Fracture of Divertor Structures

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ARIES Meeting

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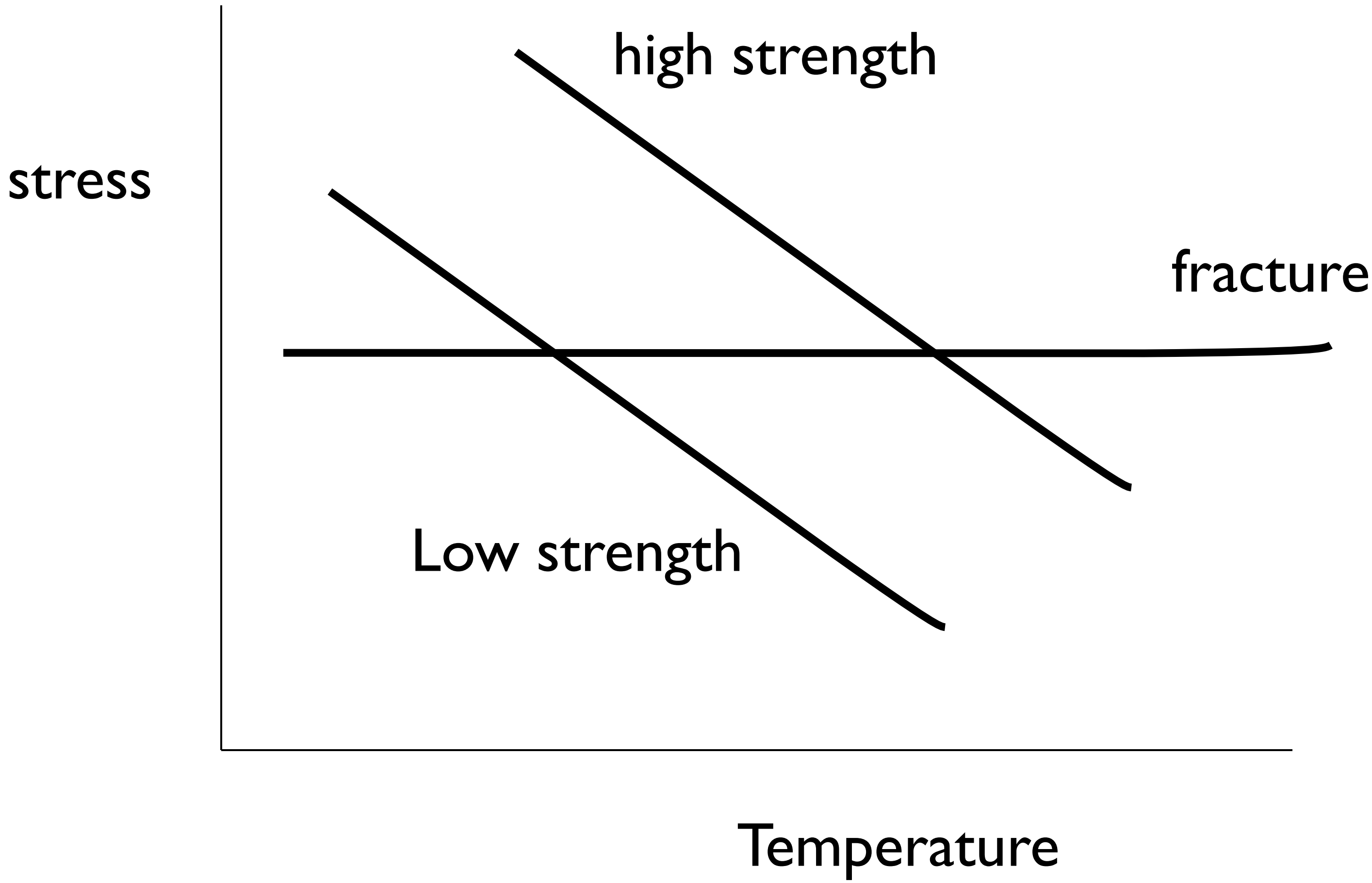
Outline

- Primer on Fracture Mechanics
- Preliminary Results for Divertor Structures
- Future Plans

Design of Engineering Structures

- In early 20th century, design of metal structures was strictly stress based
- Onset of high performance ships (Liberty ships, WWII) changed things

What happened?

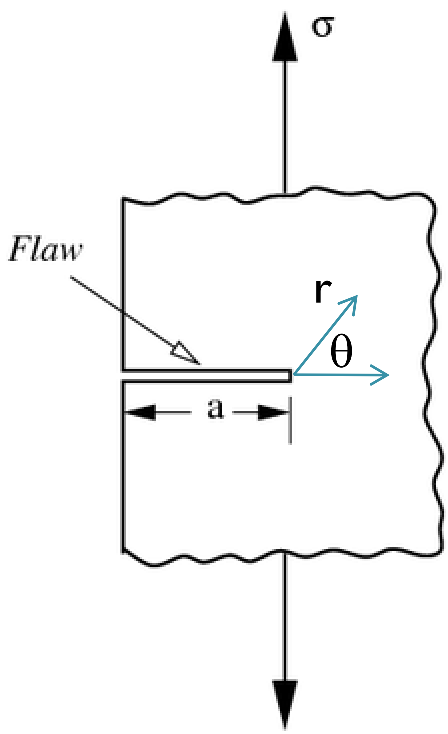


Fracture Mechanics

- Size and Orientation of Cracks
- Stress Fields
- Material Properties

Crack Tip Stress Fields (Elastic)

- Consider a sharp crack in an elastic material



$$\sigma_{ij} \approx \left(\frac{K}{\sqrt{2\pi r}}\right) f_{ij}(\theta)$$

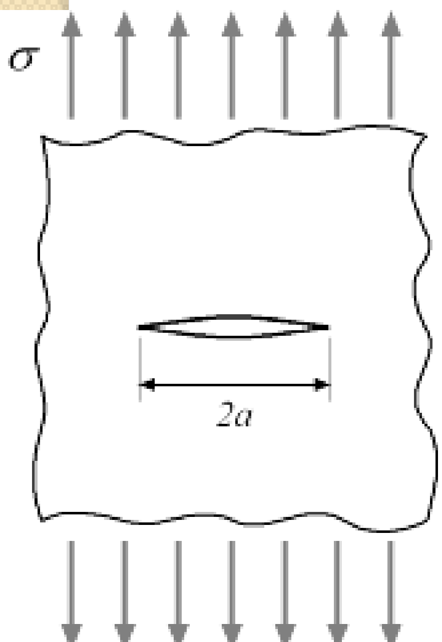
- K is stress intensity factor
- Function of geometry and loading
- Fracture occurs when K reaches critical value (K_{IC} – fracture toughness)

An Example

- Consider an infinite plate with a through crack

$$K_I = \sigma\sqrt{\pi a} = K_{IC}$$

$$\sigma_{allow} = \frac{K_{IC}}{\sqrt{\pi a}}$$



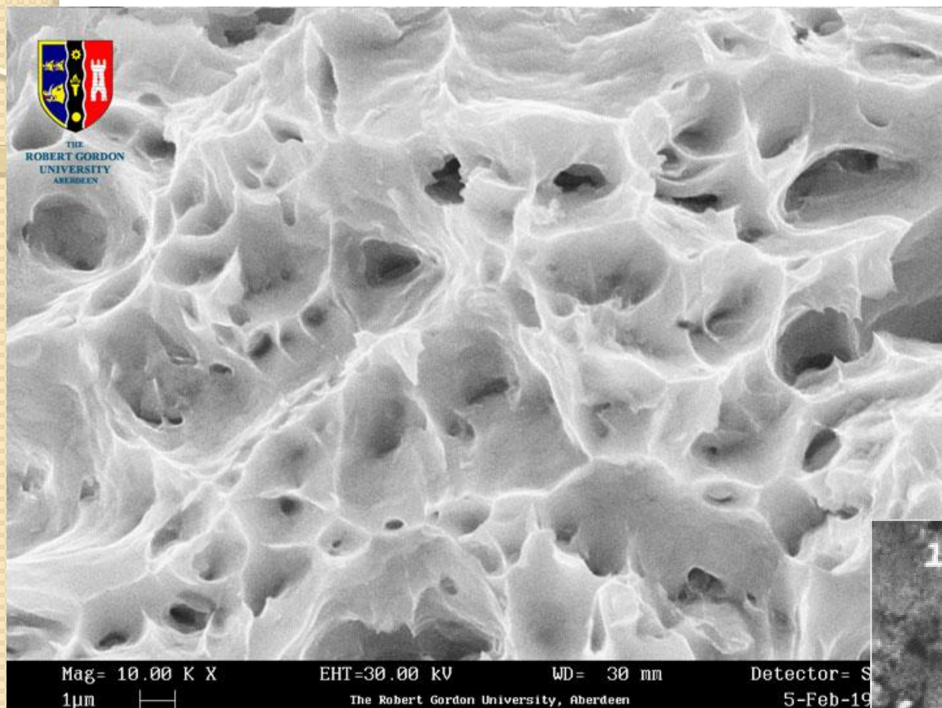
- Glass: K_{IC}=1 MPa-$m^{0.5}$
- Al: K_{IC}=20 MPa-$m^{0.5}$
- For a=100 microns, fracture stresses are 56 MPa for glass and 1,100 MPa for Al

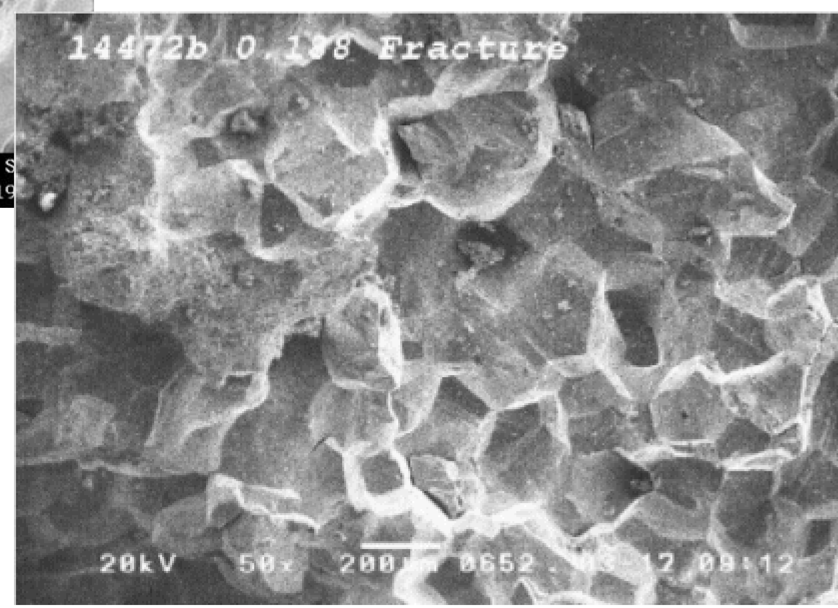
Fracture Toughness (room temp)

Material	Toughness (MPa – m^0.5)
7075 Aluminum	24
4340 Steel	50
Silicon Carbide	4
Polystyrene	1
Tungsten (polycrystalline)	5
Beryllium	10

These values depend strongly on processing.

Ductile vs. Brittle





Temperature Dependence

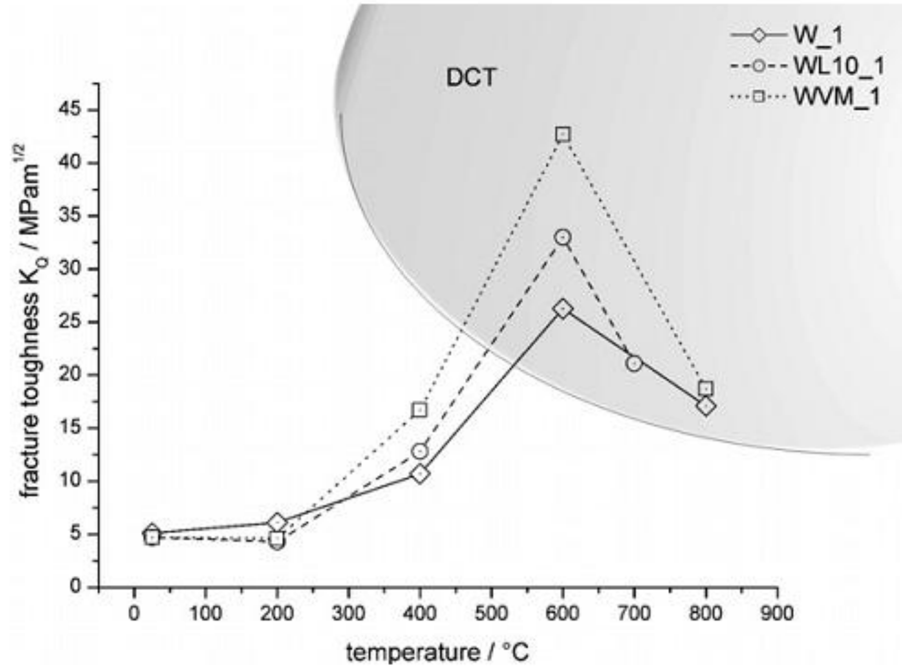


Fig. 1. Fracture toughness of tungsten alloys in the as sintere condition (DCT). The grey area marks the region where linea fracture mechanics is no longer valid.

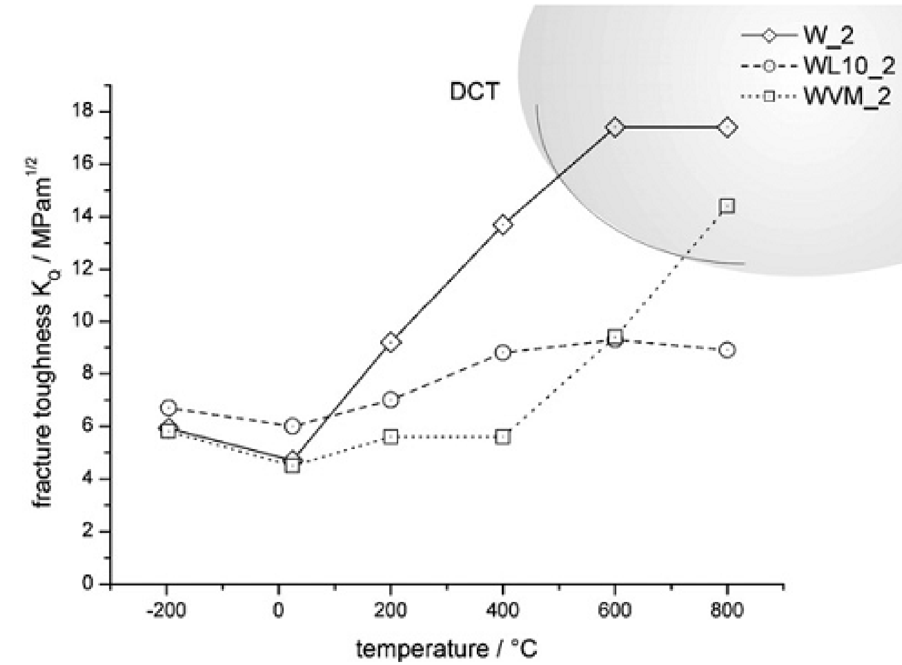
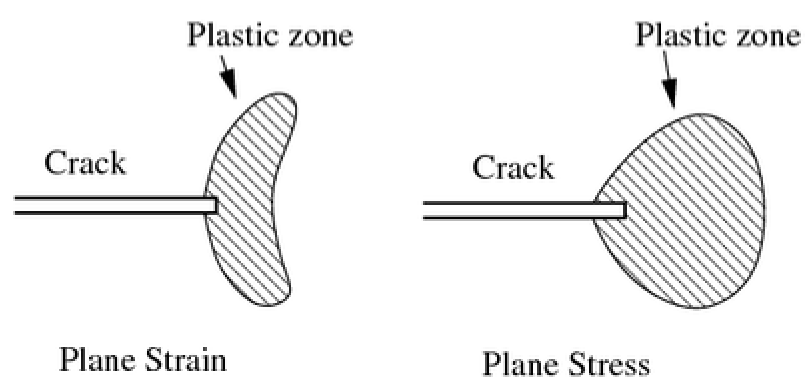


Fig. 2. Fracture toughness of tungsten alloys in the as-rolled condition (60% reduction, DCT). The grey area marks the region where linear fracture mechanics is no longer valid.

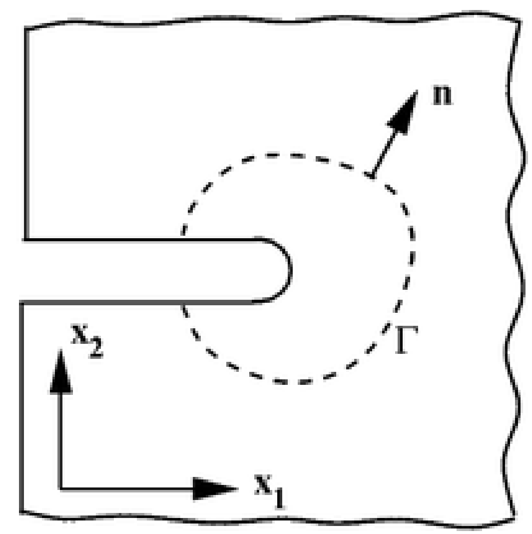
Stress Fields in Ductile Materials

- Ductile materials will develop plastic deformation at crack tips
- This toughens material and resists catastrophic crack growth
- Previous analysis is not valid
- Analysis uses integral around crack tip, rather than stress intensity factor



Failure Criterion for Ductile Materials

- Base failure prediction on work required to create fresh fracture surface
- Write as line integral

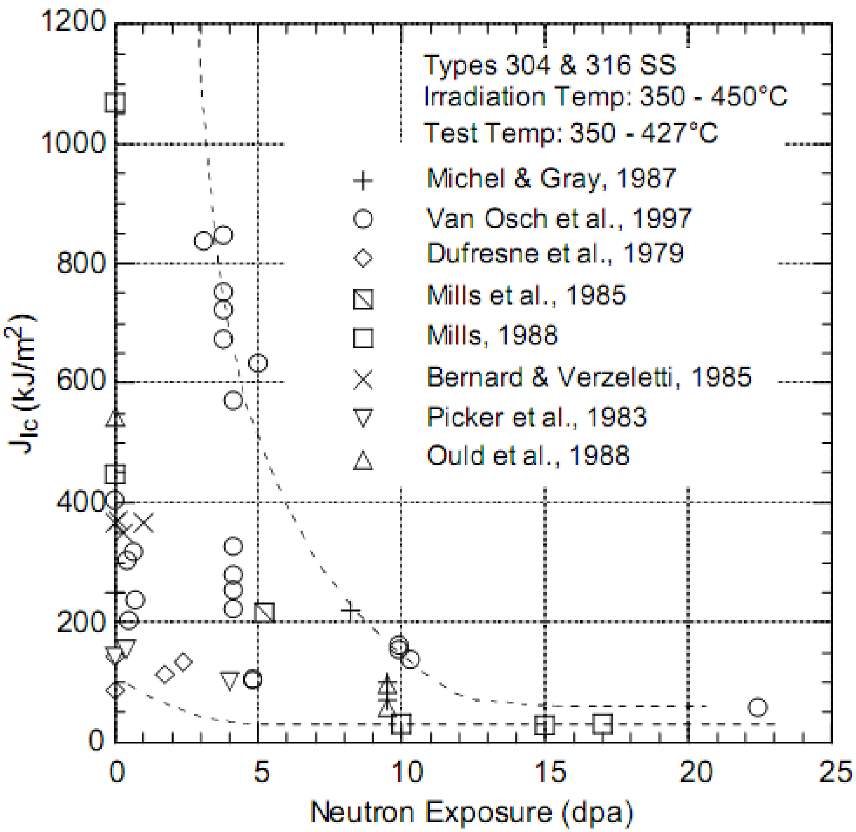


$$J_I = \int_{\Gamma} \left(W dx_2 - t \cdot \frac{\partial u}{\partial x_1} ds \right)$$

$$J_{IC} = K_{IC}^2 \left(\frac{1-\nu^2}{3E} \right)$$

W=strain energy density
T=tractions
U=displacement

Irradiated Materials



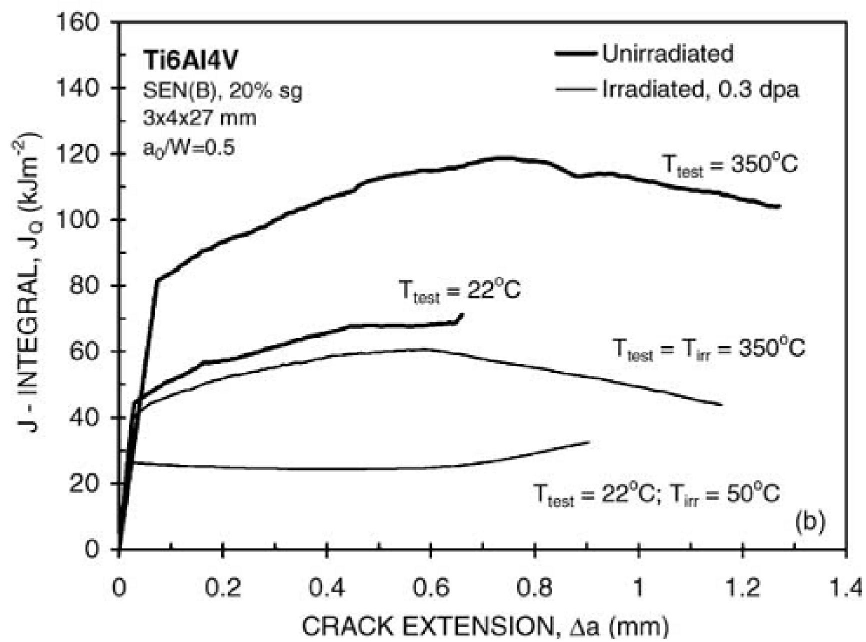
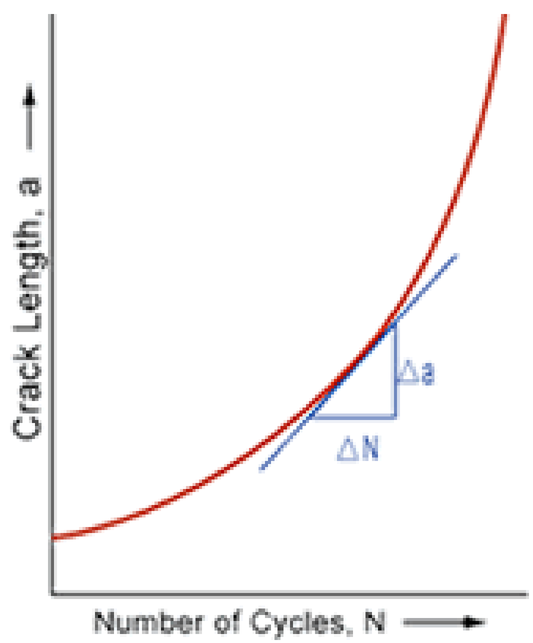
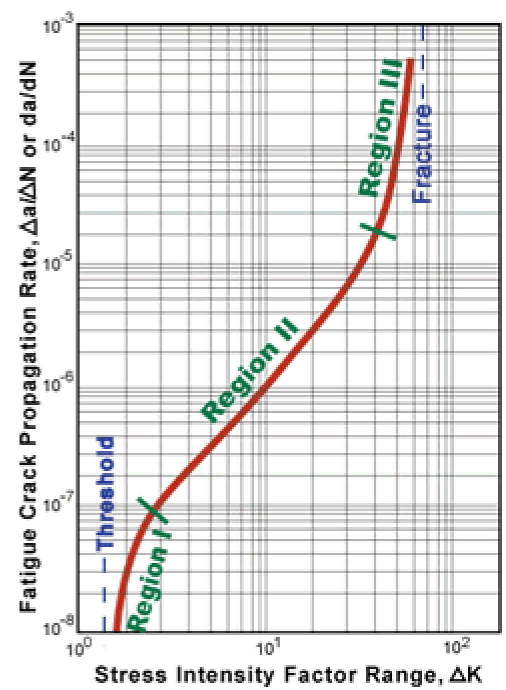


Fig. 3. Fracture resistance curves of (a) Ti5Al2.5Sn (α) alloy and (b) Ti6Al4V (α + β) alloy at different test temperatures in unirradiated and neutron irradiated (0.3 dpa) conditions.

Fatigue Crack Growth

- Previous analyses refer to catastrophic, unstable crack growth
- Repeated application of loads can lead to incremental crack growth





Characterizing Cracks

- Key Question: What is initial crack size?
- We need non-destructive examination (NDE)
- Options:
  - Dye penetrant
  - Ultrasound
  - X-rays
  - Eddy currents
  - Thermography
  - Etc.
- Costs and capabilities vary

ITER Structural Design Criteria

- Primary Loads

$$K_I < 0.33 K_C$$

- Primary + Secondary Loads

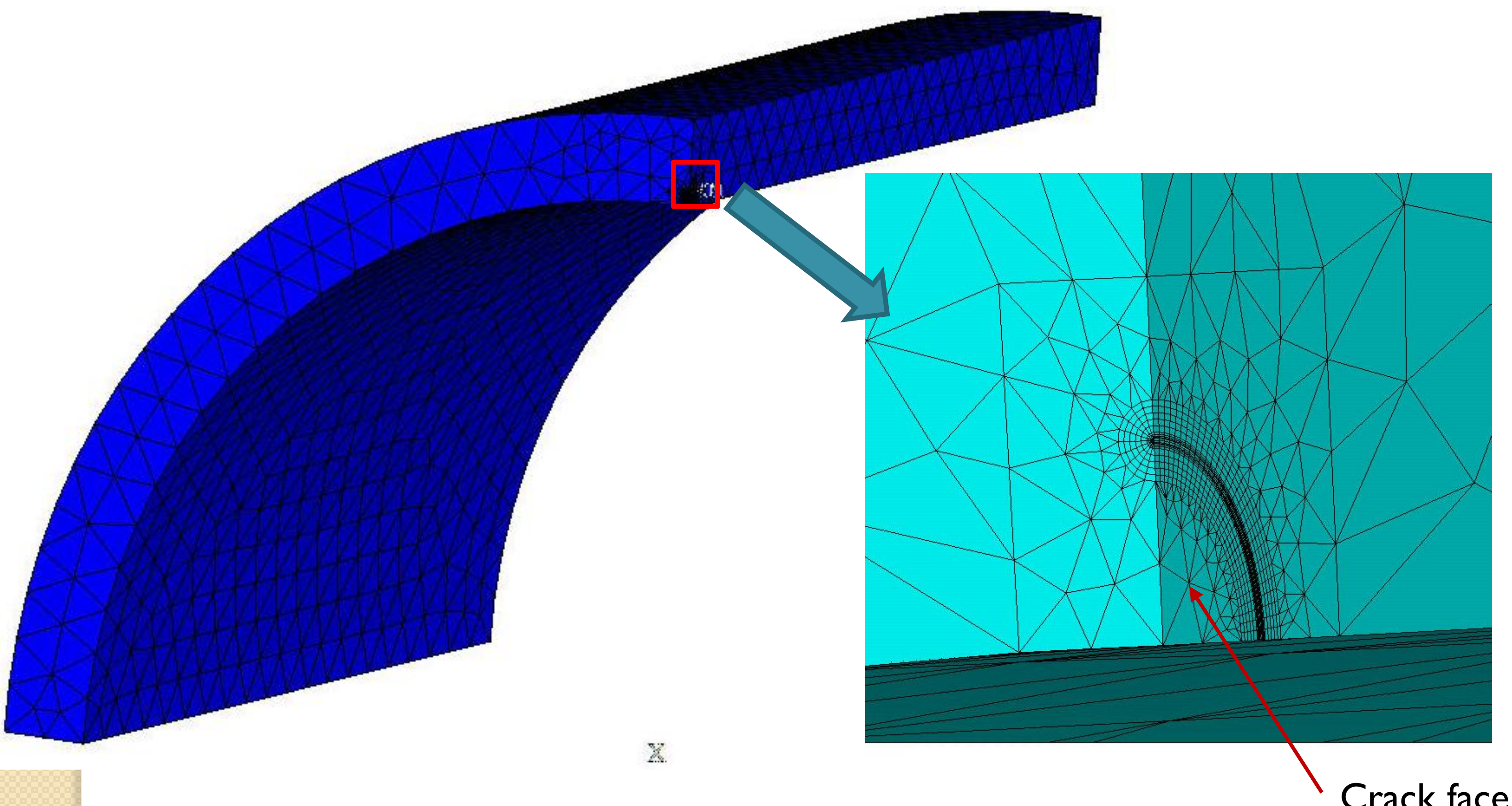
$$K_I < 0.67 K_C$$

- Elasto-Plastic Analysis

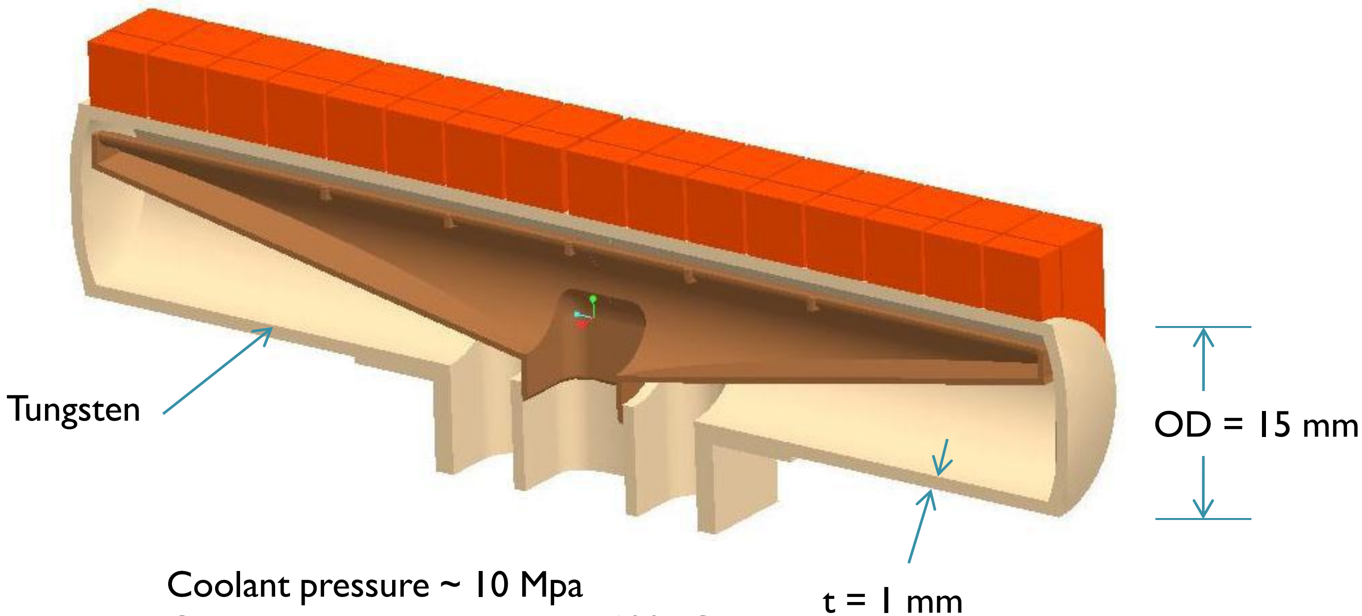
$$J_I < 0.67 J_C$$

ANSYS Finite Element Model of Circumferential Crack

- Stress intensities along crack face using the ANSYS CINT command
- Elastic-Plastic material properties for Tungsten used
- Currently only pressure loads are considered, but thermal stresses to be included

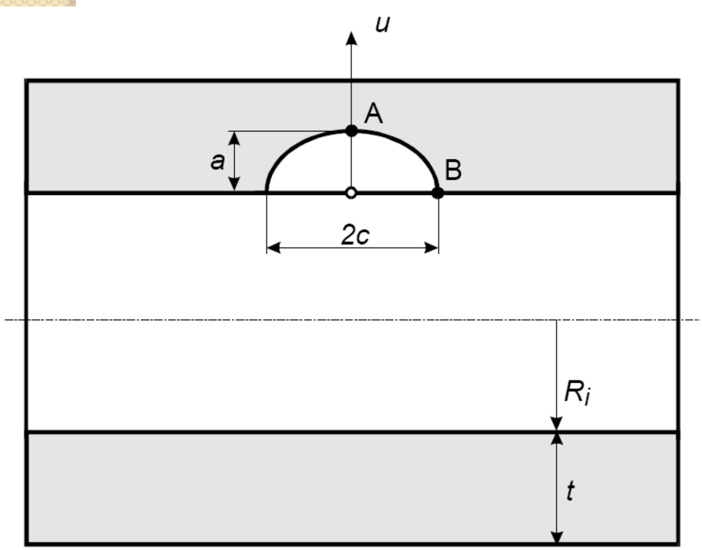


Initial Fracture Studies Based on T-Tube Geometry and Pressure Loads



Coolant pressure ~ 10 Mpa
Coolant inlet temperature ~ 600 ^{o}C

Initial Studies Compute Stress Intensities for Axial Cracks in Pressurized Cylinder



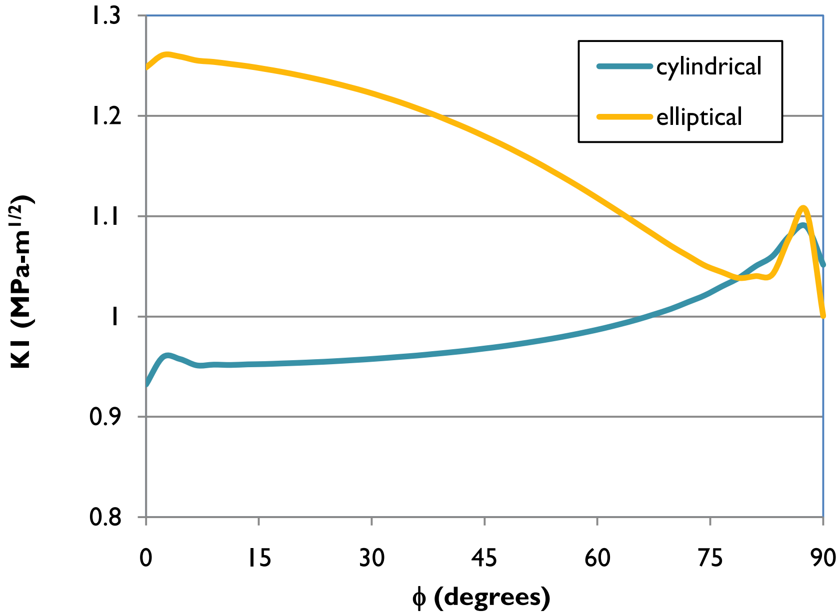
Case 1: Circular crack; c/a=1

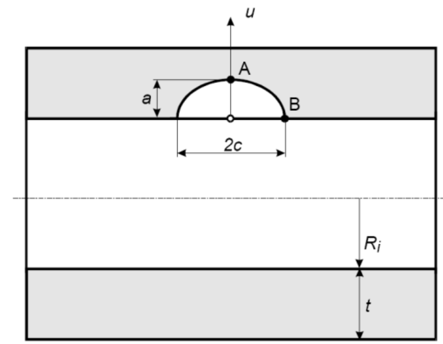
Case 2: Elliptical crack; c/a=2

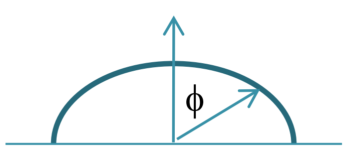
Use elastic-plastic properties for tungsten.

Calculate J_I and then report equivalent K_I.

Variation of Stress Intensity with Location along Crack Tip (a = 0.1 mm)







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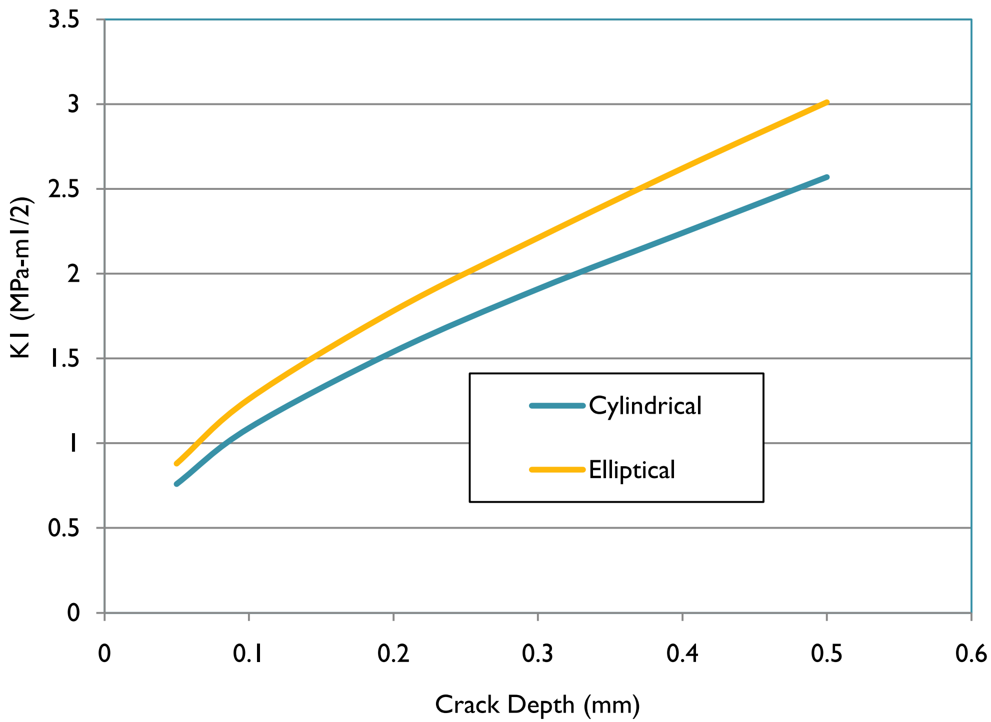
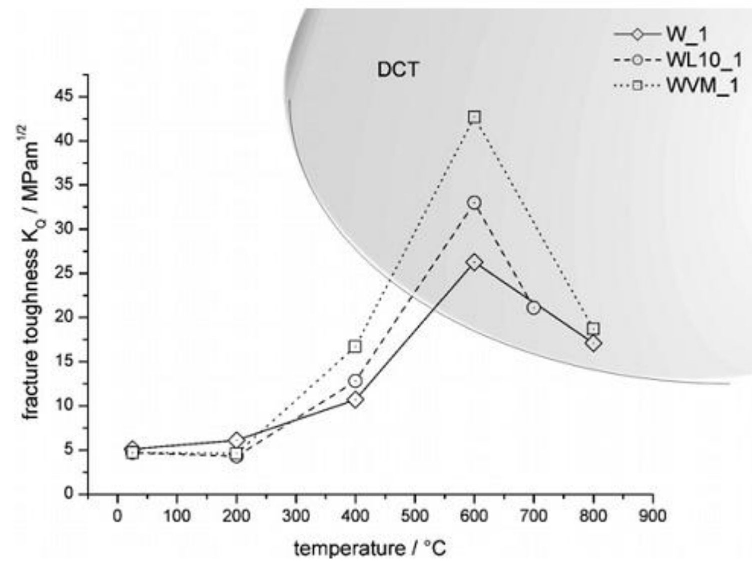
Case 2: Elliptical crack; c/a=2

a = 0.1mm

Maximum Stress Intensity as a Function of Crack Depth





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Conclusions

- We've got to include fracture in our design analysis, particularly when using materials with limited ductility
- So far, there are no major red flags
- We will include thermal stresses in the future