Two-Dimensional Stress Corrosion Cracking Model for Reactor Structural Materials

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Background and Objective

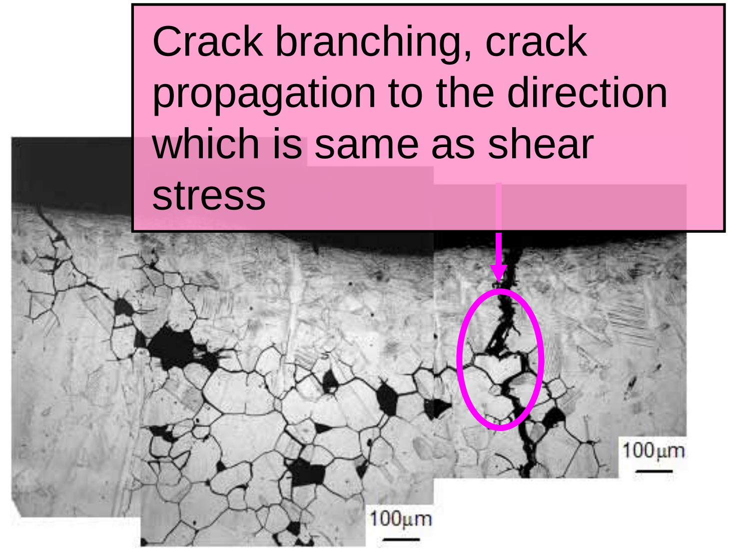
[Background]

Stress corrosion cracking (SCC) is one of the main causes of the trouble in the nuclear power plant.

<SCC model yet proposed>

- •rate equation theory
- •SCC crack growth model (only vertical stress)

New SCC crack growth model is expected (includes crack branching, corrosion, ...)



SCC crack at core shroud of boiled water reactor

[Objective]

- •Development of new Intergranular stress corrosion cracking (IGSCC) growth model
- •Determination of the cause of each IGSCC behavior

Several micron-order effects are modeled and crack growth path is obtained

- Strength of grain boundary à small fluctuation in strength
- Influence of shear stress à "net stress" constructed with vertical and shear stress
- degradation of grain boundary à corrosion of grain boundary

2-Dimensional SCC Crack Growth Model

1) Setting on the strength of grain boundary

Strength of grain boundary is different by kinds of grain boundary ,dislocation, ...

↔ Face centered cubic (FCC) structure has many slip planes

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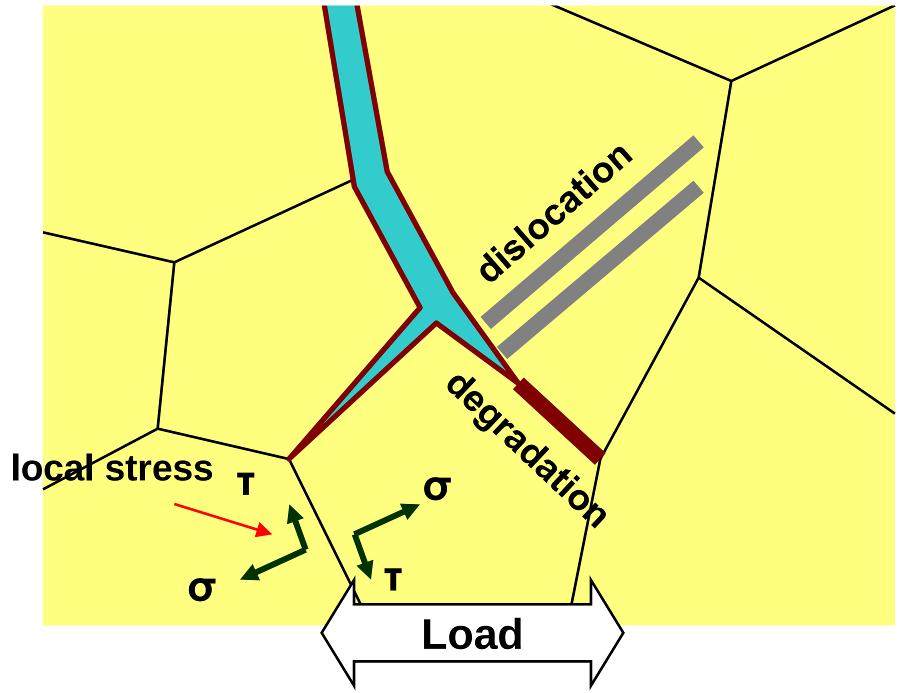
variations of strength of grain boundary would become small due to slip dislocation.



The strength of grain boundary with small fluctuation s_{th} is defined

$$s_{th} = s_0 + \mathrm{fl}$$

s_0 : base strength of grain boundary
fl : fluctuation using normal distribution function

2-Dimensional SCC Crack Growth Model

2) Influence of shear stress

... Complex stress constructed by vertical and shear stress is "*locally*" acted on the grain boundary around crack tip

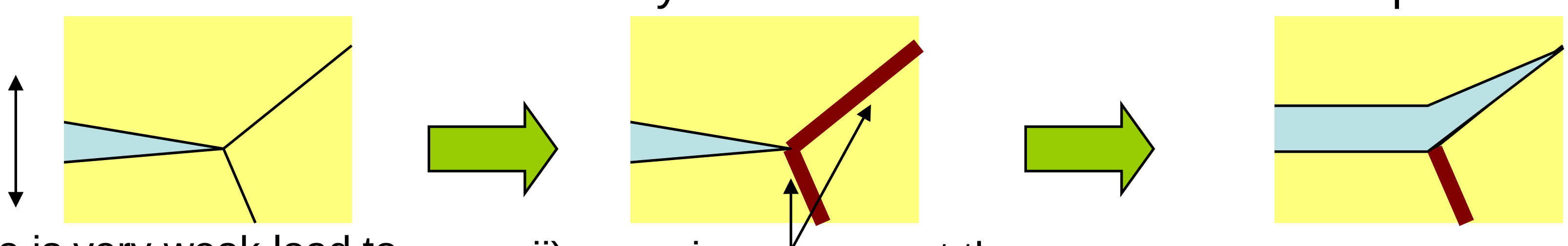
"Net stress" h is defined

$$h \equiv s + at$$

s : vertical stress against grain boundary
t : shear stress against grain boundary
a : parameter to control the effect of shear stress

3) Degradation of grain boundary

Assumption :
When the stress that acts on the grain boundary is very weak, the influence of corrosion is dominant relatively to that of stress factor on fracture process.



i) there is very weak load to the system.

ii) corrosion occures at the grain boundary, and strength weakens.

iii) crack propagates

Corrosion is modeled by introducing the "slow fracture" of grain boundary.

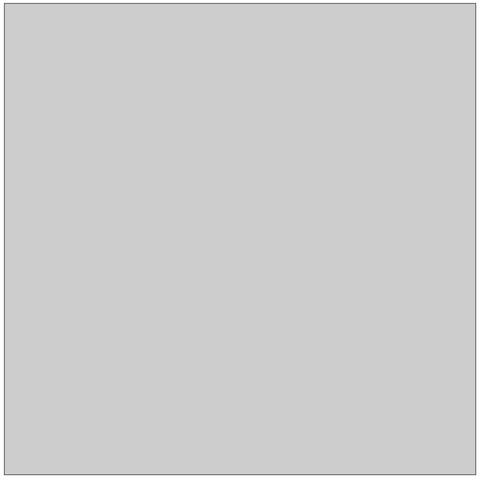
Analytical Equation of Stress at Grain Boundary

- **Vertical and shear stress around crack tip**

[Mode I]

$$\sigma_{\mathrm{I}}(r,\theta)=\frac{K_{\mathrm{I}}}{4\sqrt{2\pi}}r^{-1/2}\left(3\cos\frac{\theta}{2}+\cos\frac{3\theta}{2}\right)$$

$$\tau_{\mathrm{I}}(r,\theta)=\frac{K_{\mathrm{I}}}{4\sqrt{2\pi}}r^{-1/2}\left(\sin\frac{\theta}{2}+\sin\frac{3\theta}{2}\right)$$



Analytical Equation of Stress at Grain Boundary

K_I and K_{II} are obtained *"roughly"* using the analytical equations of stress intensity factor for the microcrack in infinite parallel-plate

$$K_{\mathrm{I}} = \sigma_0 \sin^2 \phi \cdot \sqrt{\pi a}$$

$$K_{\mathrm{II}} = \sigma_0 \sin \phi \cos \phi \cdot \sqrt{\pi a}$$

- σ_0 : tensile stress
- a : half length of microcrack
- ϕ : angle from the direction of microcrack to that of tensile stress

In the model, stress dispersion by crack branching is considered.

$$k = \frac{K}{\sqrt{n}}$$

- K : stress intensity factor for no branching crack
- k : stress intensity factor for branching crack
- n : number of crack branching

The stress around the crack tip in the model is defined as

$$\sigma(r,\phi) = \sigma_{\mathrm{I}}(r,\phi) + \sigma_{\mathrm{II}}(r,\phi)$$
$$\tau(r,\phi) = \tau_{\mathrm{I}}(r,\phi) + \tau_{\mathrm{II}}(r,\phi)$$

Flow of the Simulation

(1) setting the system with grains, strength of grain boundary s_{th}, and initial crack

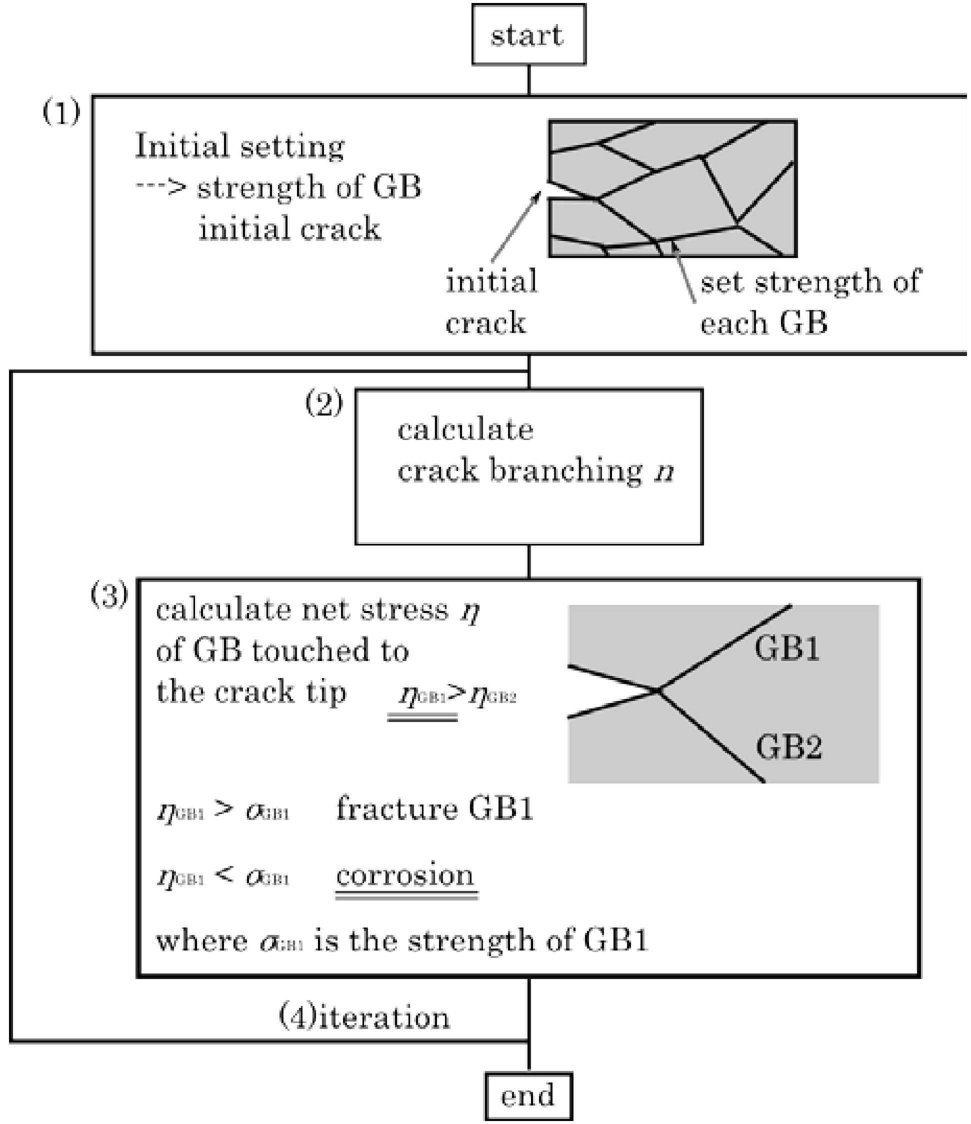
(2) calculating number of crack branching n

(3) calculating net stress h at the grain boundaries touched to the crack tips, and selecting largest h.

If $h > s_{th}$,
effect of stress is dominant
à **quick fracture**

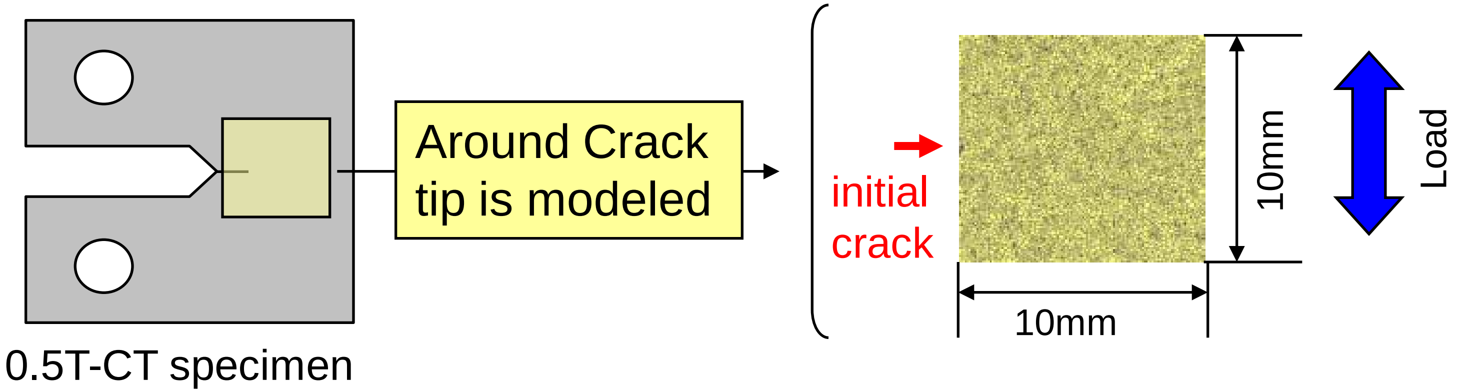
If $h < s_{th}$,
effect of corrosion is dominant
à **slow fracture**

(4) If not final step, return to (2)



Type304 Stainless Steel IGSCC Growth Analyses

[Example] IGSCC analyses of type304 stainless steel at 400℃



About 10000 grains (~0.1mm) are set using 2D Voronoi space division.

- **strength of grain boundary**

  base strength is set to half of yield stress

  à 60MPa + 10% fluctuation

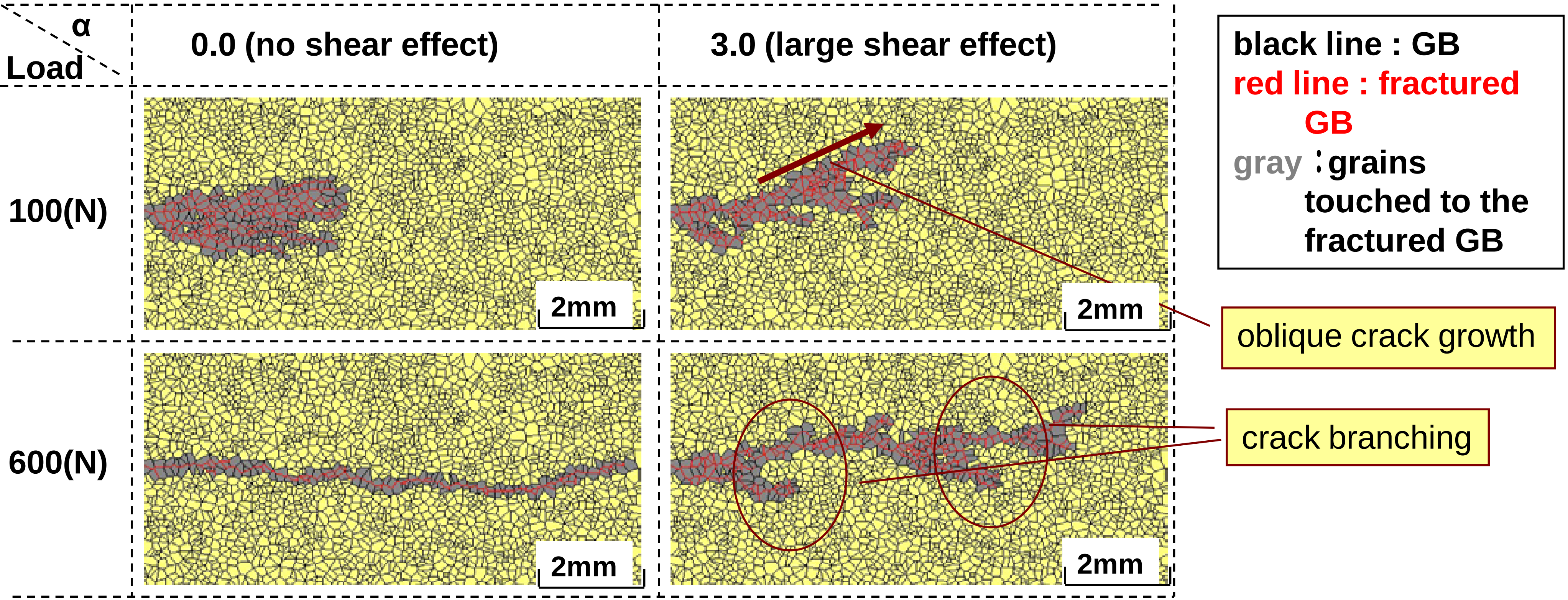
  Assumption: grain boundary is fractured when the half of yield stress of the applied material locally acts on the grain boundary

- **Load condition**
  - 100 (N) : influence of corrosion is dominant
  - 600 (N) : influence of stress is dominant

- **parameter to controll the effect of shear stress**
  - 0.0 : no shear effect
  - 3.0 : large shear effect

- **corrosion** Grain boundary fractures after 3 simulation step (fixed)

Type304 Stainless Steel IGSCC Growth Analyses: results



- **600(N),a=3.0 :** **crack branching**

  à The main factor of crack branching is the effect of shear stress

- **100(N),a=3.0 :** **oblique crack growth**

  à Synergistic effect of shear stress and corrosion of grain boundary leads to crack growth to oblique direction.

Summary

- **Development of New IGSCC Crack Growth Model**

  3 kinds of characteristic effects were introduced into the model

  ↓

  Strength of grain boundary, Influence of shear stress,
  and degradation of grain boundary

- **Type304 Stainless Steel IGSCC Crack Growth Analyses**

  Using developed model, type304 stainless steel at 400℃ has been analyzed.
  à Determine cause of IGSCC behavior

  (1) The main factor of crack branching is the shear stress effect.
  (2) The crack growth to oblique direction occures by the synergistic effect of shear stress and corrosion of grain boundary.

- **Future Plans**

  1. IGSCC simulation in BWR condition
  2. Refinement of the effect of corrosion behavior in the model
  3. Extension the model to 3-Dimensional model
  4. Combination the model with Finite Element Method