Unit 5: Radiation Effects on Mechanical Properties

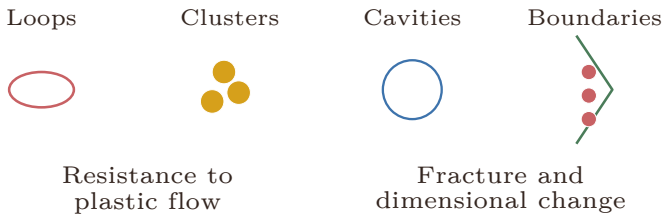
ME 5203 – Nuclear Materials

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How the irradiated microstructure changes properties



- Unit 4 described the defects that remain and evolve.
- Unit 5 asks how they change plastic deformation, fracture and component shape.
- The answer depends on the material, temperature, stress and exposure history.

Unit 5: Learning Objectives

Hardening and fracture

- Explain how defects obstruct dislocations.
- Estimate hardening from obstacle size and number density.
- Distinguish strength, ductility and fracture toughness.
- Explain the transition-temperature shift in ferritic steels.

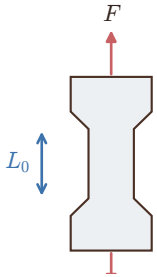
Deformation during service

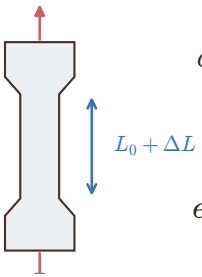
- Explain irradiation creep through defect motion.
- Separate creep, swelling and irradiation growth.
- Explain how helium can promote grain-boundary failure.
- Connect these mechanisms to materials choices.

Different tests measure different properties

Test	Quantity	Physical question
Tensile test	Yield strength, elongation	How much load starts plastic flow? How far can the sample stretch?
Charpy impact test	Absorbed energy	How much energy breaks a notched specimen under impact?
Fracture test	Crack-growth resistance	How readily does an existing sharp crack extend?
Creep test	Strain versus time	How much permanent deformation accumulates under sustained stress?

Engineering stress and strain





$$\sigma_e = F/A_0$$

$$e = \Delta L/L_0$$

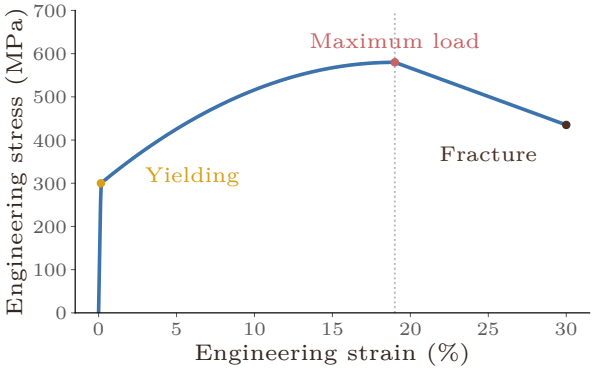
Definition: Stress

F: tensile force. A_0: original cross-sectional area.
$\sigma_e = F/A_0$ has units Pa or MPa.

Definition: Strain

L_0: original gauge length. ΔL: extension.
$e = \Delta L/L_0$ is dimensionless.

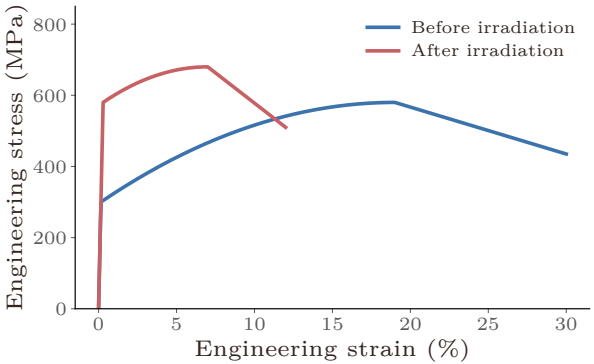
Reading a tensile curve



Schematic tensile curve.

- **Yield strength**: stress associated with the onset of appreciable plastic flow.
- **Ultimate tensile strength**: maximum engineering stress.
- **Uniform elongation**: extension before necking starts.
- **Total elongation**: extension at fracture.

Irradiation can raise strength while reducing elongation



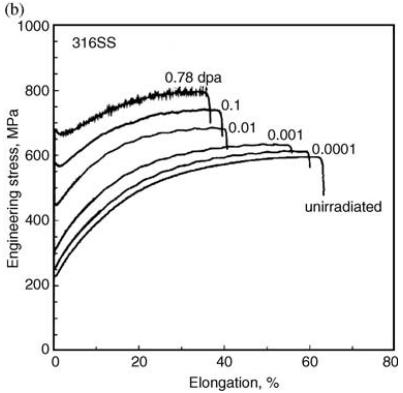
Schematic curves at the same elastic modulus.

- More stress is needed to start plastic flow in this example.
- The irradiated sample has less capacity for further strain hardening.
- Necking and fracture occur at smaller elongations.

Interpretation

Higher yield strength alone does not establish better performance.

Measured tensile curves in irradiated 316 stainless steel



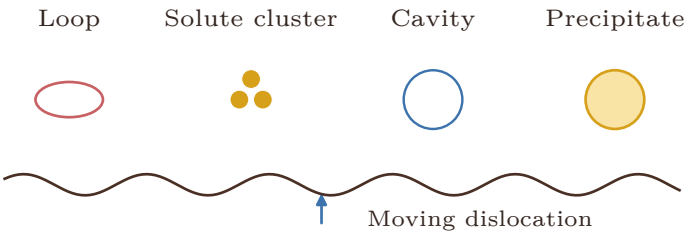
- Horizontal axis: elongation, %.
- Vertical axis: engineering stress, MPa.
- Curve labels give dose in dpa.
- Higher-dose curves begin plastic flow at higher stress and end at lower elongation here.

Note

Compare both the height and the horizontal extent of each curve.

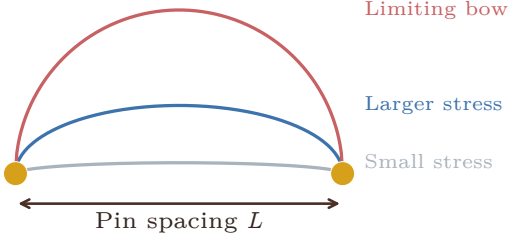
Murty and Charit (2013), Fig. 6.23b.

Radiation defects act as obstacles to dislocations



- Plastic flow requires dislocation motion.
- Defects can pin, deflect or react with a moving dislocation.
- Additional applied stress helps the dislocation pass these obstacles.

A pinned dislocation bows under stress

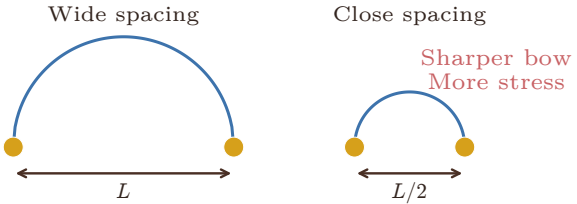


- The ends remain pinned while the segment bows.
- Applied shear stress pushes the line forward.
- Line tension resists bending.

Analogy

A cord held at two points resists sideways deflection. A dislocation also has an energy cost per unit length.

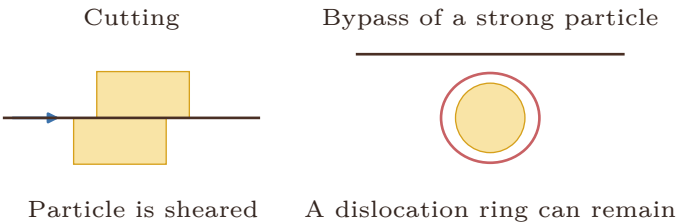
Closer obstacles require a sharper bow



$$\tau b \simeq \frac{\mathcal{T}}{R}, \qquad \mathcal{T} \sim \frac{Gb^2}{2}, \qquad R_{\text{critical}} \sim \frac{L}{2} \quad \Rightarrow \quad \tau_{\text{critical}} \sim \frac{Gb}{L}$$

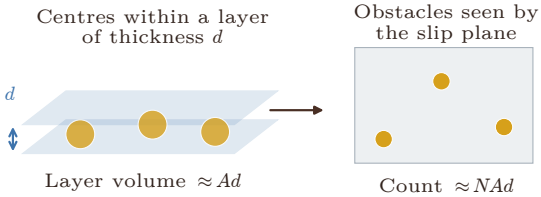
τ: shear stress. b: Burgers-vector magnitude. $\mathcal{T}$: line tension.
R: bow radius. G: shear modulus. L: pin spacing.

A dislocation can cut an obstacle or pass around it



- Some particles and defect clusters can be cut or absorbed.
- A sufficiently strong particle can force a dislocation to bypass it.
- Both routes require extra stress, but the required stress differs.

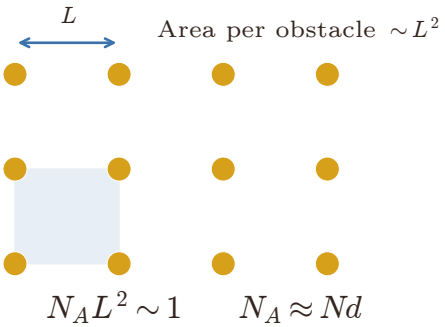
Why the product Nd appears in the hardening model



- N is the number of obstacles per unit volume, in m^{-3}.
- d is their characteristic diameter, in m.
- A slip-plane area A intersects obstacles whose centres lie within a layer of thickness about d.

$$\text{Obstacles per unit slip-plane area:} \qquad N_A \approx \frac{NAd}{A} = Nd$$

Obstacle spacing follows from area per obstacle



For randomly distributed obstacles, an average area of order L^2 gives:

$$N_A L^2 \sim 1$$

Using $N_A \approx Nd$:

$$L \approx \frac{1}{\sqrt{Nd}}$$

More intersections leave shorter free segments of dislocation.

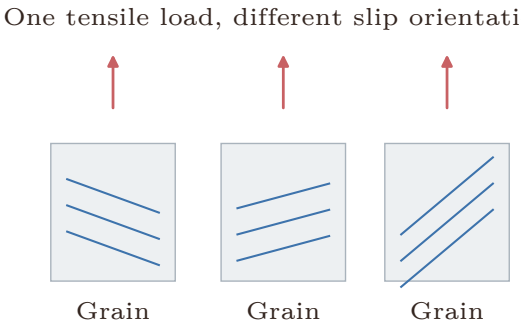
The dispersed barrier hardening equation

Definition: Increase in tensile yield strength

$$\boxed{\Delta\sigma_y = M\alpha Gb\sqrt{Nd}}$$

Symbol	Meaning	Units
$\Delta\sigma_y$	Irradiation-induced increase in yield strength	Pa
M	Conversion from slip resistance to polycrystal tensile strength	Dimensionless
α	Effective barrier strength factor	Dimensionless
G	Shear modulus	Pa
b	Burgers-vector magnitude	m
N	Obstacle number density	m^{-3}
d	Obstacle diameter	m

The Taylor factor connects slip to a tensile test

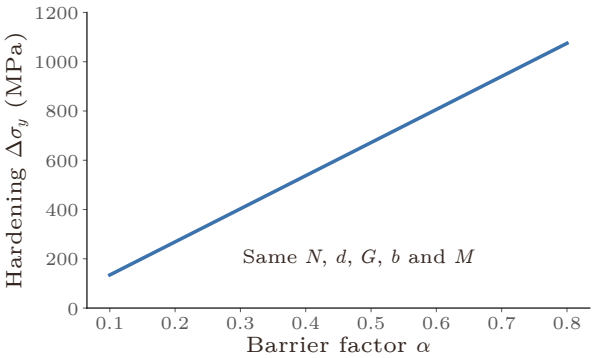


- Dislocations respond to shear stress on slip systems.
- A tensile test loads many differently oriented grains.
- M represents the conversion for the assumed polycrystal model.

$$\Delta\sigma_y = M\Delta\tau$$

For an ideal random FCC aggregate, $M \approx 3.06$ is a common estimate.

The barrier factor describes how hard an obstacle is to pass



- Two populations with the same N and d can produce different hardening.
- A larger α means a stronger effective obstacle in this model.
- Size, structure, temperature and dislocation character can change α.

Note

Use a value supported for the material and obstacle population.

Calculated example: $M = 3.06$, $G = 77$ GPa, $b = 0.255$ nm, $N = 5 \times 10^{22}$ m^{-3}, $d = 10$ nm.

Worked example: obstacle spacing

Example: Given

$N = 5 \times 10^{22}\,\mathrm{m}^{-3}$, $d = 10\,\mathrm{nm} = 10^{-8}\,\mathrm{m}$.

Question

What is the estimated spacing on a slip plane?

Worked example: obstacle spacing

Example: Given

$N = 5 \times 10^{22}\,\mathrm{m}^{-3}$, $d = 10\,\mathrm{nm} = 10^{-8}\,\mathrm{m}$.

Question

What is the estimated spacing on a slip plane?

$$Nd = (5 \times 10^{22})(10^{-8}) = 5 \times 10^{14}\,\mathrm{m}^{-2}$$

Worked example: obstacle spacing

Example: Given

$N = 5 \times 10^{22}\,\mathrm{m}^{-3}$, $d = 10\,\mathrm{nm} = 10^{-8}\,\mathrm{m}$.

Question

What is the estimated spacing on a slip plane?

$$Nd = (5 \times 10^{22})(10^{-8}) = 5 \times 10^{14}\,\mathrm{m}^{-2}$$

Answer

$$L = \frac{1}{\sqrt{5 \times 10^{14}}} = 4.47 \times 10^{-8}\,\mathrm{m} = 44.7\,\mathrm{nm}$$

Worked example: yield-strength increase

Example: Given

Use $L = 44.7$ nm, $G = 77$ GPa, $b = 0.255$ nm, $\alpha = 0.4$ and $M = 3.06$.

Question

How much extra tensile yield strength does the model predict?

Worked example: yield-strength increase

Example: Given

Use $L = 44.7$ nm, $G = 77$ GPa, $b = 0.255$ nm, $\alpha = 0.4$ and $M = 3.06$.

Question

How much extra tensile yield strength does the model predict?

$$\Delta\tau = \frac{\alpha G b}{L} = \frac{0.4(77 \times 10^{9})(0.255 \times 10^{-9})}{44.7 \times 10^{-9}} \approx 176\,\text{MPa}$$

Worked example: yield-strength increase

Example: Given

Use $L = 44.7$ nm, $G = 77$ GPa, $b = 0.255$ nm, $\alpha = 0.4$ and $M = 3.06$.

Question

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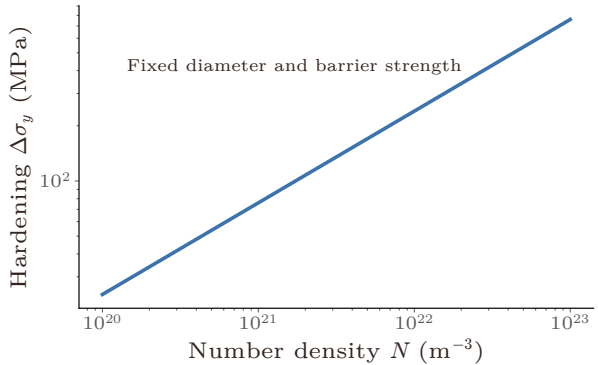
$$\Delta\tau = \frac{\alpha G b}{L} = \frac{0.4(77 \times 10^{9})(0.255 \times 10^{-9})}{44.7 \times 10^{-9}} \approx 176\,\text{MPa}$$

Answer

$$\Delta\sigma_y = M\Delta\tau \approx 3.06(176) = 538\,\text{MPa}$$

This is the **increase**, to be added to the chosen unirradiated reference strength.

How number density changes hardening

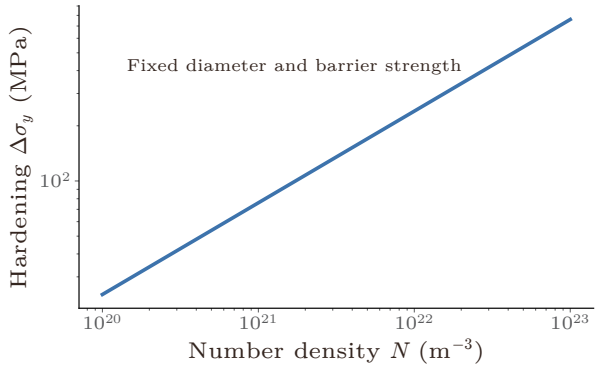


Question

If N becomes four times larger while the other terms stay fixed, what happens to $\Delta\sigma_y$?

Calculated example: $M = 3.06$, $\alpha = 0.4$, $G = 77$ GPa, $b = 0.255$ nm, $d = 10$ nm.

How number density changes hardening



Question

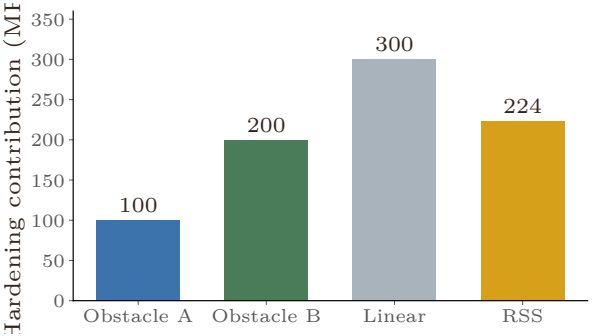
If N becomes four times larger while the other terms stay fixed, what happens to $\Delta\sigma_y$?

Answer

It doubles: $\sqrt{4N} = 2\sqrt{N}$. The estimated spacing halves.

Calculated example: $M = 3.06$, $\alpha = 0.4$, $G = 77$ GPa, $b = 0.255$ nm, $d = 10$ nm.

Combining obstacle populations requires a model



Two separate increments: 100 and 200 MPa.

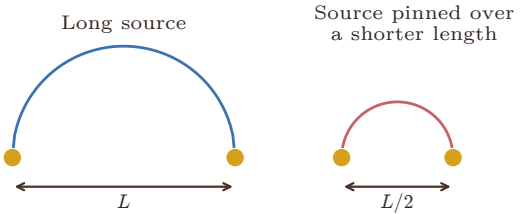
$$\Delta\sigma_{\text{linear}} = 100 + 200$$

$$\Delta\sigma_{\text{RSS}} = \sqrt{100^2 + 200^2}$$

Note

RSS means root-sum-square. Obstacle interactions determine which combination is appropriate.

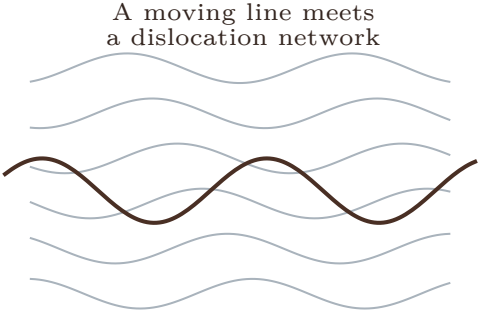
Source hardening raises the stress needed to start a source



$$\tau_{\mathrm{FR}} \sim \frac{Gb}{L}$$

- Radiation defects can shorten the free length of a pinned dislocation source.
- A shorter segment needs more stress to emit a dislocation loop.
- Friction hardening resists motion after the source starts.

The dislocation network also resists slip

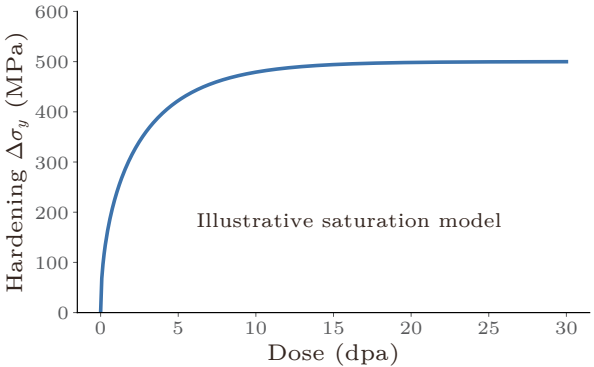


Definition: Taylor hardening

$$\tau_{\text{network}} \sim \alpha_d G b \sqrt{\rho_d}$$

- ρ_d: dislocation line length per unit volume, m^{-2}.
- α_d: interaction factor.
- Increasing line density reduces the free distance between interactions.

Hardening can approach a plateau with dose

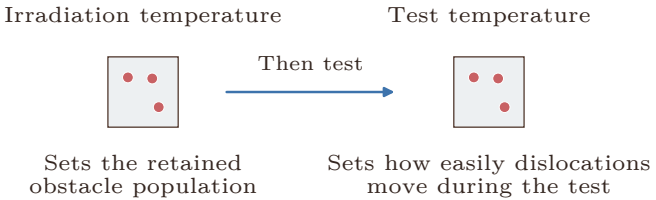


- Early irradiation adds obstacles.
- Recombination, loss, coarsening and overlap can limit further growth of the effective obstacle population.
- Some materials show an approximate hardening plateau.

Note

There is no universal saturation dose. Precipitation and other changes can continue.

Irradiation temperature and test temperature play different roles



- Irradiation temperature affects which defects and precipitates remain.
- Test temperature affects slip and fracture during the measurement.
- Heating can promote recovery, but solute trapping or precipitation can also cause additional hardening.

Coarsening can reduce hardening at fixed obstacle volume



Question

If diameter doubles and number density falls to $N/8$, what happens to hardening when α stays fixed?

Coarsening can reduce hardening at fixed obstacle volume



Question

If diameter doubles and number density falls to $N/8$, what happens to hardening when α stays fixed?

Answer

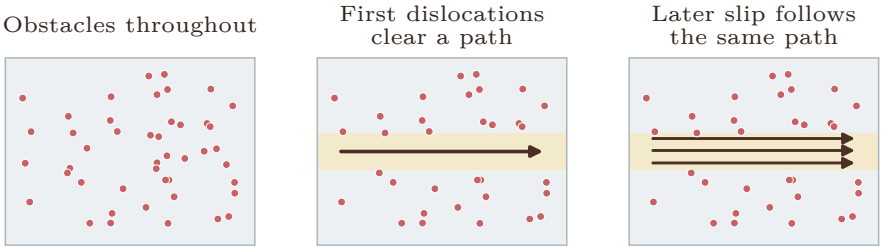
$N'd' = (N/8)(2d) = Nd/4$, so $\Delta\sigma_y$ halves. The spherical-obstacle volume fraction stays the same.

Hardening, ductility and toughness describe different behaviour

Property	Meaning	Possible irradiation effect
Yield strength	Resistance to starting plastic flow	Often increases when obstacles accumulate
Ductility	Plastic deformation before fracture	Can decrease through localized flow or boundary damage
Fracture toughness	Resistance to extending a crack	Can decrease even when yield strength increases

A strong material can still have poor tolerance of cracks.

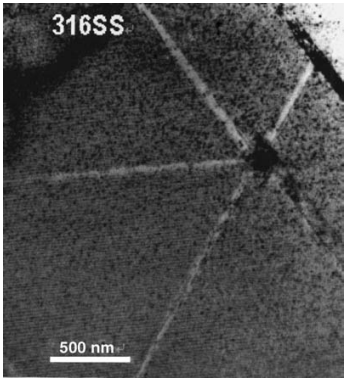
Dislocation channeling concentrates plastic flow



Schematic obstacle population

- Moving dislocations can remove or rearrange some irradiation obstacles.
- Later dislocations encounter less resistance along the same path.
- Plastic strain concentrates in a narrow band while nearby material deforms less.

A TEM example of dislocation channels



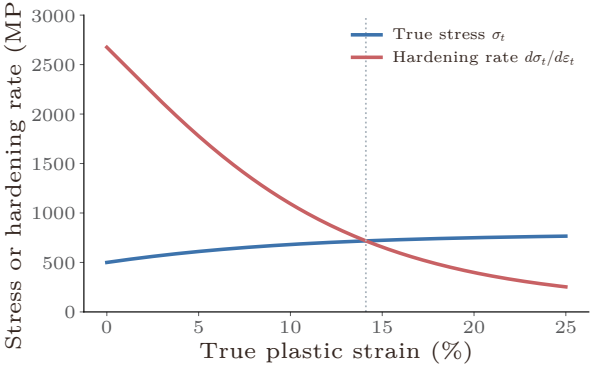
- Material: 316 stainless steel.
- The 500 nm scale bar gives the size of the observed region.
- The narrow bands show localized deformation associated with reduced defect contrast.

Note

The image records the result of deformation after irradiation.

Murty and Charit (2013), Fig. 6.30.

Reduced strain hardening makes necking easier



Two effects compete during stretching:

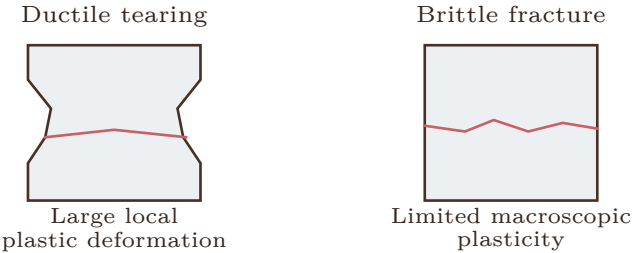
- The cross-section becomes smaller.
- Strain hardening raises the local flow stress.

Neglecting elasticity and rate sensitivity, necking begins when

$$\frac{d\sigma_t}{d\varepsilon_t} = \sigma_t.$$

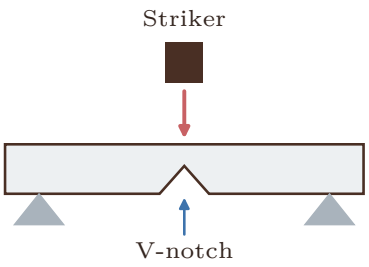
If hardening cannot compensate for area loss, deformation localizes.

Ductile tearing and brittle fracture



- Ductile fracture involves substantial local plastic deformation, often with cavity growth and joining.
- Cleavage can propagate with much less macroscopic deformation.
- Grain-boundary fracture is another path when boundaries lose resistance.

The Charpy test measures absorbed impact energy



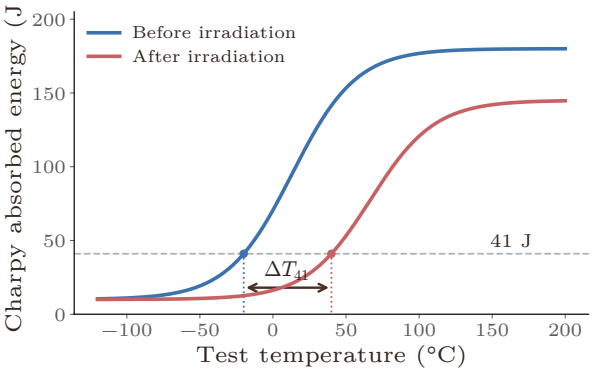
Impact acts opposite the notch

- A pendulum striker breaks a notched specimen.
- The machine measures the energy absorbed, in joules.
- Repeating the test at different temperatures gives a transition curve.

Measured quantity

Charpy energy is a test result for a specified specimen and loading condition.

Irradiation can shift the ductile–brittle transition



- Lower shelf: low absorbed energy.
- Upper shelf: higher absorbed energy.
- The transition lies between them.
- Here irradiation moves the curve toward higher temperatures and lowers its upper shelf.

Note

T_{41}: temperature at 41 J in this schematic ferritic-steel response.

Worked example: reading a transition-temperature shift

Example: Same test and energy criterion

Before irradiation: $T_{41} = -20\,^{\circ}\mathrm{C}$.
After irradiation: $T_{41} = 40\,^{\circ}\mathrm{C}$.

Question

What is the shift, and what does its direction mean?

Worked example: reading a transition-temperature shift

Example: Same test and energy criterion

Before irradiation: $T_{41} = -20\,^{\circ}\mathrm{C}$.
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Question

What is the shift, and what does its direction mean?

Answer

$$\Delta T_{41} = 40 - (-20) = 60\,^{\circ}\mathrm{C}$$

The specimen must be tested 60 degrees warmer to reach the same 41 J absorbed energy.

Worked example: reading a transition-temperature shift

Example: Same test and energy criterion

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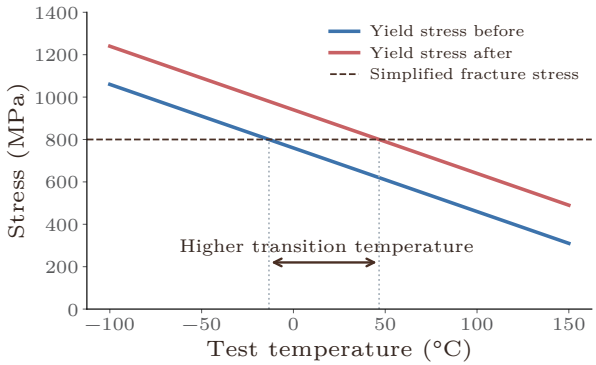
Answer

$$\Delta T_{41} = 40 - (-20) = 60\,^{\circ}\mathrm{C}$$

The specimen must be tested 60 degrees warmer to reach the same 41 J absorbed energy.

A temperature **difference** of $60\,^{\circ}\mathrm{C}$ is also 60 K.

Why hardening can raise the transition temperature



Schematic yield–fracture competition.

- In ferritic steels, cooling can make plastic flow much harder.
- Irradiation adds resistance to dislocation motion.
- Cleavage can then compete with plastic relaxation at a higher temperature.

Physical picture

The crack tip has less opportunity to relax by plastic flow.

A simple estimate connects hardening to a temperature shift

Assume an unchanged fracture-stress criterion. The reference yield curve locally falls by m MPa per kelvin:

$$\sigma_y(T + \Delta T) \approx \sigma_y(T) - m\Delta T, \qquad m > 0.$$

To offset an added hardening $\Delta\sigma_y$:

$$m\Delta T \approx \Delta\sigma_y \quad \Rightarrow \quad \Delta T \approx \frac{\Delta\sigma_y}{m}$$

Question

If $\Delta\sigma_y = 100$ MPa and $m = 2$ MPa/K, what is ΔT?

A simple estimate connects hardening to a temperature shift

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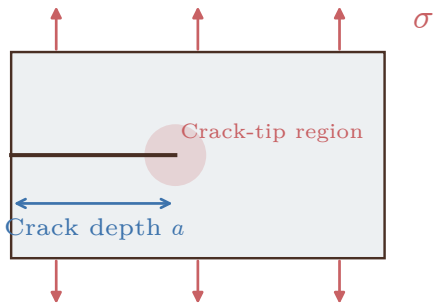
Question

If $\Delta\sigma_y = 100$ MPa and $m = 2$ MPa/K, what is ΔT?

Answer

$\Delta T \approx 50$ K. The coefficient $1/m$ belongs to this local model.

A crack concentrates the applied load

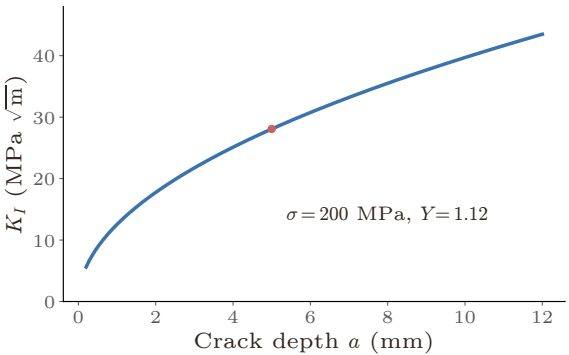


For a simple linear-elastic crack geometry:

$$K_I = Y\sigma\sqrt{\pi a}$$

- K_I: opening-mode stress intensity, MPa$\sqrt{\text{m}}$.
- σ: applied tensile stress, MPa.
- a: crack size, m, defined for the geometry.
- Y: dimensionless geometry factor.

Worked example: stress intensity at an edge crack

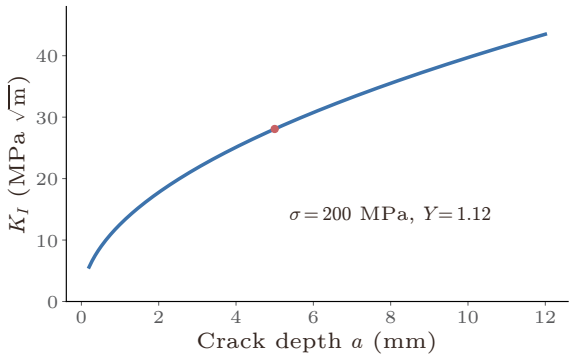


Wide-plate edge crack; linear elasticity and small-scale yielding.

Example: Given

$\sigma = 200$ MPa, $a = 5$ mm,
$Y = 1.12$.

Worked example: stress intensity at an edge crack



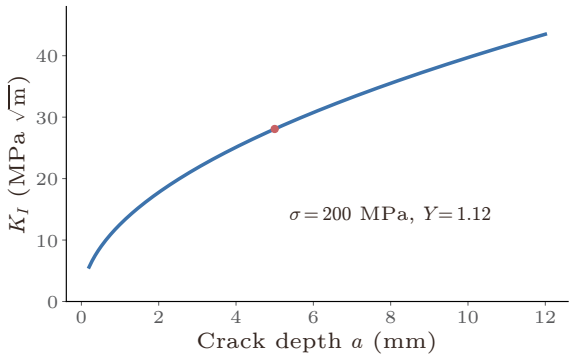
Wide-plate edge crack; linear elasticity and small-scale yielding.

Example: Given

$\sigma = 200$ MPa, $a = 5$ mm,
$Y = 1.12$.

$$K_I = 1.12(200)\sqrt{\pi(0.005)}$$

Worked example: stress intensity at an edge crack



Wide-plate edge crack; linear elasticity and small-scale yielding.

Example: Given

$\sigma = 200$ MPa, $a = 5$ mm, $Y = 1.12$.

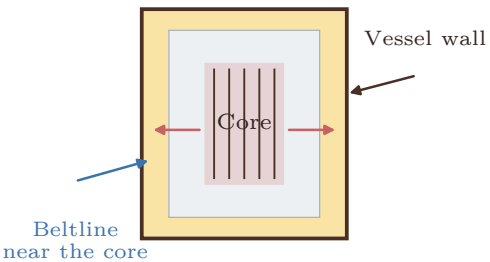
$$K_I = 1.12(200)\sqrt{\pi(0.005)}$$

Result

$$K_I = 28.1\,\text{MPa}\sqrt{\text{m}}$$

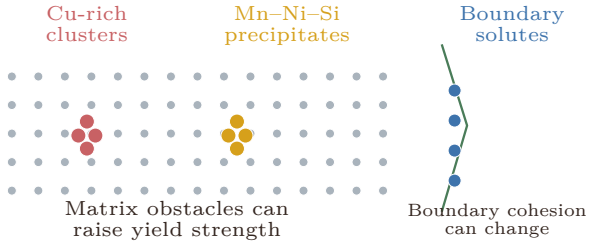
Four times the crack depth gives twice K_I, if Y stays fixed.

The vessel beltline receives neutron exposure



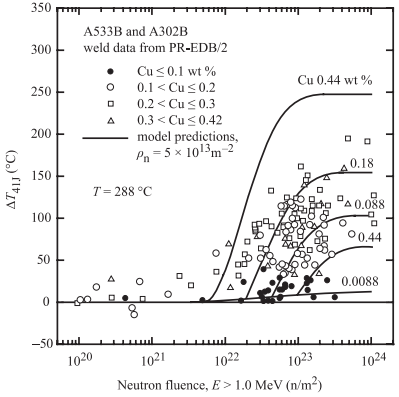
- The pressure vessel contains the reactor core and coolant.
- Low-alloy ferritic steels provide strength and toughness.
- The beltline lies near the height of the fuel.
- Neutron exposure there can change the steel's crack resistance.

Different changes can affect matrix strength and boundaries



- Defect clusters and solute-rich precipitates can obstruct dislocations.
- Cu-rich features matter in steels with sufficient residual copper.
- Mn–Ni–Si precipitates can matter even at low copper contents.
- Boundary segregation can alter resistance to intergranular fracture.

A measured example of copper-dependent embrittlement



- x: fast-neutron fluence, n/m^2, on a logarithmic scale.
- y: shift in the 41 J transition temperature, °C.
- Symbols group weld measurements by copper content.
- Solid curves are model predictions.

The low-Cu measurements generally show smaller shifts in this dataset.

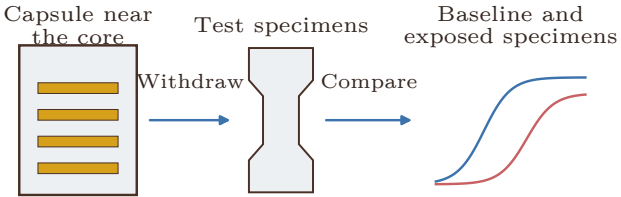
Was (2007), Fig. 13.23.

Lower copper does not remove every embrittlement mechanism

Feature	Materials effect	What must be assessed
Cu-rich clusters	Additional obstacles in susceptible steels	Residual Cu, other solutes and irradiation history
Mn–Ni–Si precipitates	Can add substantial hardening at high exposure	Composition-dependent precipitation kinetics
Boundary segregation	Can change boundary cohesion	Local chemistry and the active fracture path

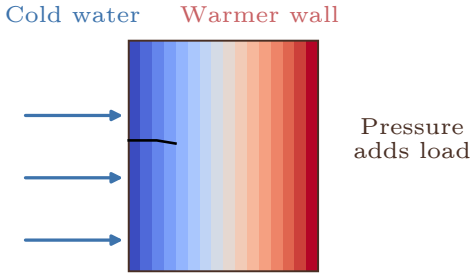
Composition control reduces particular mechanisms. Surveillance checks the actual response.

Surveillance specimens track changes during operation



- Representative vessel materials are irradiated in capsules.
- Capsules are withdrawn and tested according to the plant's programme.
- Tests and dosimetry connect property changes to exposure.
- The results update the assessment of the vessel material.

Pressurized thermal shock combines cooling and pressure



Rapid cooling creates a thermal gradient

1. Cold water rapidly cools the vessel's inner region.
2. The warmer surrounding wall restrains contraction.
3. Thermal stress acts together with pressure loading.
4. Reduced toughness makes crack resistance especially important.

Vessel assessment connects measurements to operating limits

Material condition

- Unirradiated reference properties.
- Changes measured or predicted after exposure.
- Uncertainty and required margins.

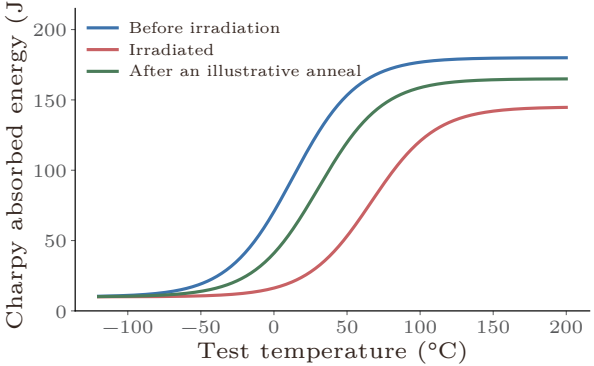
Loading conditions

- Pressure and temperature history.
- Thermal gradients and flaws.
- Relevant crack-resistance criteria.

Note

In the US, 10 CFR Part 50 Appendix G addresses fracture toughness and Appendix H addresses vessel-material surveillance.

Annealing can recover some irradiation-induced changes



Schematic transition curves.

- Heating allows some defects and solute structures to change.
- Hardening and transition temperature can partly recover.
- The result depends on composition, temperature and hold time.
- Later neutron exposure can cause further embrittlement.

Class question: does a higher yield strength prove improvement?

Example: Two exposed steels at the same test temperature

Steel A has the higher yield strength. Steel B has the lower transition temperature and higher crack resistance.

Question

Which measurement matters when the concern is fracture from an existing flaw during a cold transient?

Class question: does a higher yield strength prove improvement?

Example: Two exposed steels at the same test temperature

Steel A has the higher yield strength. Steel B has the lower transition temperature and higher crack resistance.

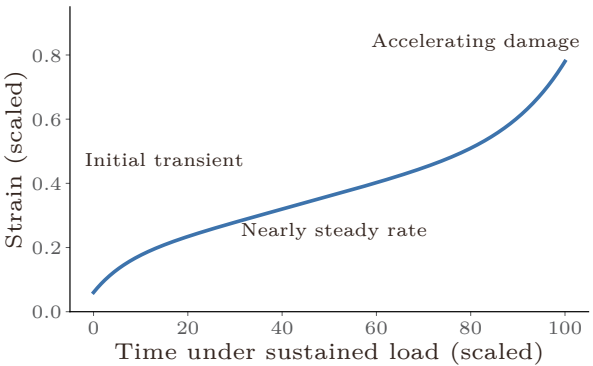
Question

Which measurement matters when the concern is fracture from an existing flaw during a cold transient?

Answer

The relevant crack resistance at that temperature must be compared with crack loading. Yield strength alone cannot settle the question.

Creep is deformation that accumulates under sustained load

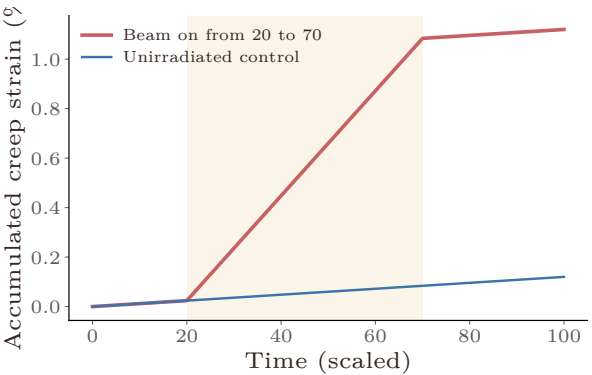


- Apply a load and hold it.
- The specimen can continue to change length with time.
- This time-dependent plastic strain is creep.
- It can occur below the yield stress measured in a short tensile test.

Read the slope

The slope is the creep rate: $\dot{\varepsilon}_c = d\varepsilon_c/dt$.

Irradiation can add a deformation rate while the beam is on

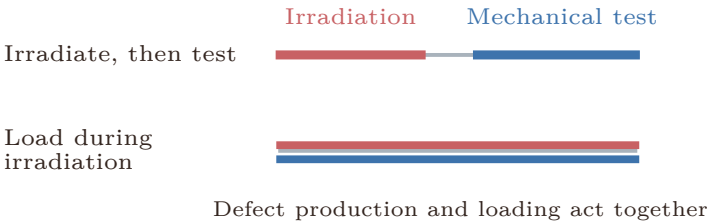


- Compare tests at the same temperature and stress.
- In this model, the slope rises when irradiation starts.
- It falls when irradiation stops.
- The strain already accumulated remains.

Note

Real transients also depend on the evolving defect population.

Testing after irradiation and testing during irradiation differ



- **After irradiation:** the test probes the retained microstructure.
- **During irradiation:** new defects are supplied while stress acts.
- The second test can reveal irradiation creep that the first cannot reproduce.

A simple creep law connects stress, dose rate and strain rate

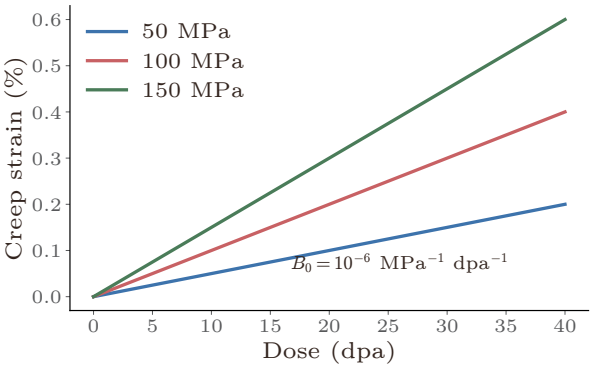
$$\dot{\varepsilon}_c = B_0 \, \sigma \, \dot{\mathcal{D}}$$

Symbol	Meaning	Unit
$\dot{\varepsilon}_c$	Irradiation creep strain per unit time	s^{-1}
B_0	Creep compliance per unit dose	$\mathrm{MPa}^{-1}\ \mathrm{dpa}^{-1}$
σ	Applied uniaxial stress	MPa
$\dot{\mathcal{D}}$	Damage dose accumulated per unit time	dpa/s

Note

At fixed material state, twice the stress gives twice the predicted rate in this linear model.

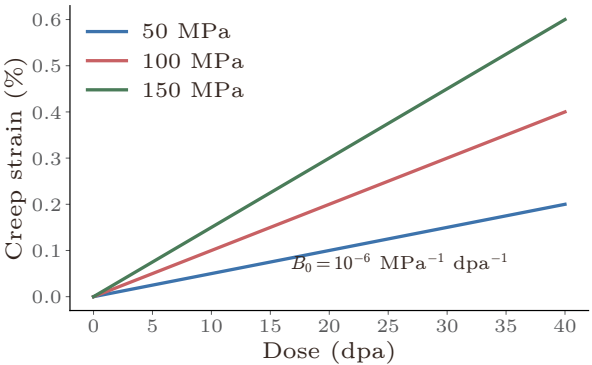
Worked example: convert accumulated dose into creep strain



Example: Constant stress and B_0

$B_0 = 10^{-6}$ MPa^{-1} dpa^{-1},
$\sigma = 100$ MPa, $\mathcal{D} = 20$ dpa.

Worked example: convert accumulated dose into creep strain

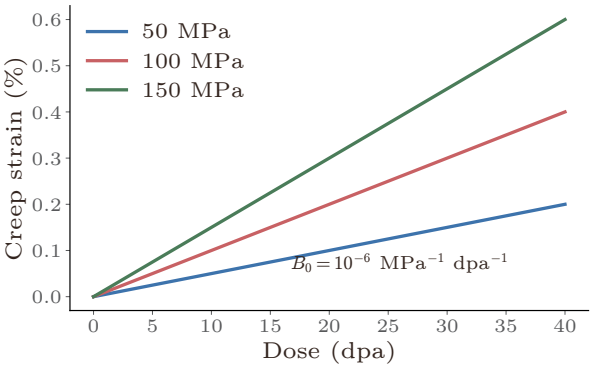


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$B_0 = 10^{-6}$ MPa^{-1} dpa^{-1},
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$$\varepsilon_c = B_0 \sigma \mathcal{D} = 10^{-6}(100)(20)$$

Worked example: convert accumulated dose into creep strain



Example: Constant stress and B_0

$B_0 = 10^{-6}$ MPa^{-1} dpa^{-1},
$\sigma = 100$ MPa, $\mathcal{D} = 20$ dpa.

$$\varepsilon_c = B_0 \sigma \mathcal{D} = 10^{-6}(100)(20)$$

Result

$\varepsilon_c = 0.002 = 0.2\%$.
A 1 m gauge length extends by 2 mm.

Class question: what happens if the dose rate doubles?

Example: Use only the simple linear model

Keep temperature, stress and B_0 fixed.

$$\dot{\varepsilon}_c = B_0 \sigma \dot{\mathcal{D}}$$

Question

Compare the strain after the same time, and after the same total dose.

Class question: what happens if the dose rate doubles?

Example: Use only the simple linear model

Keep temperature, stress and B_0 fixed.

$$\dot{\varepsilon}_c = B_0 \sigma \dot{\mathcal{D}}$$

Question

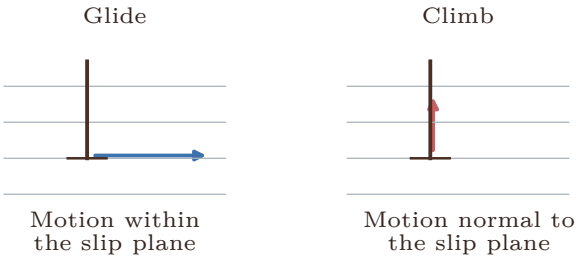
Compare the strain after the same time, and after the same total dose.

Answer

Same time: twice the dose and twice the creep strain.

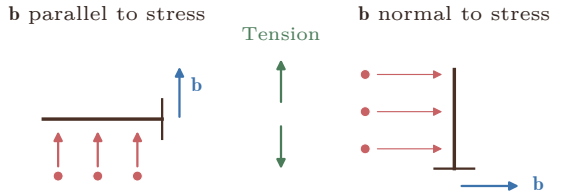
Same dose: the same creep strain, reached in half the time.

Glide and climb move a dislocation in different directions



- **Glide:** motion within the slip plane under shear stress.
- **Climb:** motion normal to that plane by absorbing or emitting point defects.
- Irradiation supplies defects that can support climb.

SIPA: stress changes point-defect capture



Stress makes point-defect capture depend on dislocation orientation

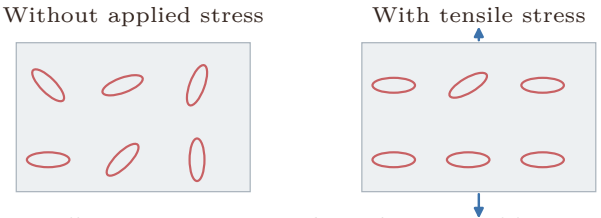
- SIPA means **stress-induced preferential absorption**.
- Dislocations with different orientations respond differently to the applied stress.
- Unequal point-defect absorption produces unequal climb.
- The combined motion can give a net strain in the loading direction.

Two different meanings of bias

	Sink bias in Unit 4	**Stress-induced bias in SIPA**
What differs?	Capture of interstitials and vacancies by a sink	Capture by differently oriented dislocations under stress
Is applied stress essential to this comparison?	No	Yes
Why do we care?	It changes the defect balance and can support swelling	It creates an oriented climb response and creep

A preference for a defect species and a preference caused by loading orientation are different comparisons.

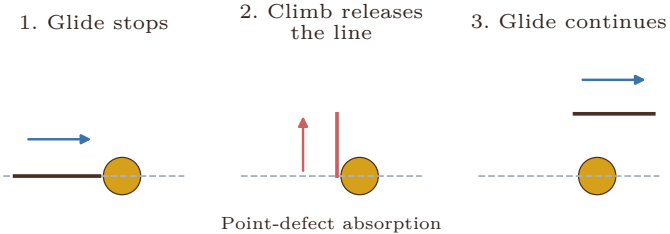
SIPN: stress can favour the formation of certain loops



Illustrative orientation bias of interstitial loops

- SIPN means **stress-induced preferential nucleation**.
- Stress changes the energy cost of forming differently oriented loops.
- A preferred loop population can produce a directional strain.
- This contribution is often associated with the early transient.

Climb-controlled glide: defects help release a blocked line



- Applied stress drives glide until an obstacle blocks it.
- Point-defect absorption allows the dislocation to climb past the obstacle.
- Glide resumes and adds plastic strain.

Note

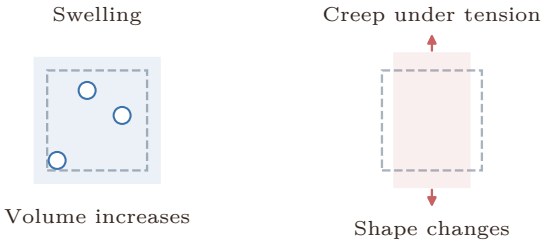
Climb can control the waiting time even when glide produces much of the strain.

Three routes from irradiation defects to creep

Mechanism	What irradiation supplies	What stress changes
SIPA	Point defects absorbed by dislocations	Capture and climb depend on orientation
SIPN	Defects that form new loops	Some loop orientations become easier to nucleate
Climb-controlled glide	Defects that enable climb past obstacles	Glide carries the released line forward

The observed rate may contain several contributions. A linear rate law does not identify a unique mechanism.

Creep and swelling are different dimensional changes



- **Swelling:** the volume increases as cavities accumulate and grow.
- **Creep:** sustained stress produces time-dependent plastic strain.
- For small, isotropic swelling $S = \Delta V/V$, the linear strain is $S/3$.

Swelling can also change the creep rate

A uniaxial empirical form

$$\dot{\varepsilon}_c = \sigma \left[B_0 \dot{\mathcal{D}} + C_s \dot{S} \right]$$

- $S = \Delta V / V$: volumetric swelling fraction; $\dot{S}$: its rate, s^{-1}.
- C_s: creep–swelling coupling coefficient, MPa^{-1}.
- B_0, σ and $\dot{\mathcal{D}}$: as in the earlier creep law.

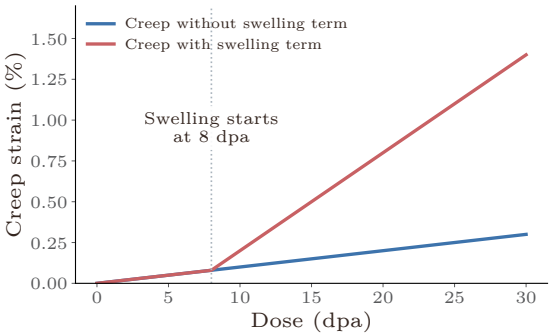
$$\frac{d\varepsilon_c}{d\mathcal{D}} = \sigma \left[B_0 + C_s \frac{dS}{d\mathcal{D}} \right]$$

Note

Both terms describe **creep**. The direct expansion $S/3$ is a separate contribution to axial strain.

Use S as a fraction and stress in MPa.

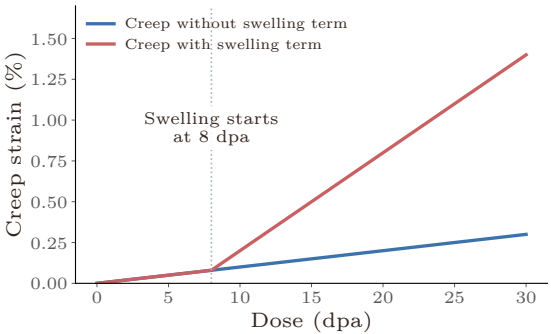
Worked example: add the swelling-dependent creep term



Example: During a steady swelling interval

$\sigma = 100$ MPa, $B_0 = 10^{-6}$ MPa^{-1} dpa^{-1},
$C_s = 0.01$ MPa^{-1},
$dS/d\mathcal{D} = 5 \times 10^{-4}$ dpa^{-1}.

Worked example: add the swelling-dependent creep term

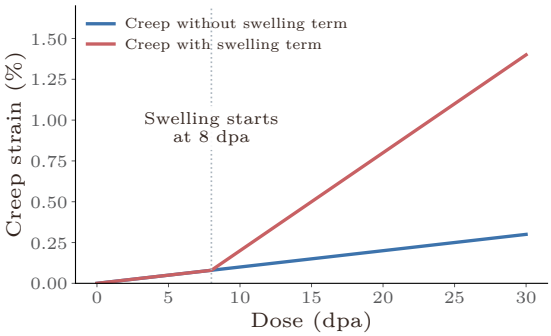


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$$\frac{d\varepsilon_c}{d\mathcal{D}} = \underbrace{10^{-4}}_{\text{baseline}} + \underbrace{5 \times 10^{-4}}_{\text{coupling}}$$

Over 10 dpa in this interval:
$\Delta\varepsilon_c = 0.006 = 0.6\%$.

Worked example: what does a length measurement contain?

Example: Small strains in one loading direction

A component has $S = 0.03$ volumetric swelling and $\varepsilon_c = 0.006$ axial creep strain. Ignore thermal strain, elastic strain and irradiation growth.

Question

What is the total axial strain if swelling is isotropic?

Worked example: what does a length measurement contain?

Example: Small strains in one loading direction

A component has $S = 0.03$ volumetric swelling and $\varepsilon_c = 0.006$ axial creep strain. Ignore thermal strain, elastic strain and irradiation growth.

Question

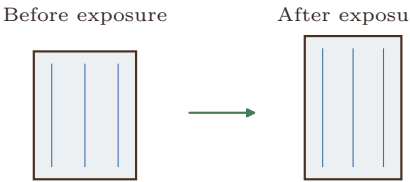
What is the total axial strain if swelling is isotropic?

Answer

$$\varepsilon_{\text{axial}} \approx \frac{S}{3} + \varepsilon_c = \frac{0.03}{3} + 0.006 = 0.016 = 1.6\%.$$

The 3% volume increase contributes about 1% to length.

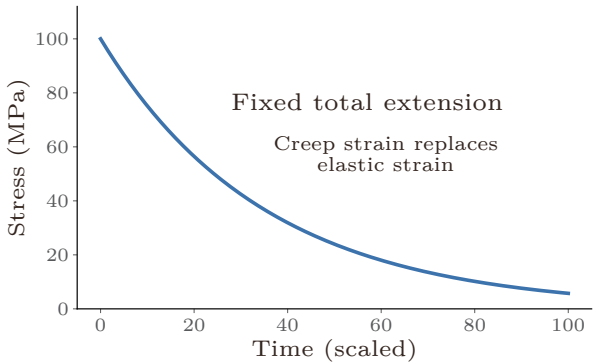
Irradiation growth can change shape without applied stress



No applied stress; crystal anisotropy and texture matter

- Some crystals accumulate different strains along different directions.
- HCP zirconium alloys are an important example.
- Crystal anisotropy and grain texture control the component response.
- In the ideal growth contribution, shape changes with little volume change.

At fixed extension, creep can relax the stress



- Hold the total extension fixed.
- Creep adds plastic strain.
- Elastic strain must decrease.
- The measured stress therefore falls.

$$\varepsilon_{\text{total}} = \frac{\sigma}{E} + \varepsilon_c$$

$$\dot{\sigma} \approx -E\dot{\varepsilon}_c$$

Constant E; no changing thermal, swelling or growth strain.

Nuclear reactions can create helium inside a metal

Example: boron

$$^{10}_{5}\mathrm{B} + ^{1}_{0}\mathrm{n} \longrightarrow ^{7}_{3}\mathrm{Li} + ^{4}_{2}\mathrm{He}$$

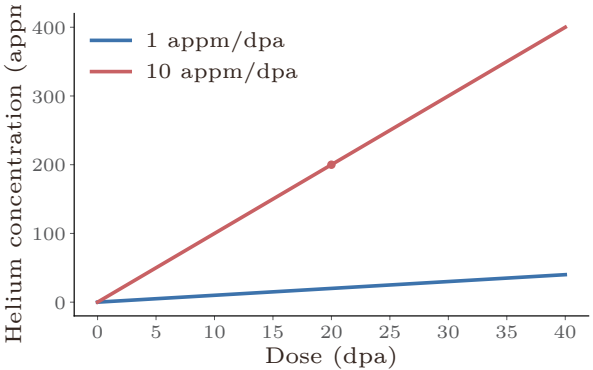
Example: a two-step nickel route

$$^{58}_{28}\mathrm{Ni}(n,\gamma)^{59}_{28}\mathrm{Ni} \qquad ^{59}_{28}\mathrm{Ni}(n,\alpha)^{56}_{26}\mathrm{Fe}$$

- An alpha particle becomes a helium atom after slowing down and capturing electrons.
- Gas production depends on composition, neutron spectrum and exposure history.
- These are examples; other reactions also produce helium.

Reaction notation omits branch-dependent excitation and energy terms.

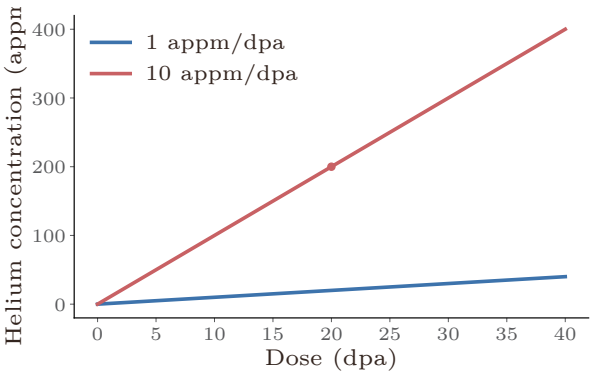
Worked example: convert He/dpa into helium concentration



Example: Chosen constant production ratio

$r_{\mathrm{He}} = 10$ appm/dpa,
$\mathcal{D} = 20$ dpa.

Worked example: convert He/dpa into helium concentration

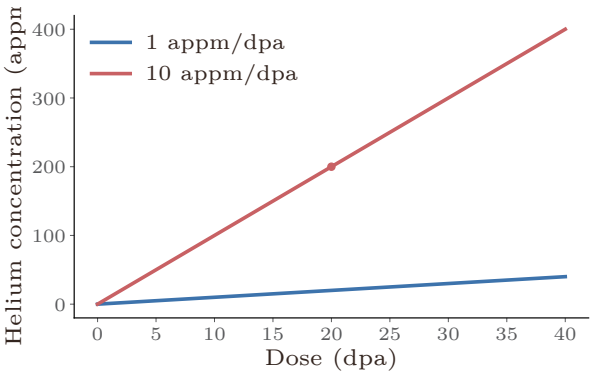


Example: Chosen constant production ratio

$r_{\mathrm{He}} = 10$ appm/dpa,
$\mathcal{D} = 20$ dpa.

$$c_{\mathrm{He}} = r_{\mathrm{He}}\mathcal{D} = 200 \text{ appm}$$

Worked example: convert He/dpa into helium concentration



Example: Chosen constant production ratio

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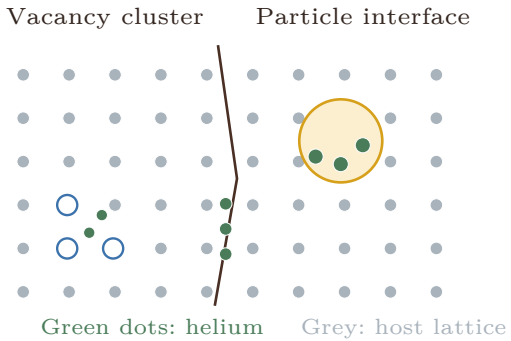
$$c_{\mathrm{He}} = r_{\mathrm{He}}\mathcal{D} = 200 \text{ appm}$$

Meaning

About 200 He atoms per million reference material atoms.

$200 \times 10^{-6} = 0.02$ at.%.

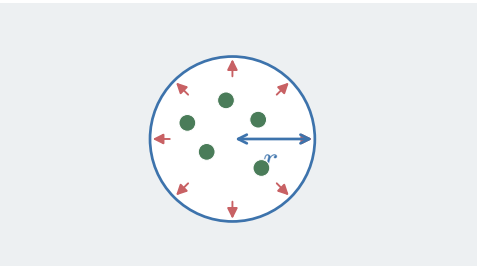
Helium can move and become trapped



- Helium has very low solubility in most metals.
- In α-Fe, interstitial helium has a low migration barrier.
- Vacancies, interfaces and dislocations can trap it.
- Trapping changes where helium accumulates and forms bubbles.

Small helium bubbles can have large internal pressure

Gas pressure acts on the cavity surface



Surface energy favours a smaller cavity

Spherical capillarity estimate (solid constraint neglected):

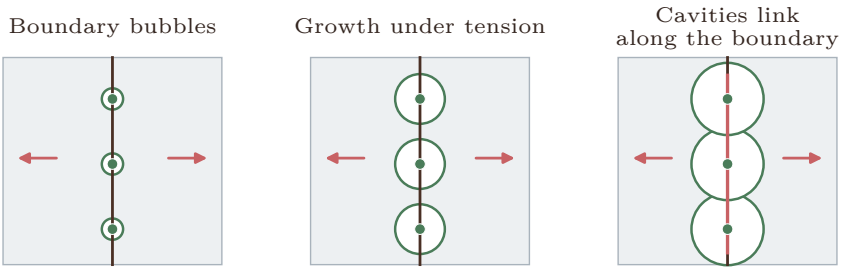
$$\Delta p = p_{\text{in}} - p_{\text{out}} \approx \frac{2\gamma}{r}$$

- γ: surface energy, J/m^2.
- r: bubble radius, m.
- Δp: pressure difference, Pa.

Example

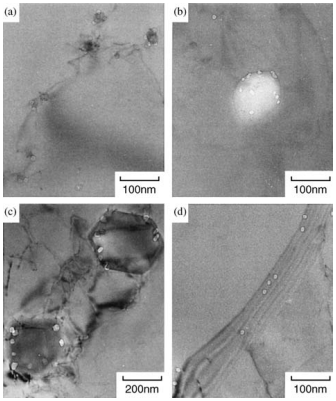
$\gamma = 2$ J/m^2, $r = 10$ nm
$\Rightarrow \Delta p \approx 400$ MPa.

Boundary cavities can grow and join under tension



- Helium can stabilize cavities at grain boundaries.
- At suitable temperature and loading, cavities can grow.
- Linked cavities reduce the load-bearing boundary area.
- The result can be intergranular failure with reduced ductility.

A real example: helium bubbles at different interfaces



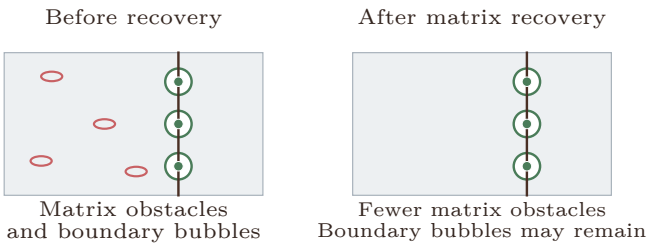
- Panels show cavities at different microstructural sites.
- Use each panel's scale bar to compare sizes.
- Compare the distribution around particles and along the boundary.

Note

Look at where cavities collect, not only how many are visible.

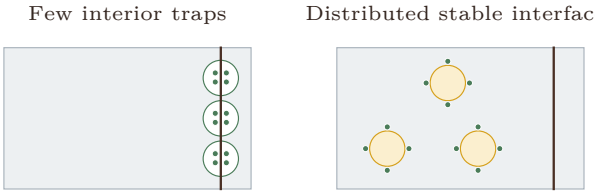
Murty and Charit (2013), Fig. 6.37.

Matrix recovery does not prove that helium damage is gone



- Some loops and point-defect clusters can recover during heating.
- Yield strength may then decrease.
- Helium trapped at boundaries can remain or redistribute into larger cavities.
- Measure ductility and crack resistance as well as strength.

One design approach: provide stable traps inside grains



Trapping changes where helium accumulates

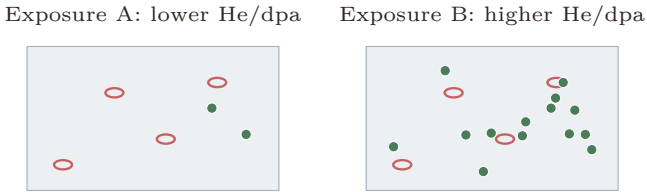
- Distributed particle interfaces can trap helium away from major boundaries.
- A fine dispersion can provide many trapping sites.
- Traps must remain stable during irradiation and service.
- Their capacity is finite; weldability, toughness and fabrication still matter.

ODS: oxide-dispersion-strengthened.

Material choice depends on the failure mode

Material family	Why it may be useful	What still needs attention
Austenitic steels	Fabrication, toughness and corrosion performance	Swelling, creep and helium-assisted boundary damage
Ferritic/martensitic steels	Often better swelling resistance in comparable regimes	Low-temperature hardening and cleavage transition; high-temperature strength
ODS alloys	Stable dispersions can strengthen and supply interfaces	Joining, anisotropy, interface stability and toughness
Ni-base alloys	Strength and corrosion resistance for selected duties	Spectrum-dependent helium production and boundary damage
Tungsten-based materials	High-temperature and plasma-facing applications	Brittle fracture, irradiation hardening and gas-induced damage

The same dpa does not guarantee the same mechanical response

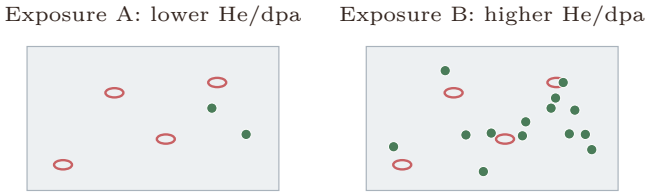


Same stated dpa; gas production can differ

Question

What else must match before two irradiation tests can be compared?

The same dpa does not guarantee the same mechanical response



Same stated dpa; gas production can differ

Question

What else must match before two irradiation tests can be compared?

Answer

Temperature, dose rate, recoil spectrum, helium production, initial microstructure, loading and test conditions.

Choose measurements for the component's main concern

Component	Possible concern	Useful measurements
Pressure vessel	Crack resistance during a cold transient	Transition shift, fracture toughness, fluence and flaw/loading history
Fast-reactor duct	Dimensional changes that affect clearances	Swelling, creep, temperature and stress history
Fusion structural component	Combined displacement damage and gas production	Hardening, ductility, creep/fracture and He/dpa under relevant conditions

Choose a material and test programme for a specified job. A claim of radiation resistance needs a defined property and exposure.

Class discussion: strength recovers but boundary bubbles remain

Example: A post-irradiation heat treatment

The yield strength moves closer to its original value. Microscopy still shows helium-containing cavities at grain boundaries.

Question

Would you approve the material using the yield-strength result alone? What would you measure next?

Class discussion: strength recovers but boundary bubbles remain

Example: A post-irradiation heat treatment

The yield strength moves closer to its original value. Microscopy still shows helium-containing cavities at grain boundaries.

Question

Would you approve the material using the yield-strength result alone? What would you measure next?

Answer

No. Test the properties tied to the service risk: ductility, fracture toughness or creep-rupture behaviour at the relevant temperature and loading. Examine the fracture path.

Summary of Equations

Equation	Output
$\Delta\sigma_y = M\alpha G b\sqrt{Nd}$	Added yield strength from an obstacle population
$\Delta T_{41} = T_{41,\mathrm{irr}} - T_{41,\mathrm{ref}}$	Measured shift of a stated transition criterion
$K_I = Y\sigma\sqrt{\pi a}$	Crack loading, to compare with crack resistance
$\dot{\varepsilon}_c = \sigma(B_0\dot{\mathcal{D}} + C_s\dot{S})$	Creep strain rate in the stated empirical model
$\varepsilon_{\mathrm{swell}} \approx S/3$	Linear strain from small isotropic swelling
$c_{\mathrm{He}} = r_{\mathrm{He}}\mathcal{D}$	He concentration when production per dpa is constant

Five questions to check the main ideas

1. Why can irradiation increase strength but reduce useful ductility?
2. Why does obstacle spacing enter a hardening calculation?
3. Why can a higher transition temperature matter to a vessel?
4. How do creep, swelling and irradiation growth differ?
5. Why must we consider helium as well as dpa?

Five questions to check the main ideas

1. Why can irradiation increase strength but reduce useful ductility?
2. Why does obstacle spacing enter a hardening calculation?
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5. Why must we consider helium as well as dpa?

The connection

Defect structure changes how dislocations move, how cracks advance and how dimensions evolve. Different properties need different measurements.

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