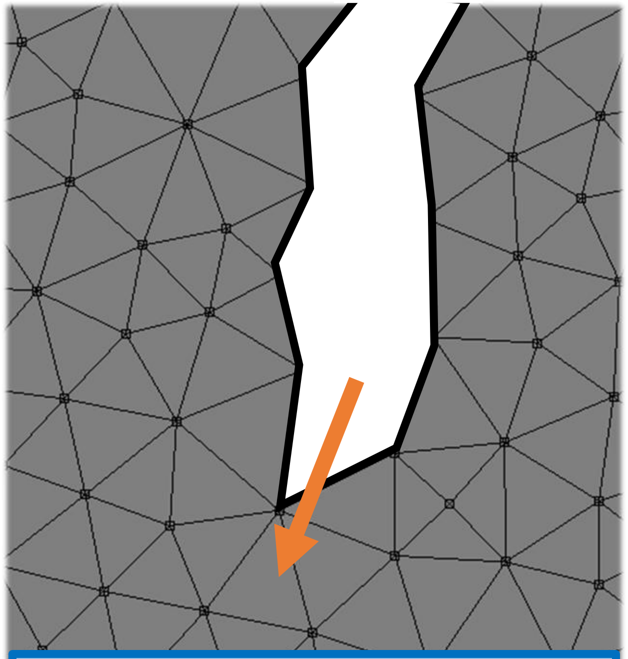
$$\frac{dD_{f}}{dt} = \frac{1}{2S_{f}}\sigma_{eq}\varepsilon_{eq}\left|\dot{\varepsilon}_{eq}\right|$$

This project is supported by TEPCO, TOCALO and JSPS KAKENHI Grant Number JP 18K03847.

Nonlinear structural analysis of gas turbine blade and thermal barrier coating

Crack propagation simulation





Nonlocal damage theory

$$\bar{D}(\boldsymbol{x}) = \frac{\int_{\Omega} D(\boldsymbol{\xi})\phi(\boldsymbol{x},\boldsymbol{\xi})\, d\Omega}{\int_{\Omega} \phi(\boldsymbol{x},\boldsymbol{\xi})\, d\Omega}$$

$$\phi(\boldsymbol{x},\boldsymbol{\xi}) = \exp\left\{-\frac{|\boldsymbol{x}-\boldsymbol{\xi}|}{d^*}\right\}$$

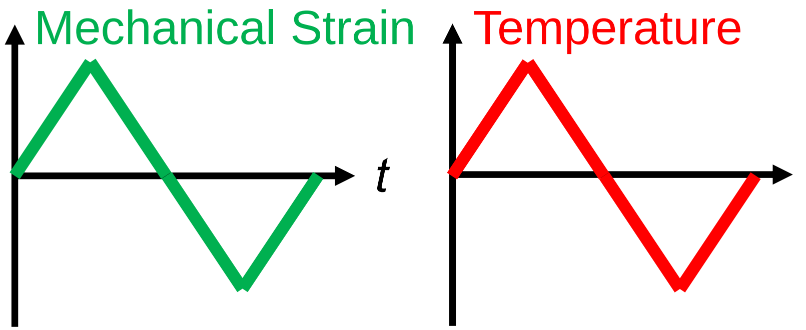
Local approach of fracture

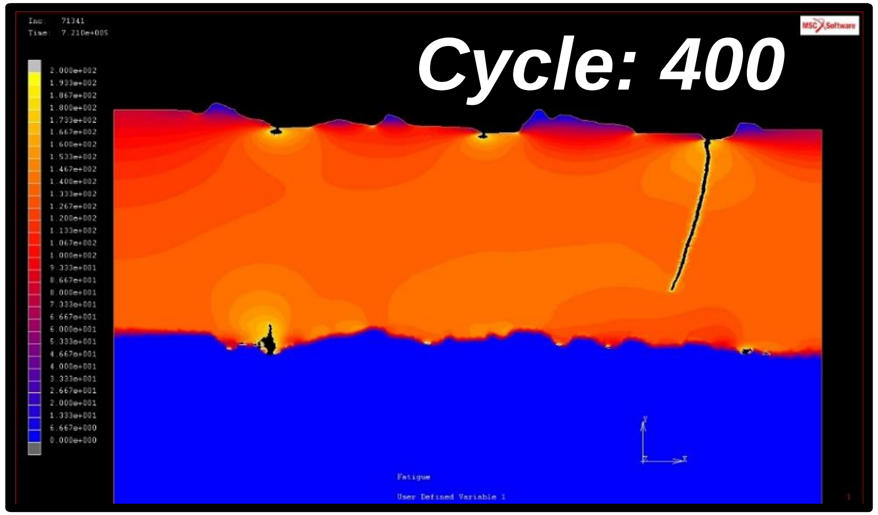
$\bar{D}$ > The critical damage D_C

Crack propagation by deactivating elements

TMF simulation

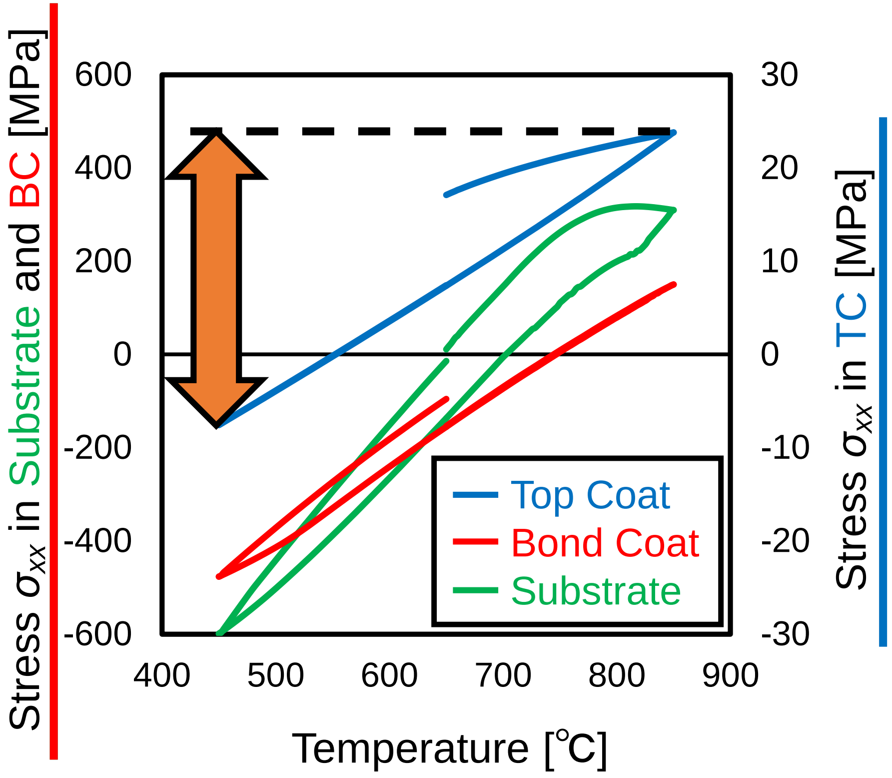
In Phase

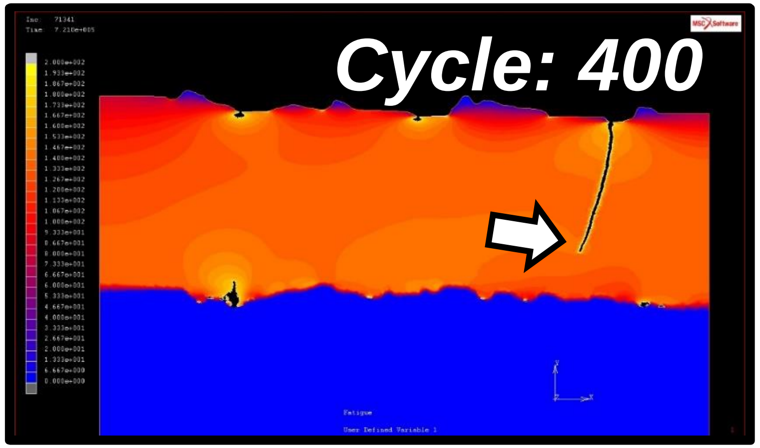




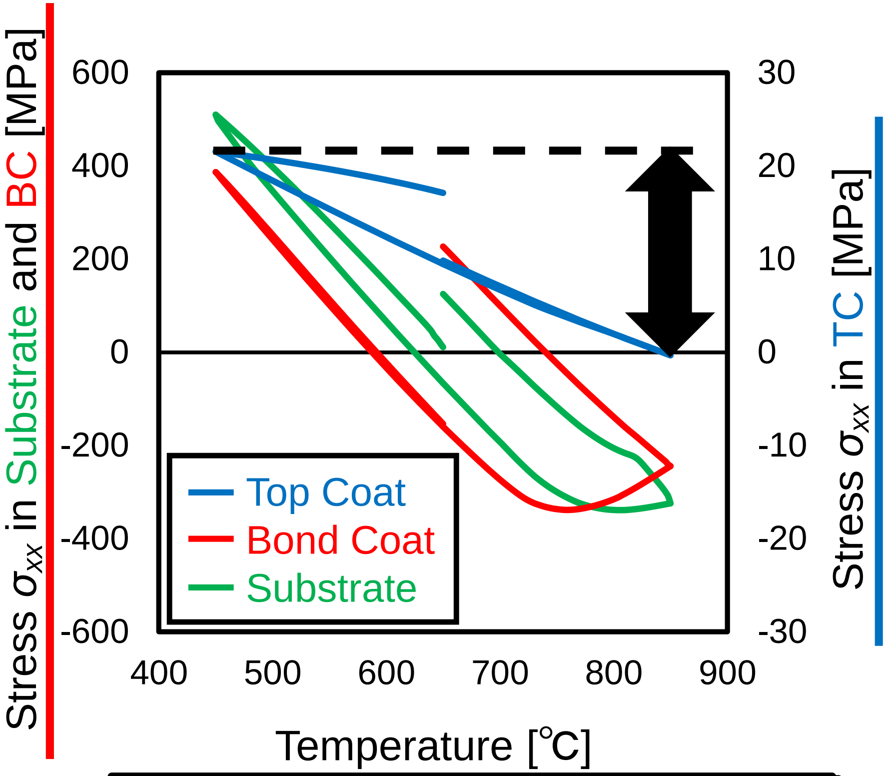
TMF simulation

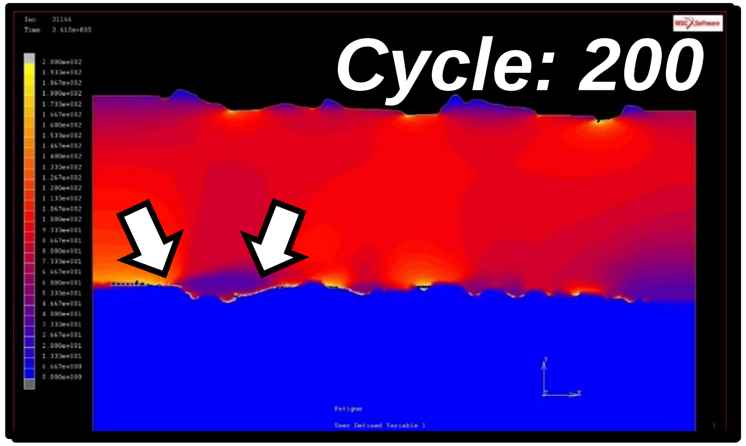
In Phase





Out of Phase



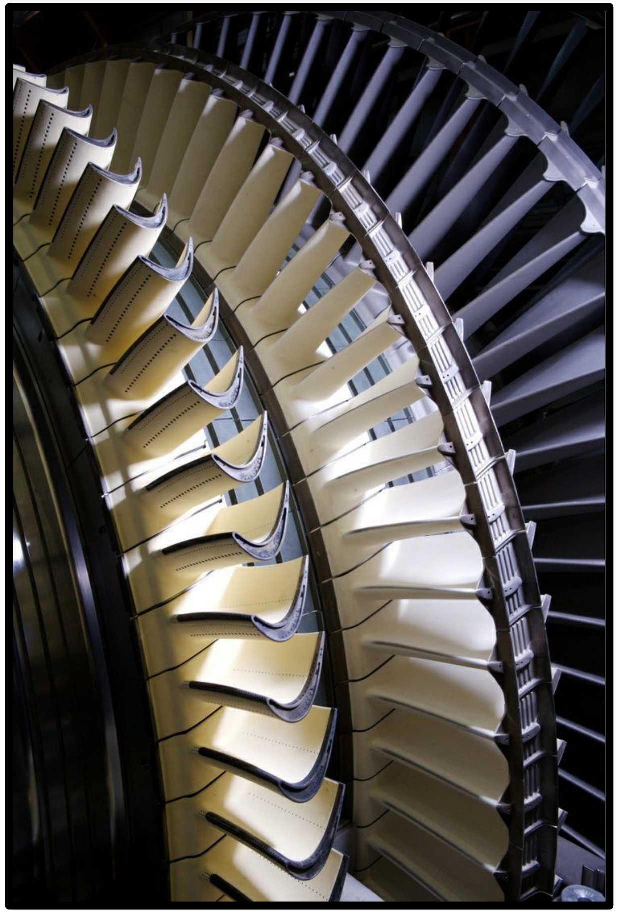


In out of phase, the interfacial crack is initiated at number of cycles shorter than one of in-phase.

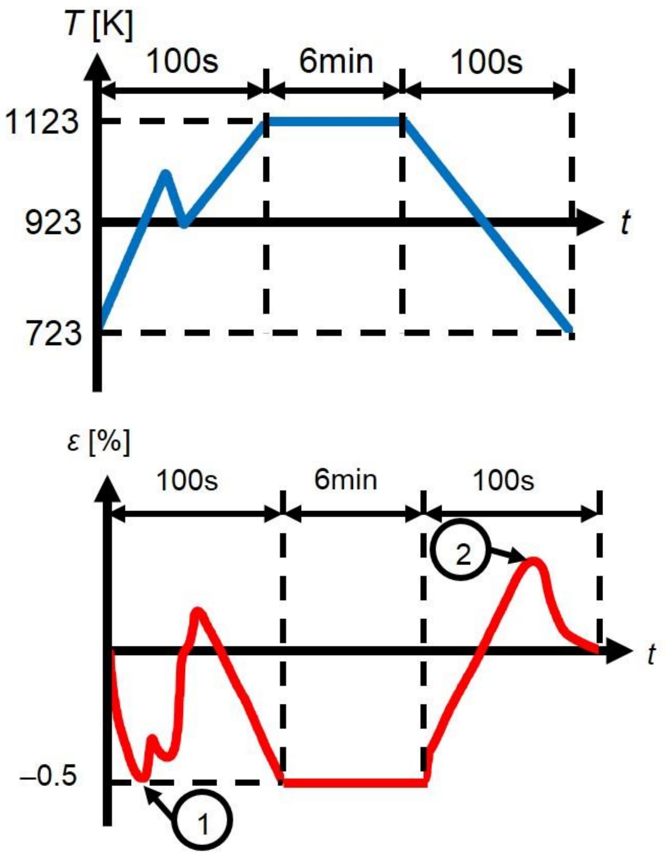
This is very important result from view of TBC maintenance as follow: Actual GT stress-temperature pattern is similar to that of out-of-phase, and it means that we can't do visible check for TBC cracking! During in-service of TBC, there is possibility of losing the detection of interfacial cracking !

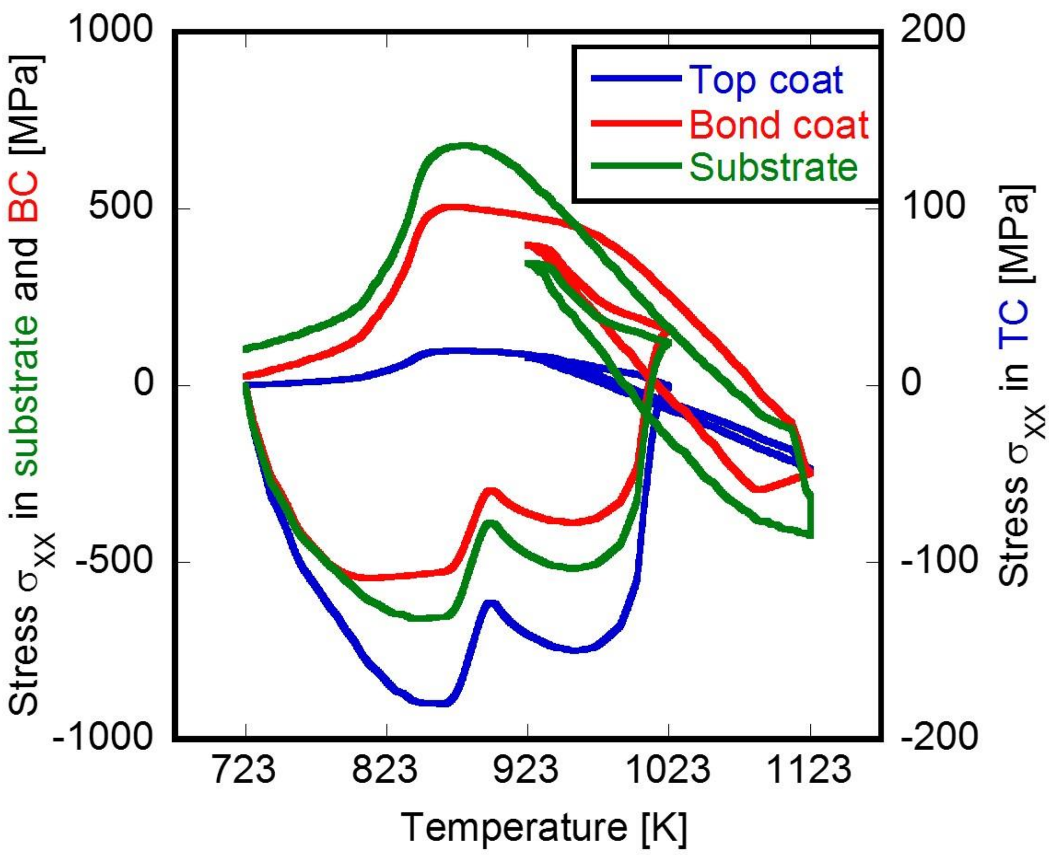
Nonlinear structural analysis of gas turbine blade and thermal barrier coating

Application to GT operation simulation



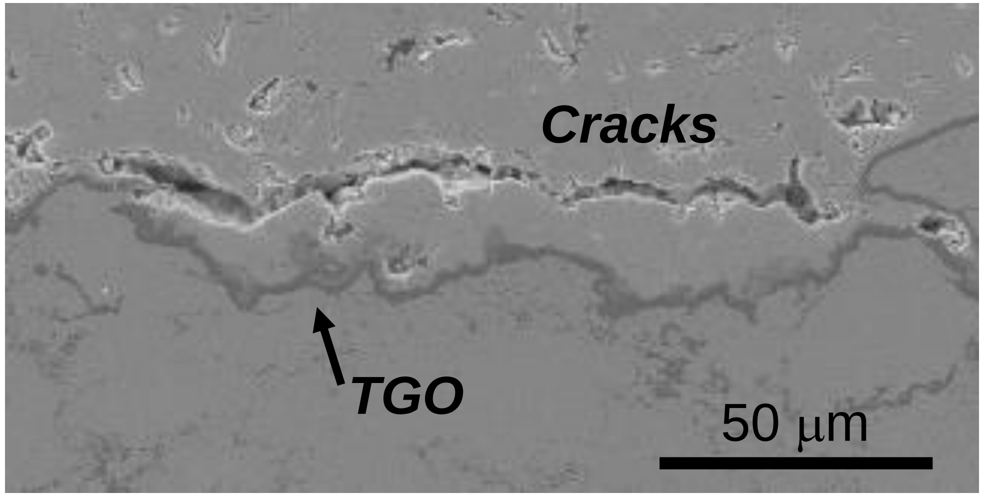
GE Turbine blade



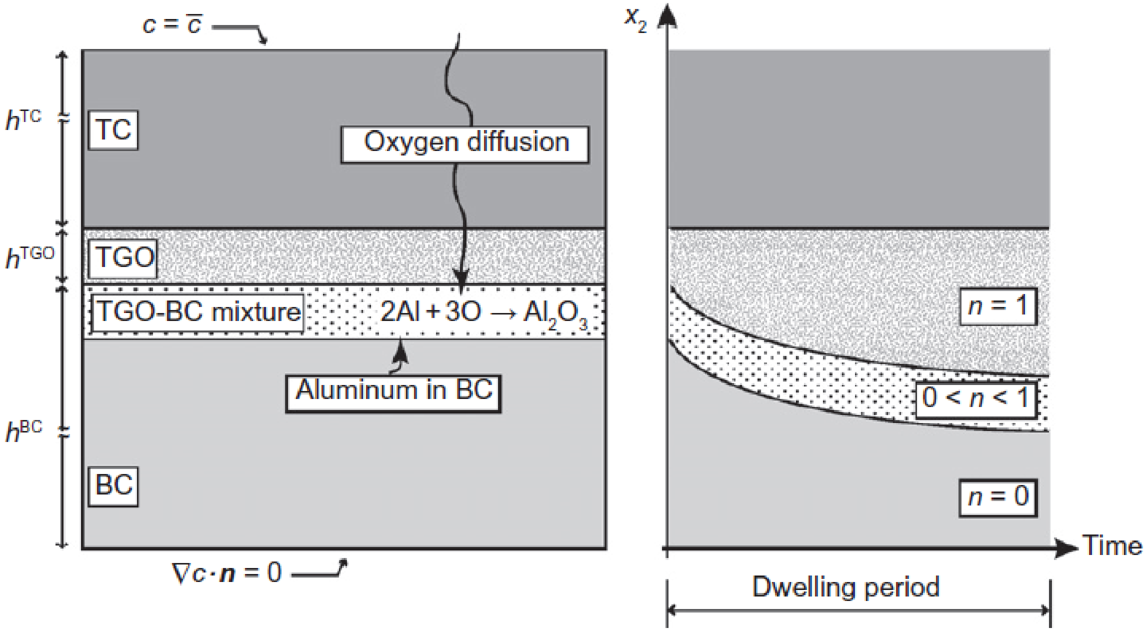


This project is supported by TEPCO, TOCALO and JSPS KAKENHI Grant Number JP 18K03847.

Other damage – Thermally grown oxide -



Thermal cycling test (60cycles@1273K)



***Oxygen diffusion-reaction model*)*:**

$$\begin{cases} \dfrac{\partial c}{\partial t} - \nabla \cdot (D \nabla c) = -MR(1-c)c \\ \dfrac{\partial n}{\partial t} = R(1-n)c \end{cases}$$

c:oxygen concentration

n:Volume fraction

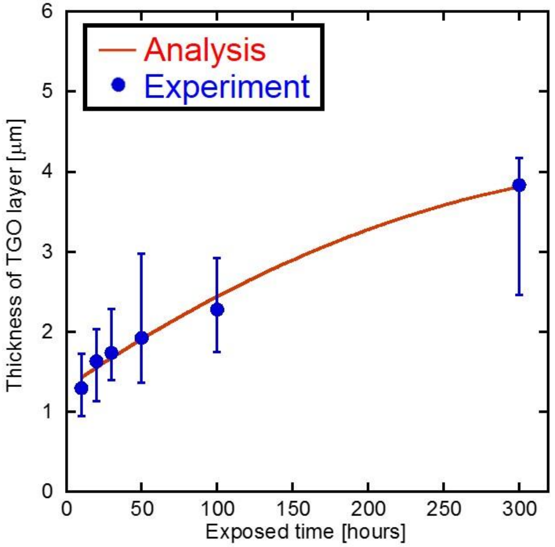
D:Oxygen diffusion coefficient

M:Oxygen molarity in alumina

R:Reaction rate in oxidation process

***Growth strain*)*:**

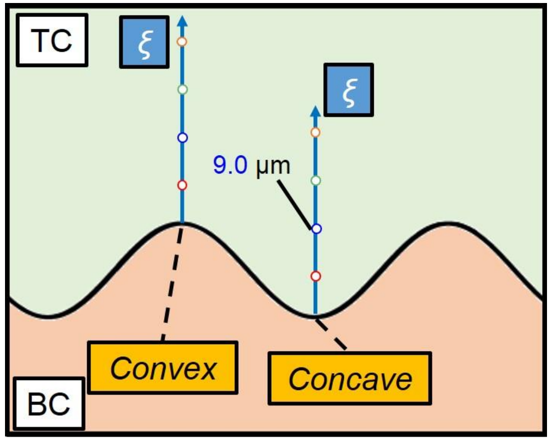
$$\Delta \varepsilon^{g}_{ij} = \Delta n \varepsilon^{g} \delta_{ij}$$

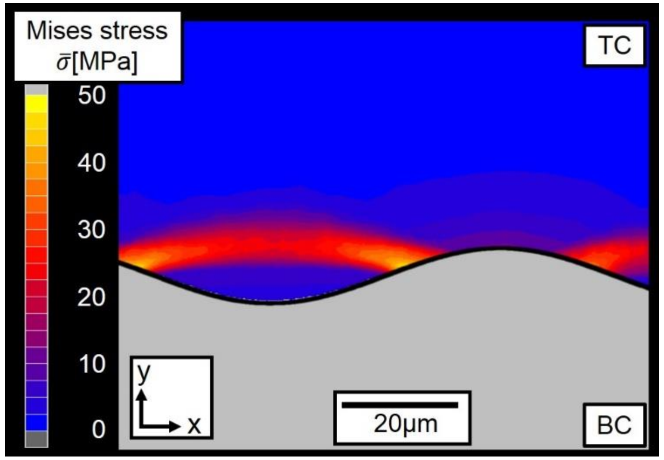


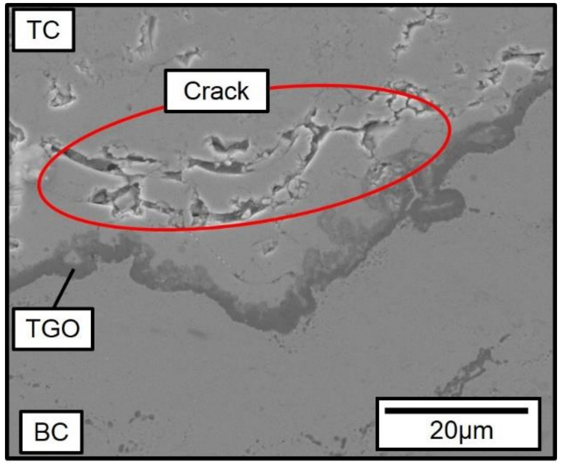
TGO growth curve

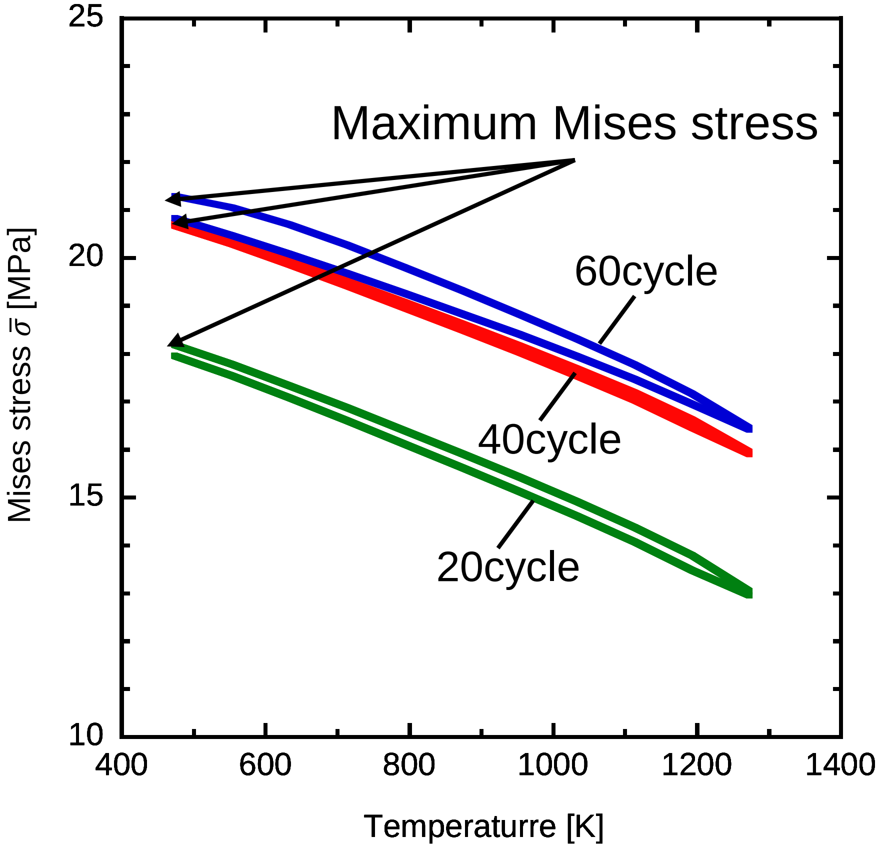
**)T.S.Hille.et al, "Oxide growth and damage evolution in thermal barrier coatings", Engineering Fracture Mechanics, Vol.78(2011), pp.2139-2152*

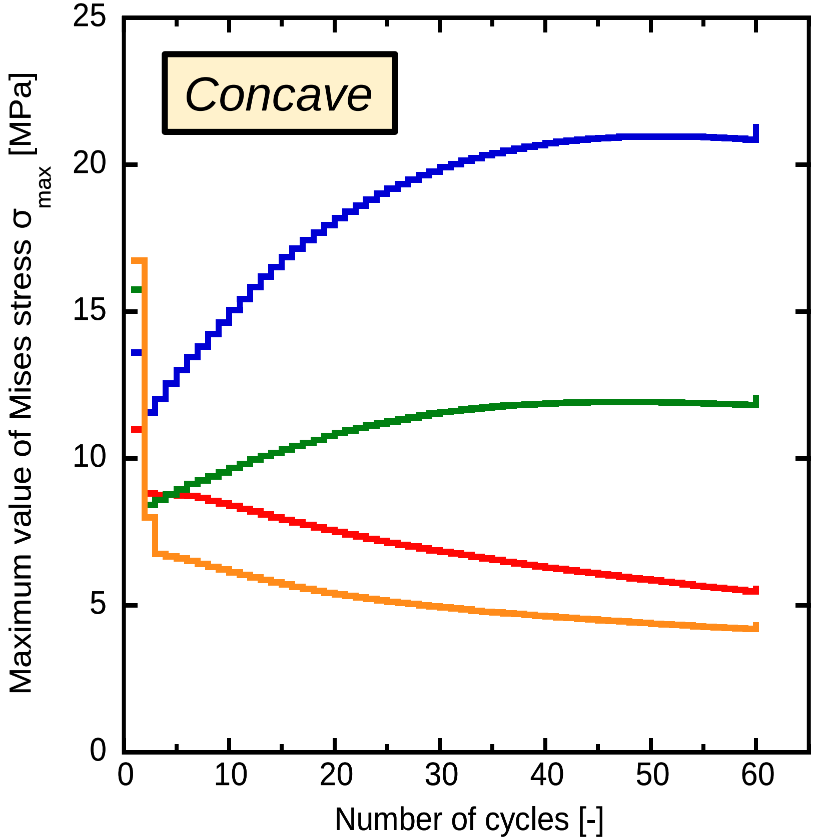
Other damage – Thermally grown oxide -











Cracks were initiated at concave in top coat, which corresponds to FE analysis.

The crack was generated by stress component after cooling process in thermal cycling test.

The validity of FE code installed TGO model was shown.

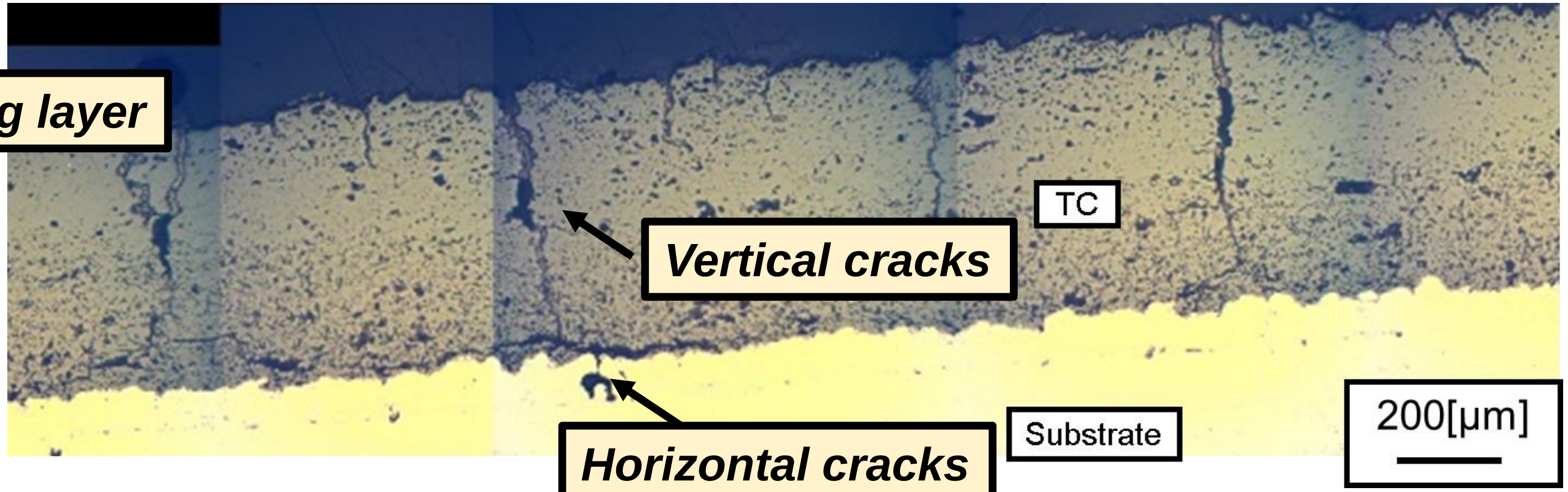
Other damage – Sintering process-

Sintering strain:

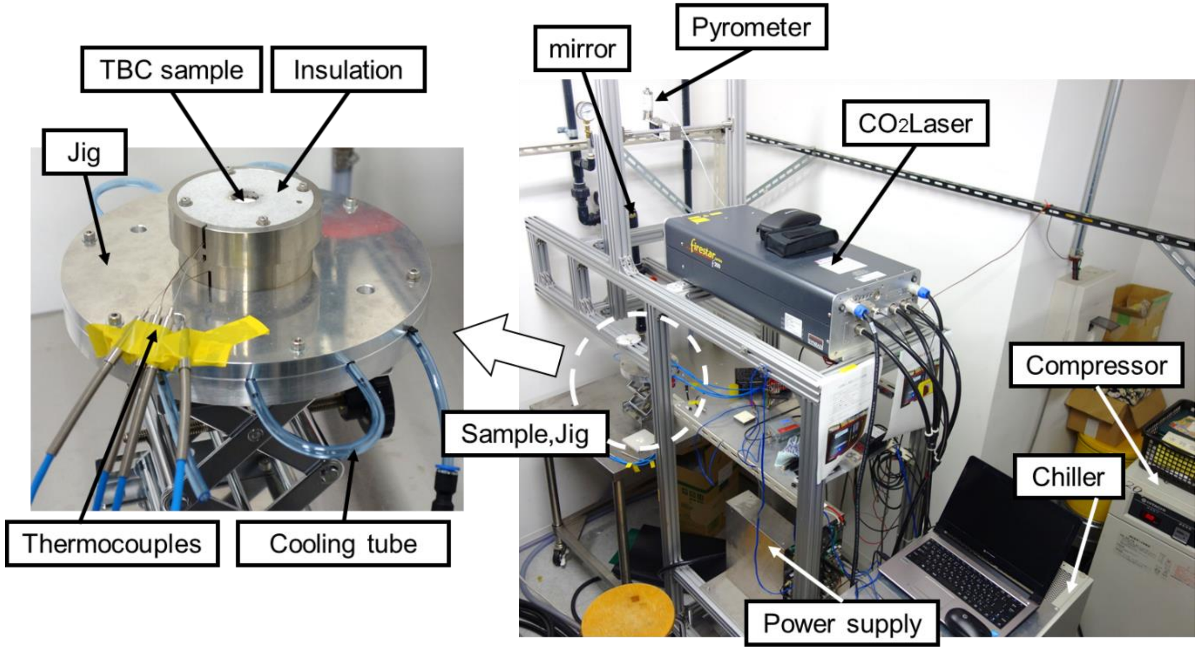
$$\Delta\varepsilon_{ij}^{s} = \Delta\varepsilon_s\delta_{ij}$$

where

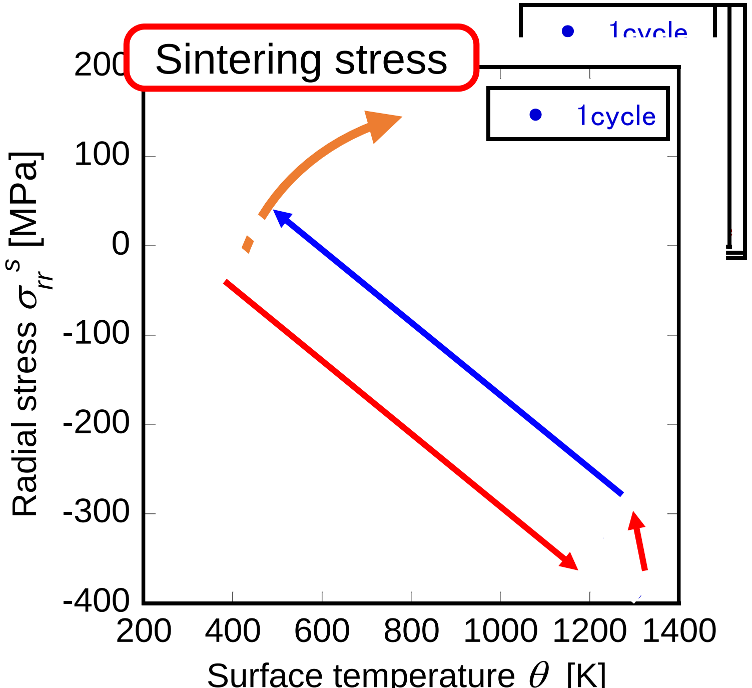
$$\Delta\varepsilon_s = -k' exp\left(-\frac{Q}{RT}\right) n t^{n-1} \Delta t$$



1273K-500K temperature gradient @ 120,000cycles



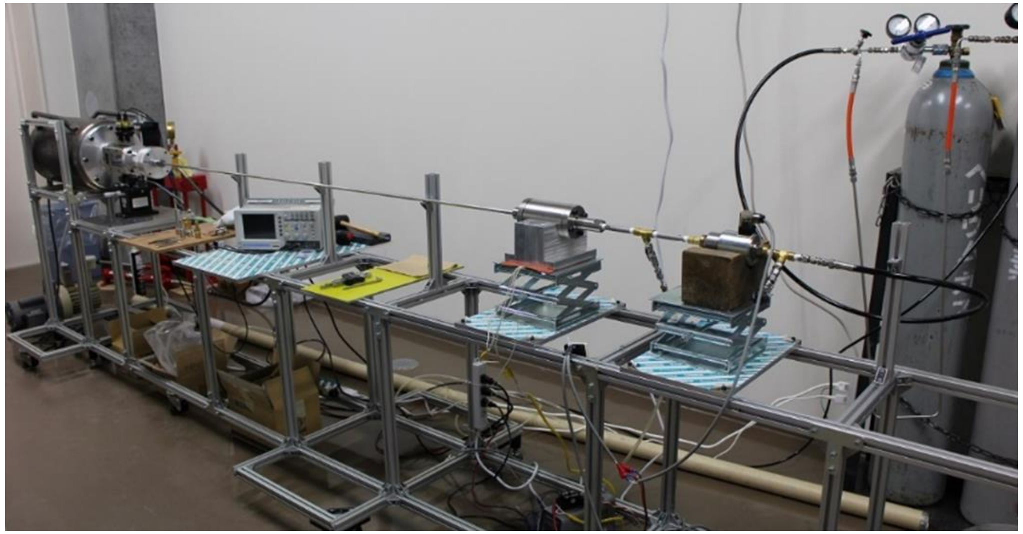
High-temperature gradient test by laser irradiation

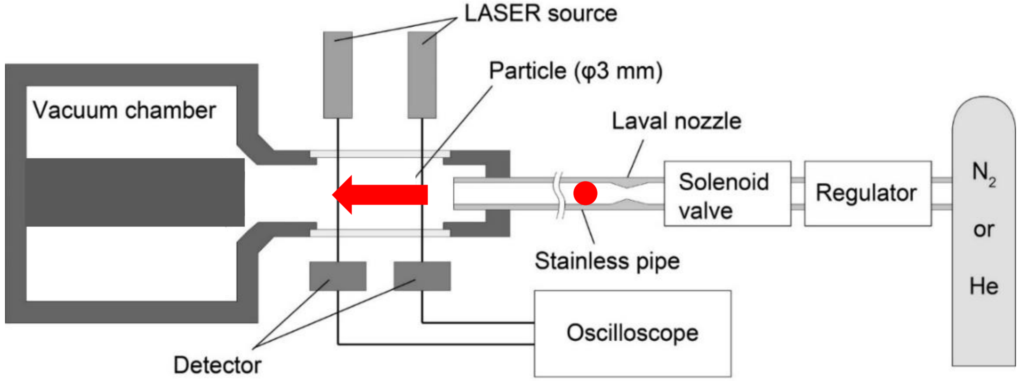


Sintering effect was taken into account in FE code. It was identified that the coating stress is increased due to sintering strain accumulation .

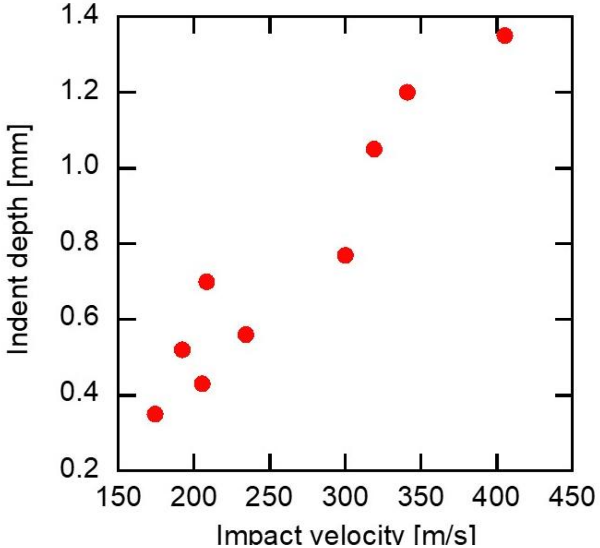
Damage evaluation for external event in gas turbine

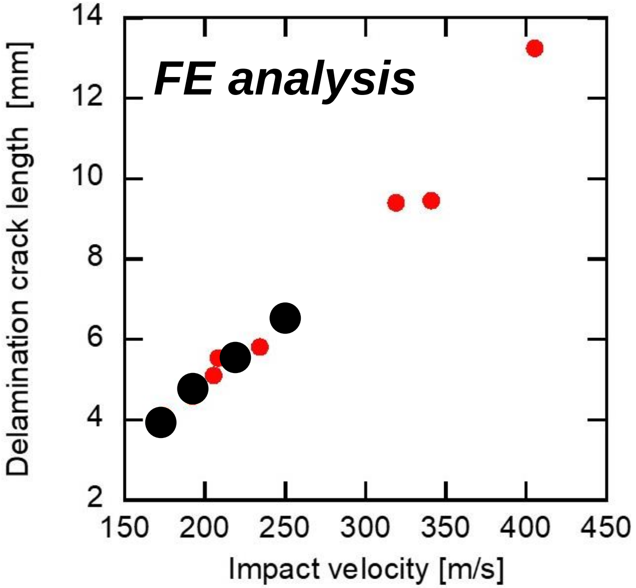
Impact event –FOD-

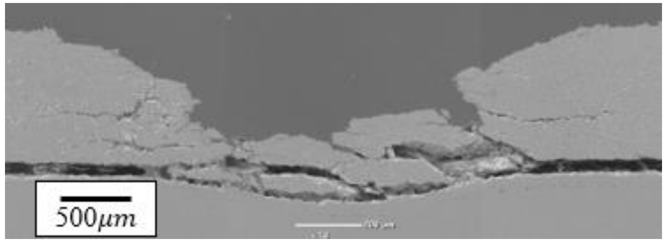




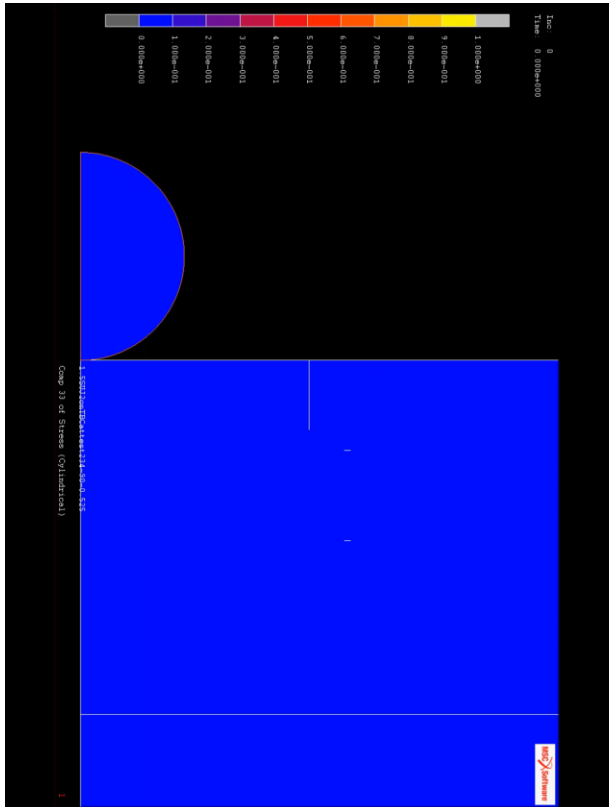
Single Particle Impact Testing System (SPITS)





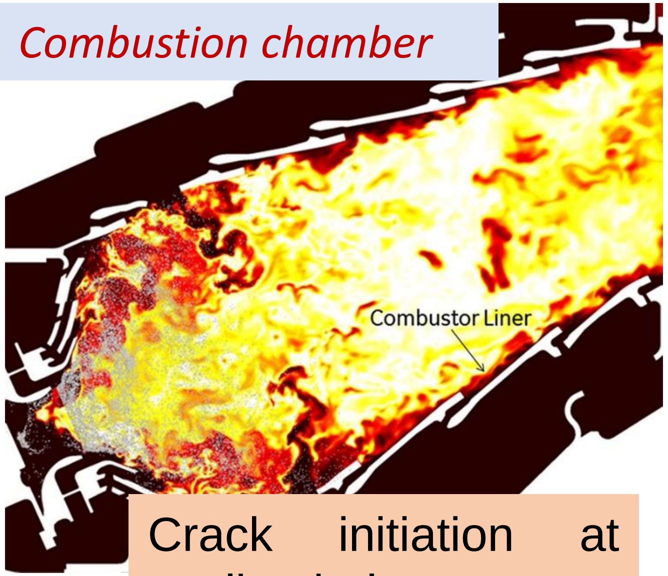


TBC surface damage by FOD

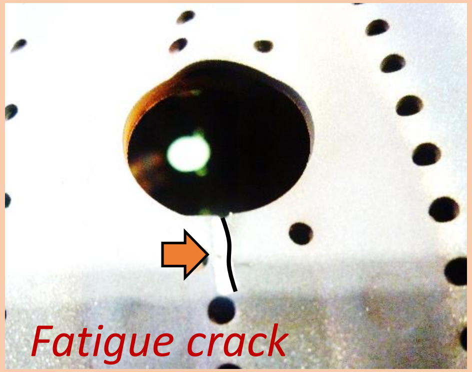


Maintenance system based upon controlling crack propagation

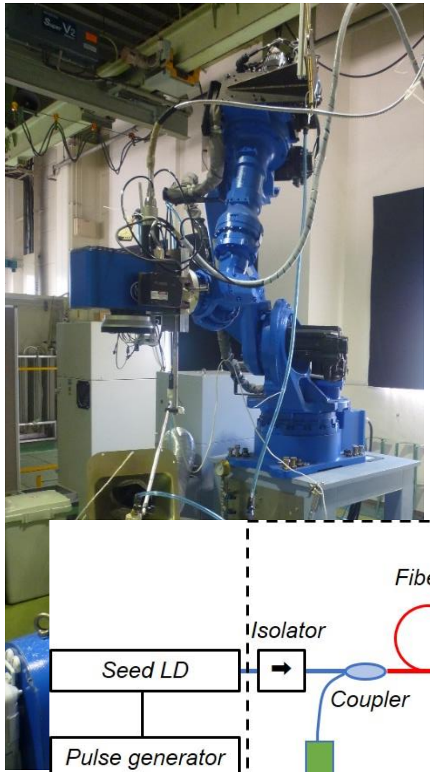
Combustion chamber

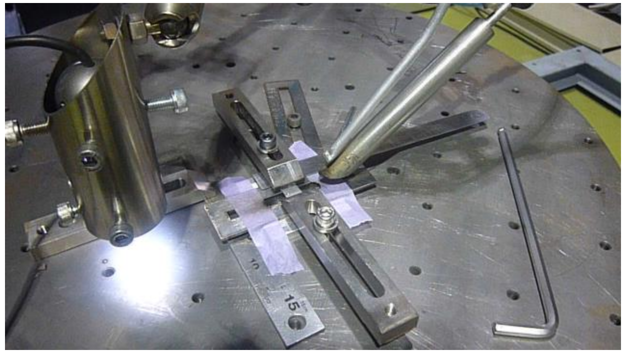


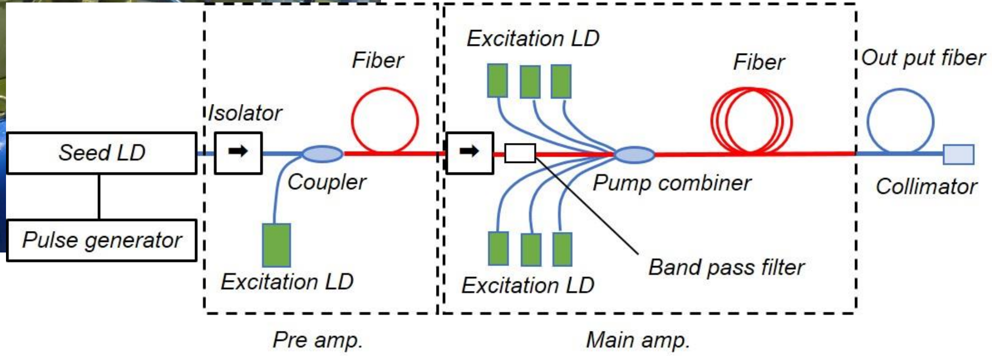
Crack initiation at cooling hole



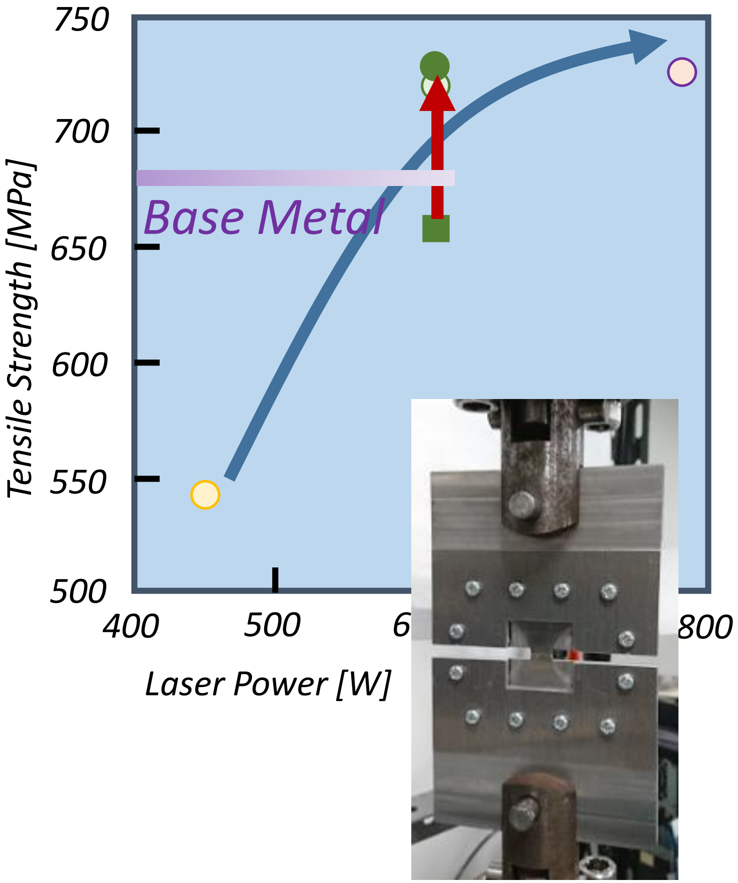
Repairing technique by fiber laser process







Fiber laser system



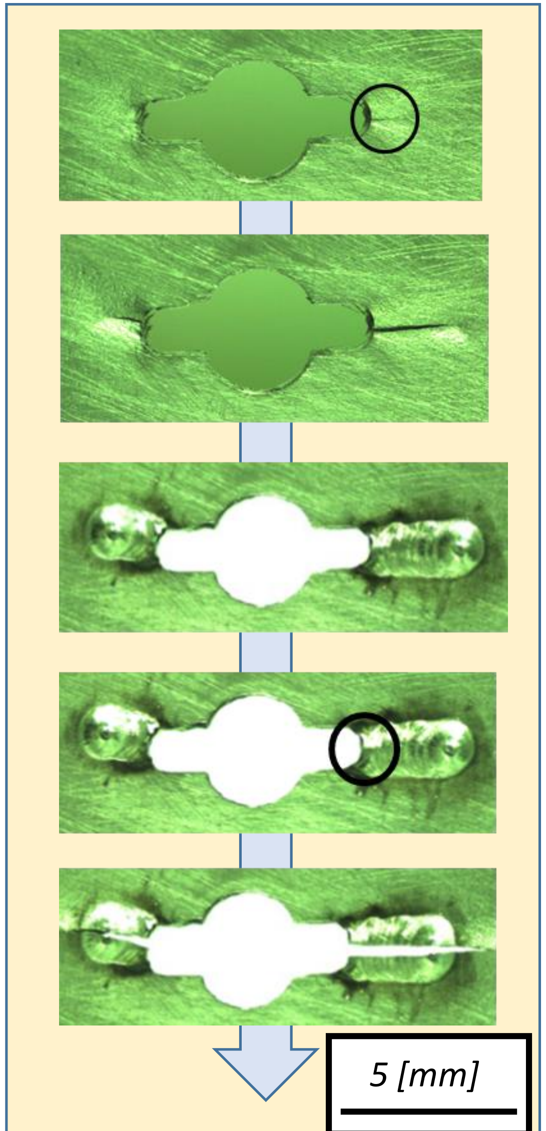
Tensile test

Tensile test results

This project is supported by Chugoku electric company and Japan ultra-high temperature material research center.

Maintenance system based upon controlling crack propagation

Crack repairing process



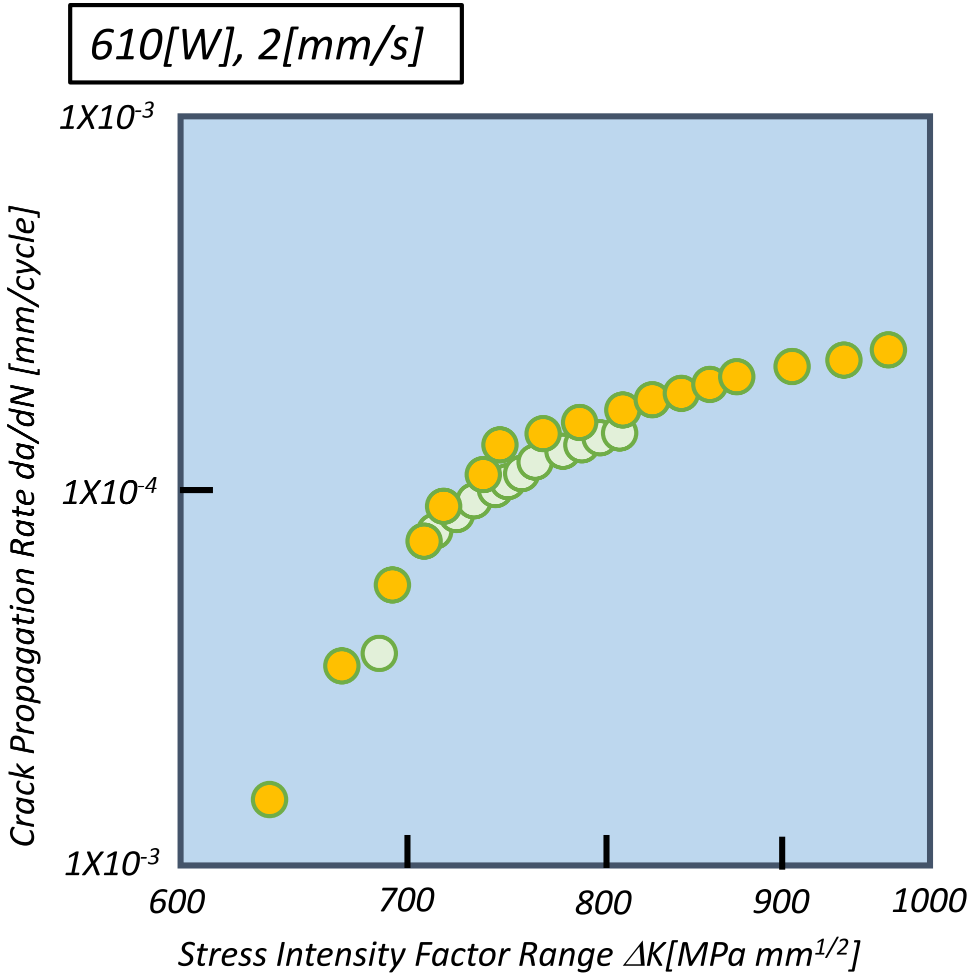
Fatigue crack initiation

Fatigue crack propagation

Fiber laser repairing

Fatigue crack initiation

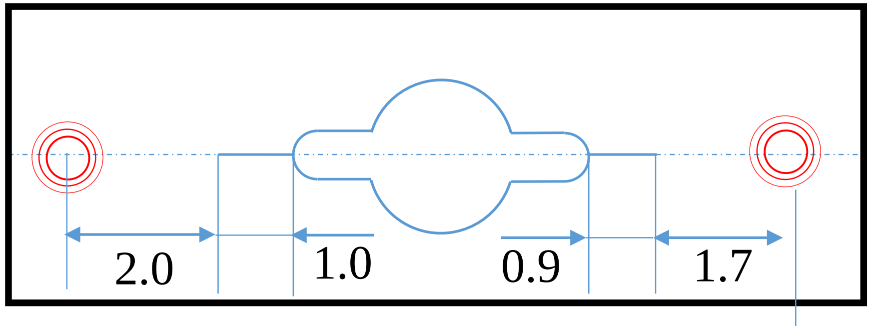
Fatigue crack propagation

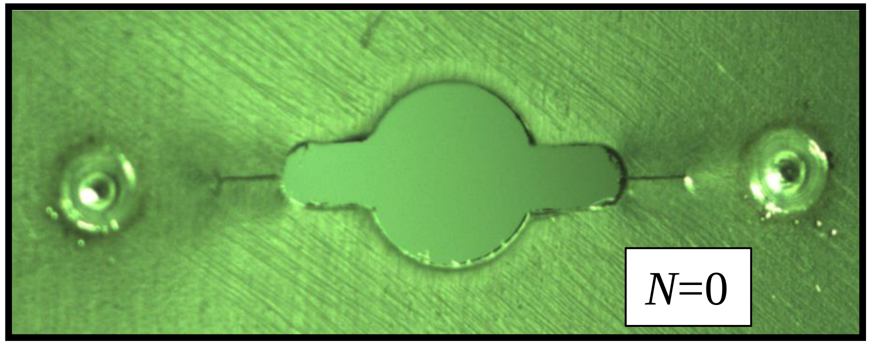


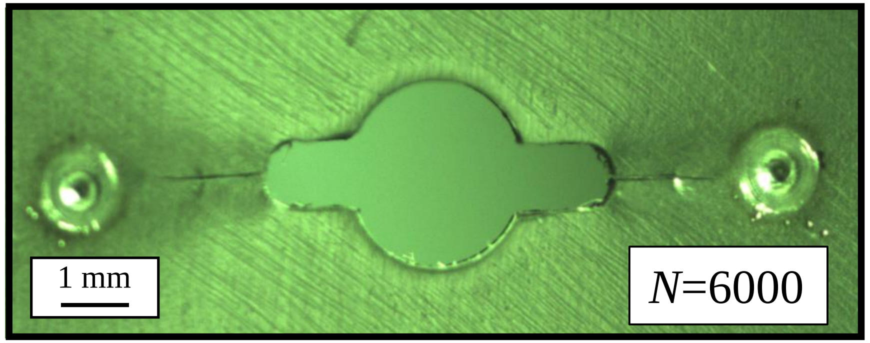
Process condition:610[W] , 2[mm/s]
The cracked specimen was recovered by fiber laser repairing treatment.

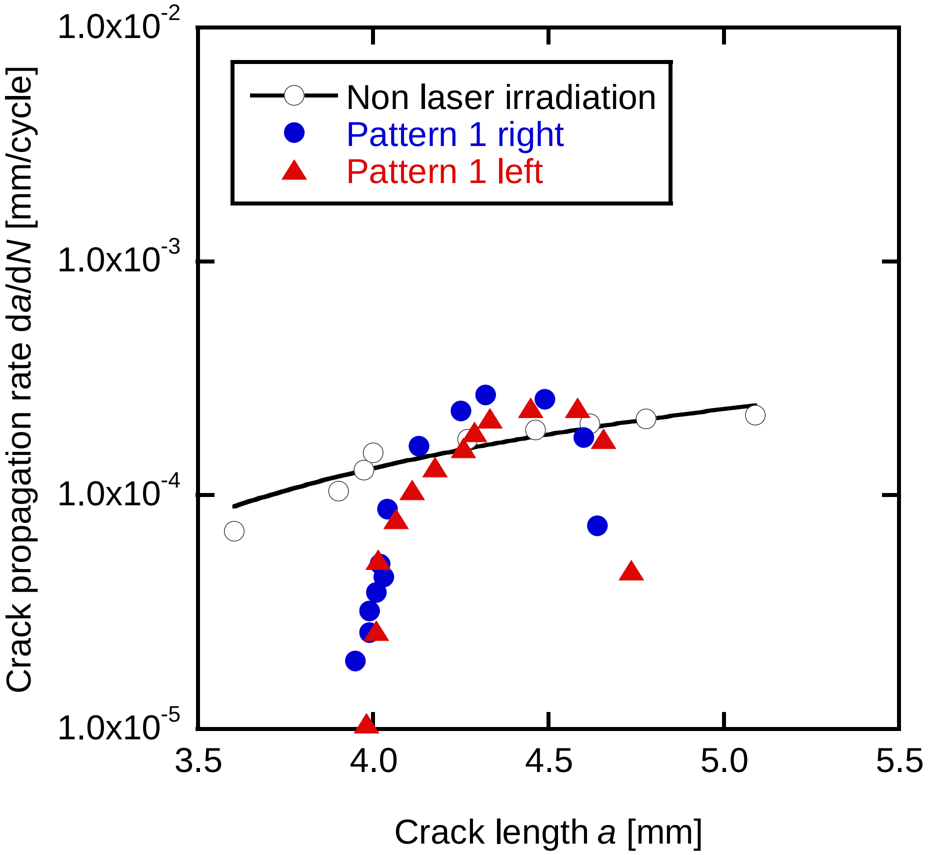
Maintenance system based upon controlling crack propagation

Repairing technique by laser irradiation ahead of crack tip







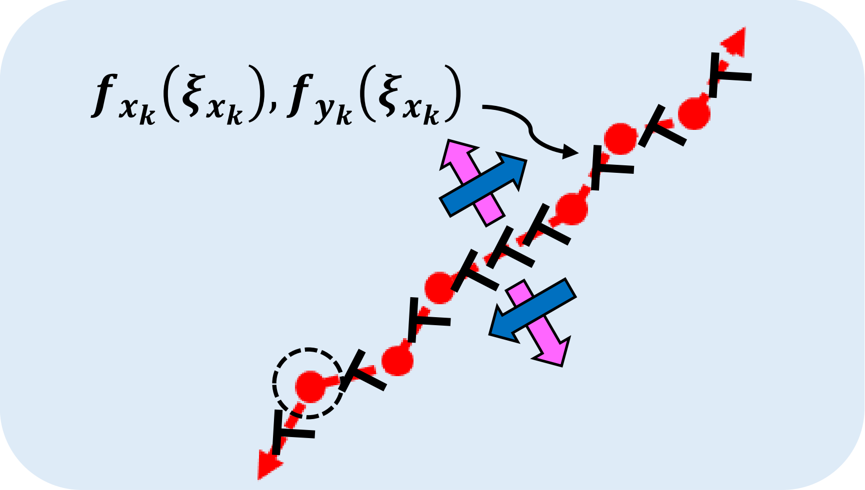


Relationship between right crack length *a* and Crack propagation rate d*a*/d*N*

It was confirmed that crack propagation rate in crack repaired by laser irradiation was delayed in comparison with that in non laser irradiation. Thus, this technique is available for repairing small-size crack in brief process period.

Maintenance system based upon controlling crack propagation

Continuous Distribution Dislocation Method



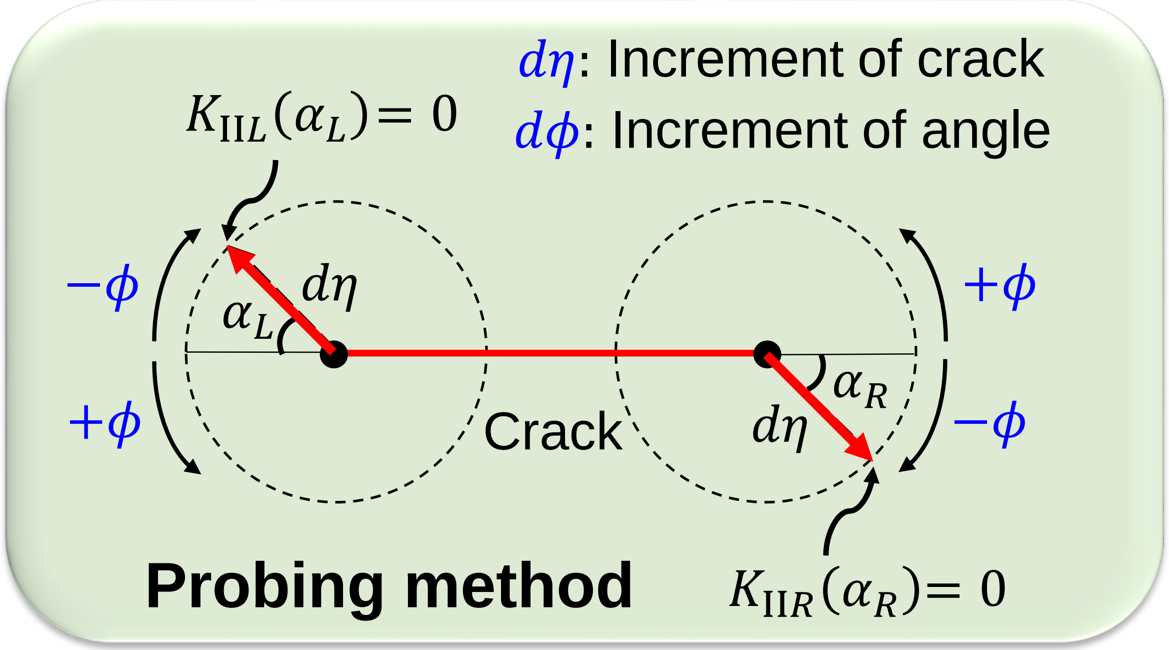
Traction due to the dislocation distribution

$$\begin{Bmatrix} \bar{\sigma}_{y_k y_k}(x_k) \\ \bar{\sigma}_{x_k y_k}(x_k) \end{Bmatrix} = \sum_{m=1}^{s} [T(\psi_m - \psi_k)] \begin{Bmatrix} \bar{\sigma}_{x_m x_m}(x_k) \\ \bar{\sigma}_{y_m y_m}(x_k) \\ \bar{\sigma}_{y_m y_m}(x_k) \end{Bmatrix}$$

$$(k = 1, 2, \ldots, s)$$

$$[T(\psi)] = \begin{bmatrix} \sin^2\psi & \cos^2\psi & \sin 2\psi \\ \frac{1}{2}\sin 2\psi & -\frac{1}{2}\sin 2\psi & \cos 2\psi \end{bmatrix}$$

Crack propagation simulation



✓ Crack propagation direction

$$\begin{cases} K_{\mathrm{II}L}(\psi_L - \phi) = K_{\mathrm{II}L\min} \\ K_{\mathrm{II}R}(\psi_R - \phi) = K_{\mathrm{II}R\min} \end{cases}$$

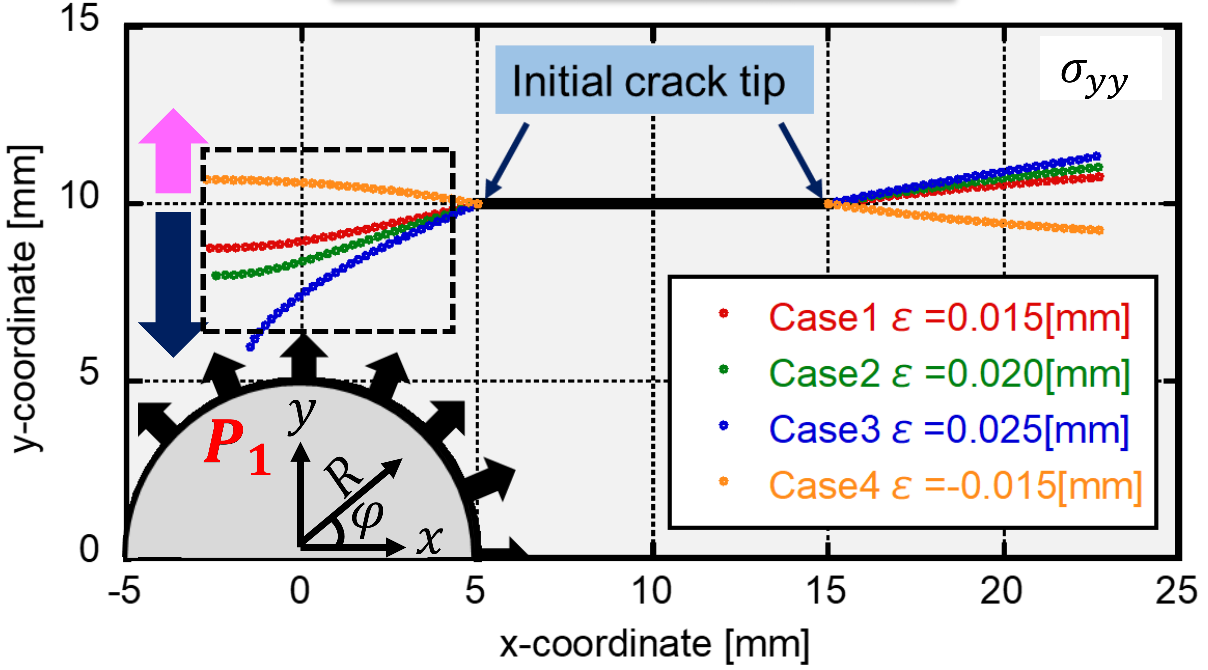
✓ Discriminant

$$\begin{cases} |K_{\mathrm{II}L}(\alpha_L)| + |K_{\mathrm{II}R}(\alpha_R)| < |K_{\mathrm{II}L\min}| + |K_{\mathrm{II}R\min}| \\ -K < |K_{\mathrm{II}L}(\alpha_L)| - |K_{\mathrm{II}R}(\alpha_R)| < K \end{cases}$$

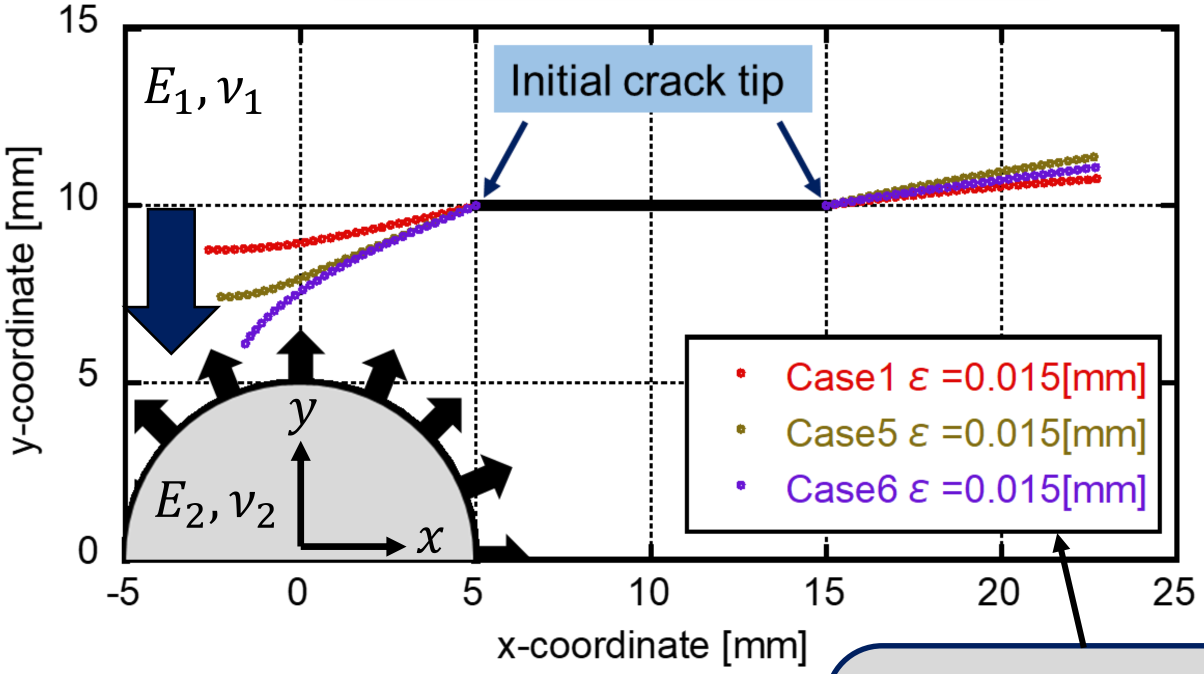
Maintenance system based upon controlling crack propagation

Continuous Distribution Dislocation Method

Influence of ε



Influence of Young's modulus



Case1 $E_1 = E_2$

Case2 $E_1 < E_2$

Case3 $E_1 > E_2$

It was confirmed that ε and Young's modulus of inclusion have an influence on the crack deflection.