Fracture Mechanics

5. Testing and fracture mechanisms

Luc St-Pierre

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Learning outcomes

After this section, you will be able to:

- Describe how fracture toughness tests are conducted.
- Explain fracture mechanisms in metals.
- Identify mechanisms leading to a rising R-curve.

Outline

- Testing
  - Basic notions: geometry, precrack and instrumentation
  - Measuring K_{Ic}
  - Measuring J_{Ic} and the R-curve
- Fracture mechanisms in metals
  - Ductile fracture
  - Cleavage
  - Intergranular fracture
- Why metals have a rising R-curve?
- Toughening mechanisms in fibre-reinforced composites
- Increasing toughness: examples from research
  - Lattice materials
  - Carbon fibre composites

Outline

Standard test methods

Fracture toughness tests are complex, consult the relevant standards:

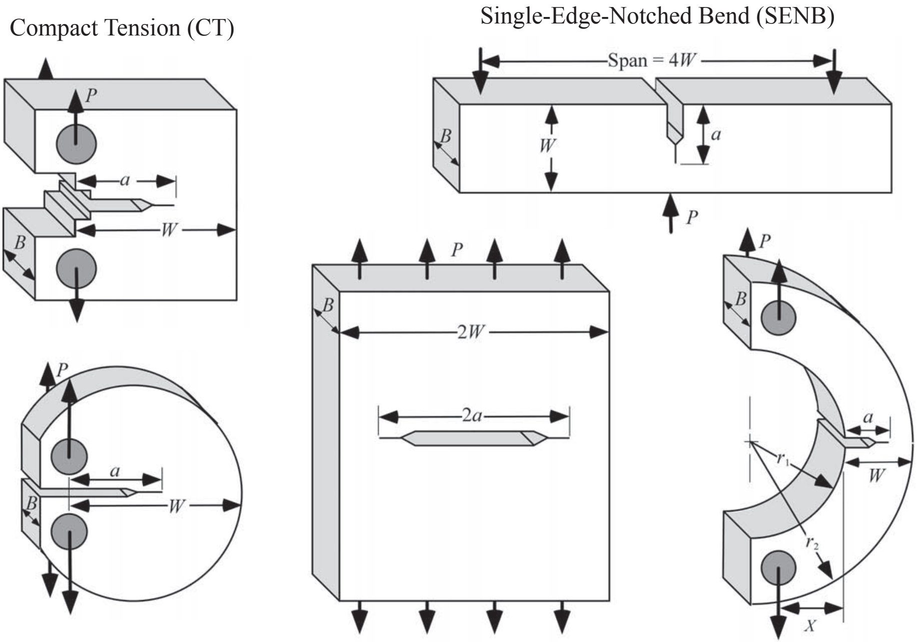
ASTM E1820 Standard test method for measurement of fracture toughness.

ASTM E399 Standard test method for linear-elastic plane-strain fracture toughness K_{Ic} of metallic materials.

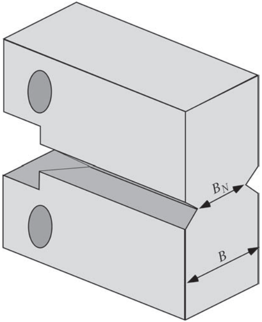
The first one, is the main reference and it covers K_{Ic}, J_{Ic} and R-curve measurements. The second one is an older version of the standard but you will often see it as a reference.

Outline

Specimen geometries



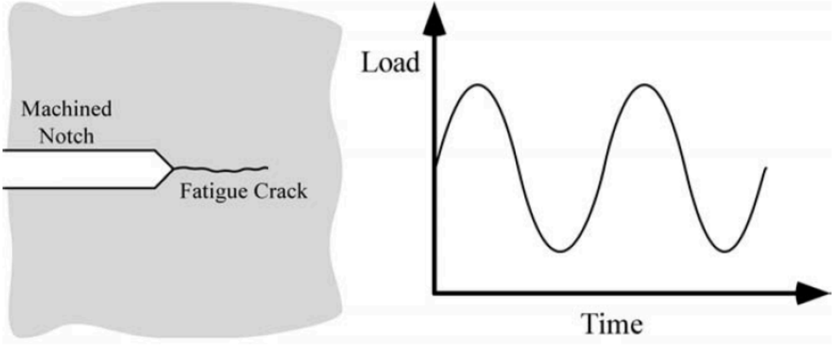
Side grooves



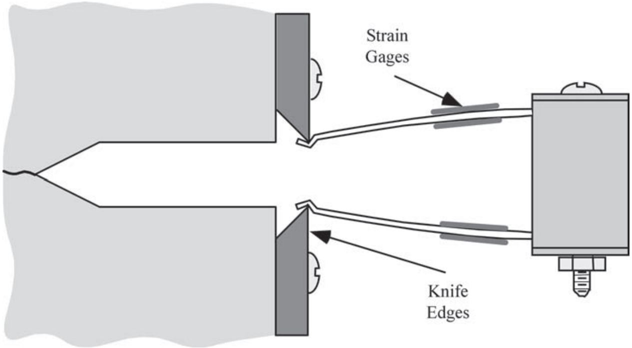
- Side grooves reduce the importance of the low triaxiality zones that exist close to the free surface.
- They help to produce a straighter crack front.
- They allow the crack to propagate in a straight line.

Fatigue precrack

From the initial notch, you need to grow a fatigue crack. For metals, there are no other way of producing a sharp crack.



Instrumentation



- The applied force is measured by the testing machine.
- The most accurate way to measure displacement is at the crack mouth using a clip gauge.

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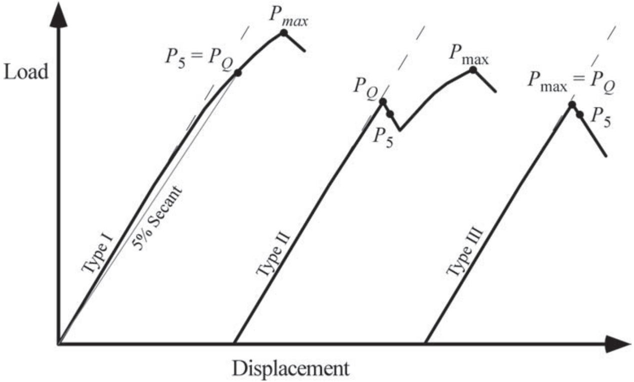
Typical load-displacement curves



The stress intensity factor is given by:

$$K_Q = \frac{P_Q}{B\sqrt{W}} f\left(\frac{a}{W}\right)$$

Validity

For the test to be a valid fracture toughness measurement, $K_Q = K_{Ic}$, we need:

$$0.45 \leq \frac{a}{W} \leq 0.55$$
$$P_{max} \leq 1.10 P_Q$$
$$a, (W - a), B \geq 2.5 \left(\frac{K_{Ic}}{\sigma_Y} \right)^2$$

If these requirements are not satisfied, then the plastic zone is too large to use LEFM and you will need to perform a J_{Ic} test instead.

Size requirement for a K_{Ic} test

Consider a structural steel with $\sigma_Y = 240\,\mathrm{MPa}$ and $K_{Ic} = 60\,\mathrm{MPa}\sqrt{\mathrm{m}}$, what would be the minimum thickness B to conduct a valid test:

$$B \geq 2.5 \left(\frac{K_{Ic}}{\sigma_Y}\right)^2 = 2.5 \left(\frac{60}{240}\right)^2 = 15.6\,\mathrm{cm!}$$

This might not seem like a large number, but a SENB specimen with this thickness B would be about $600\,\mathrm{kg}$!

For tough materials, it is almost impossible to do a K_{Ic} test, you need to go for a J_{Ic} test.

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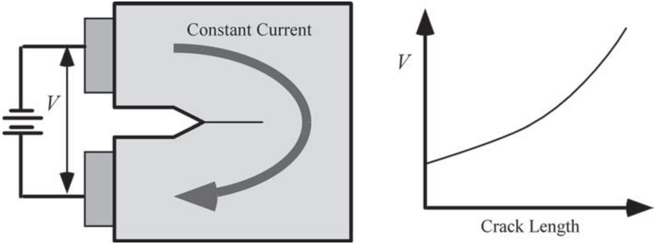
J-test

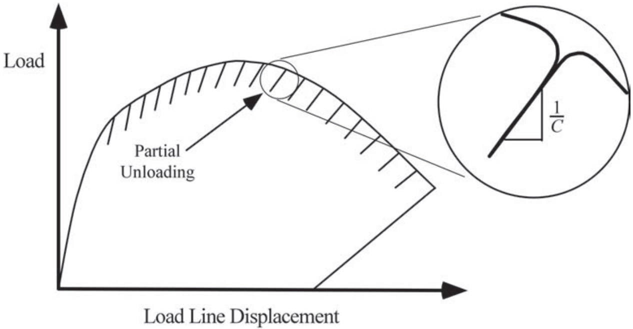
- The most commonly used geometry are the Compact-Tension (CT) and Single-Edge-Notch Bend (SENB) specimens, see slide 7.
- Again, fatigue precrack is necessary for metals.
- To plot the R-curve of the material, the crack extension needs to be measured during the test. This can be done using:
  - the potential drop technique or
  - the unloading compliance method
  - (visual observation might be possible but it is not recommended).

Measuring crack length: potential drop technique



- Advantages: accurate and offers continuous measurement during the test.
- Disadvantages: needs to be calibrated, requires extra equipment and works only with materials that conduct electricity.

Measuring crack length: unloading compliance



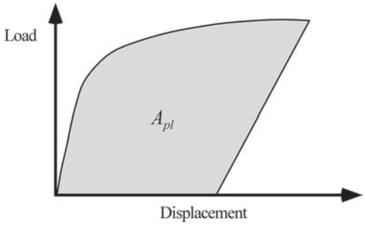
- Advantages: doesn't require additional equipment and the relationship between the crack length a and the compliance C is given for standard test geometries.
- Disadvantages: makes testing and data processing more tedious.

Computing J

The J-integral is given by:

$$J = J_{el} + J_{pl}$$

where the elastic part is:



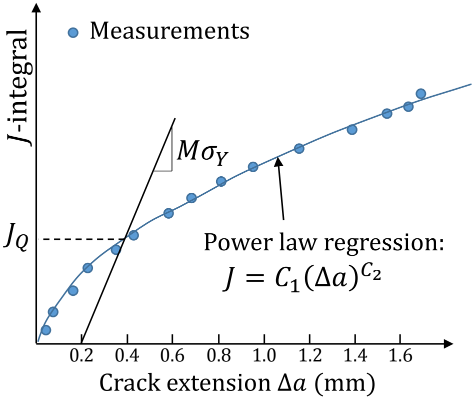
$$J_{el} = \frac{K^2(1-\nu^2)}{E} \quad \text{where} \quad K = \frac{P}{B\sqrt{W}} f\left(\frac{a}{W}\right)$$

and the plastic part is proportional to the load vs plastic displacement curve:

$$J_{pl} = \frac{\eta A_{pl}}{B b_0}$$

where the uncracked ligament $b_0 = W - a_0$ and η is a constant that depends on the specimen geometry.

Plotting the J vs Δa curve



1. Plot measurements on a J vs Δa curve.
2. Fit the data with a power law regression.
3. Find J_Q: the intersection between the power law regression and the 0.2 mm blunting line.

Test validity

The value of $J_Q = J_{Ic}$ if:

$$B, b_0 \geq \frac{25 J_Q}{\sigma_Y}$$

If this requirement is satisfied you can convert J_{Ic} to K_{Ic} with:

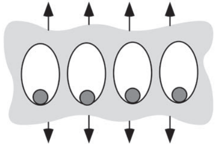
$$K_{Ic} = \sqrt{\frac{E J_{Ic}}{1 - \nu^2}}$$

With this procedure, you can have much smaller specimens and you get K_{Ic} and the R-curve with a single test.

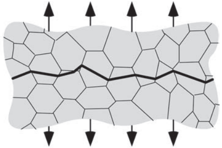
Outline

Fracture mechanisms in metals

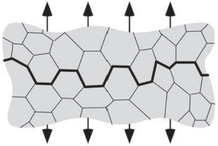
The most common fracture mechanisms in metals are:



Ductile fracture involves the nucleation, growth and coalescence of microvoids.



Cleavage is when the crack propagates along specific crystallographic planes.



Intergranular fracture is when the grain boundaries consitute the prefered crack path.

Outline

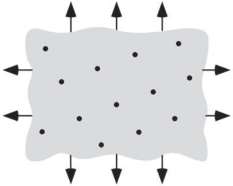
Ductile fracture

Ductile fracture is the most common fracture mechanisms in metals at room temperature. It involves three stages:

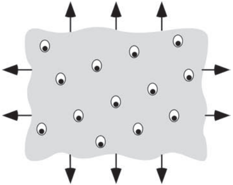
1. Inclusions break or debond from the surrounding matrix forming a void. This is called void nucleation.
2. These voids grow under plastic deformation.
3. Adjacent voids join together; this is known as void coalescence.

This process is illustrated next.

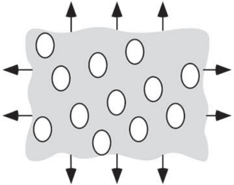
Ductile fracture process



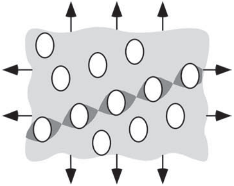
1. Inclusions in a ductile matrix



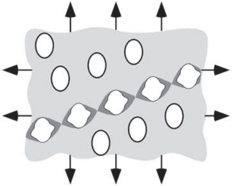
2. Void nucleation



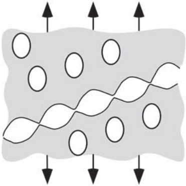
3. Void growth



4. Strain localisation between voids

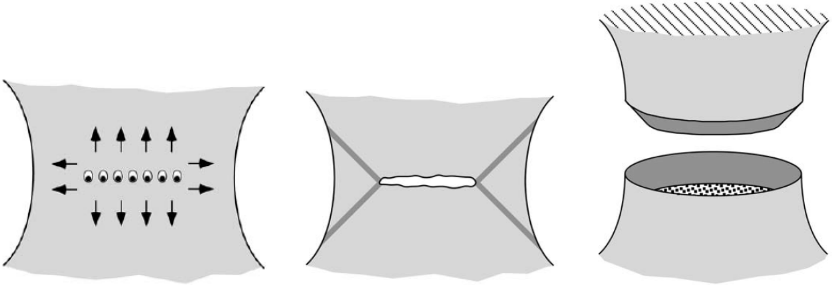


5. Necking between voids



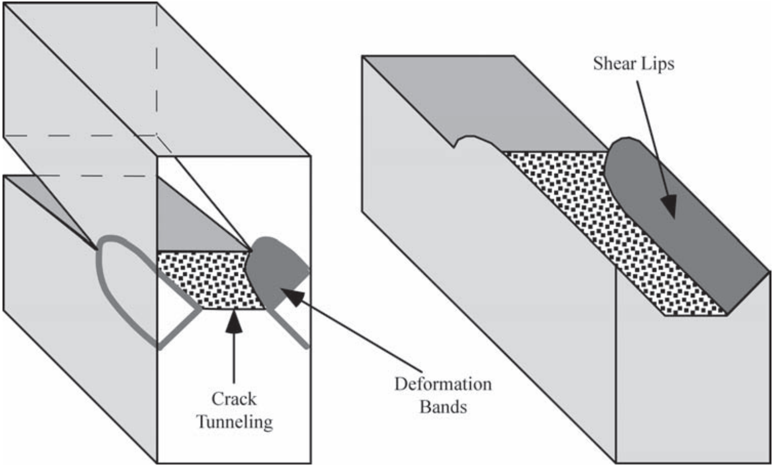
6. Void coalescence and fracture

Ductile fracture in tensile tests



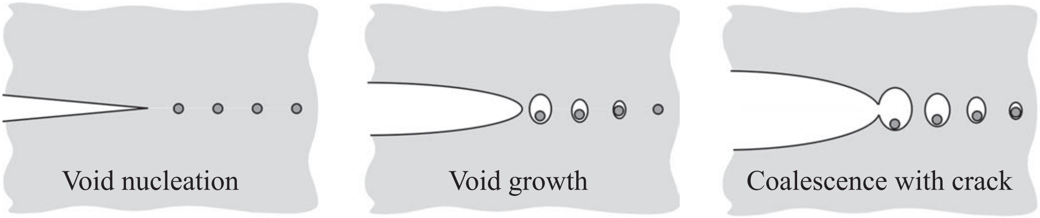
1. The triaxial stress state in the middle of the specimen promotes void nucleation and growth.
2. This leads to the formation of crack in the centre of the specimen. The crack leads to an accumulation of plastic strain along 45° bands.
3. This produces the cup and cone fracture surface observed in tensile tests.

Ductile crack propagation



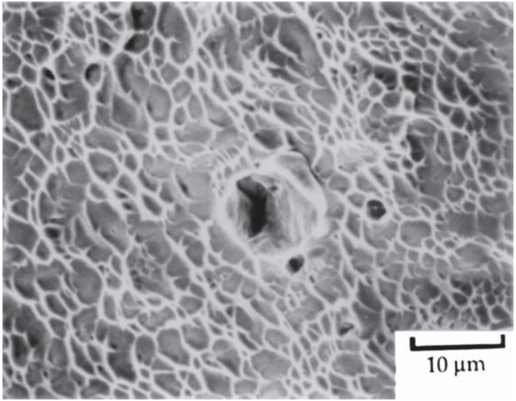
- Crack growth is flat and faster in the centre of the specimen. This is due to the higher stress triaxiality and known as crack tunneling.
- Closer to the free surfaces, the crack is often at 45°. These are called shear lips.

Ductile crack propagation



- Void nucleation and growth occurs at the crack tip because of the high stresses in this region.
- The crack grows when these voids link with the crack.
- Note how these voids also blunt the crack. This blunting effect is a cause of the rising R-curve of metals.

Fractography



Ductile fracture produces dimpled fracture surfaces. This is the fracture surface of a stainless steel.

Ductile fracture

There are multiple factors influencing the ductile fracture process:

- the volume fraction and dispersion of inclusions;
- the size and nature of inclusions;
- the stress state.

Should we remove all inclusions to increase toughness?

- Pure metal are very ductile, but have a very low yield strength so it is not a good idea to remove inclusions.
- Inclusions are also favorable for other properties such as manufacturability and resistance to corrosion.

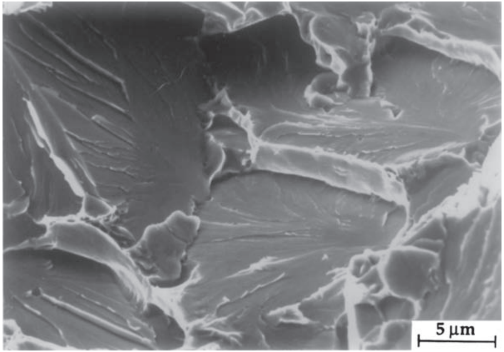
Outline

Cleavage

Cleavage is when a crack propagates rapidly along a particular crystallographic plane.

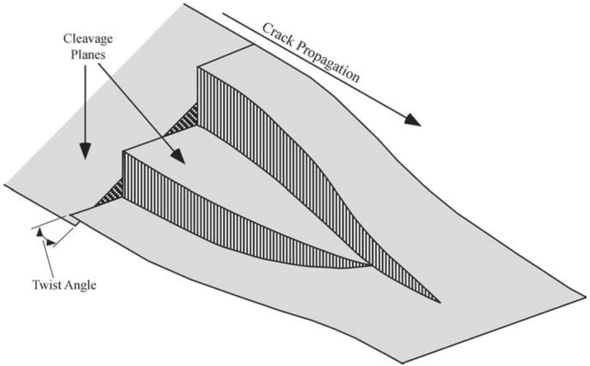
- Cleavage occurs along planes that have a low packing density (fewer bonds to break).
- Usually brittle, but may be preceeded by ductile crack growth.
- Cleavage typically happens when plasticity is restricted; for examples, at low temperatures.

Fractography



Cleavage produces multiple flat surfaces, where each facet corresponds to a grain. The thin lines on each facet are known as river patterns.

Formation of river patterns



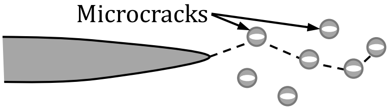
When a cleavage crack encounters a grain boundary, it has to change its orientation to follow the cleavage plane. This change in orientation produces the river patterns.

Cleavage

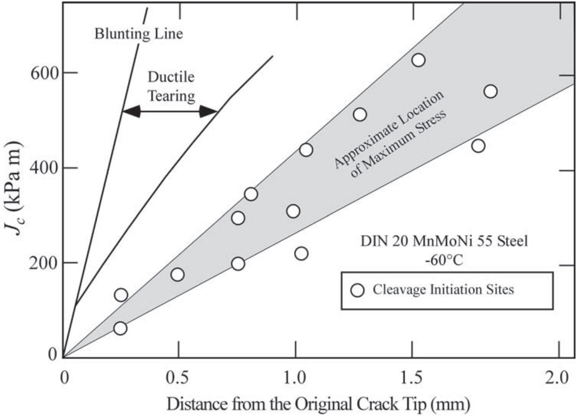
If cleavage is breaking atomic bonds along a specific crystallographic plane, can we capture this with an atomic model (see week 1)?

No, an atomic model would still be too strong.

For a cleavage crack to propagates, there needs to be additional microcracks providing a sufficient local stress concentration.



Cleavage fracture toughness



For cleavage, fracture toughness measurements are widely scattered. This is because the distance between the crack tip and the first large microcrack can vary significantly.

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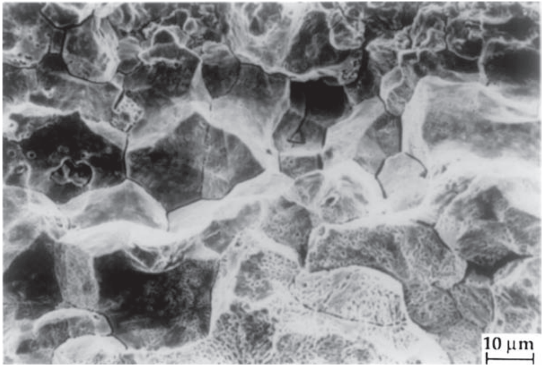
Intergranular fracture

Intergranular fracture is when the crack propagates along the grain boundaries. This is rare in metals, but it may occur in special circumstances such as when:

- the material is in a harsh environment, exposed to corrosion or radiation for example.
- a brittle phase accumulated at the grain boundaries.
- cavitation and cracking occured at the grain boundaries due to high temperatures.

Fractography

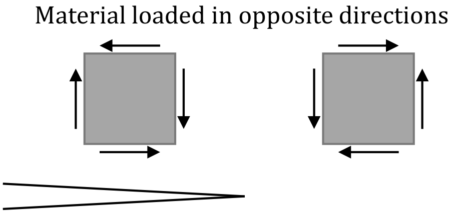


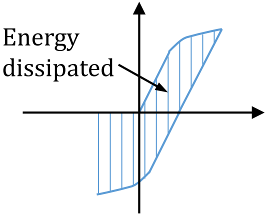
Intergranular fracture in a steel weld that was in contact with ammonia.

Outline

Why metals have a rising R-curve?

- Material ahead of the crack tip is loaded in one direction while material behind the crack is loaded in the other direction.
- When the crack advances, some material experiences a change in loading direction.
- This change dissipates energy by hysteresis.

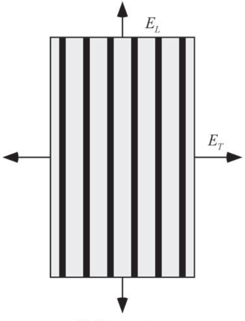


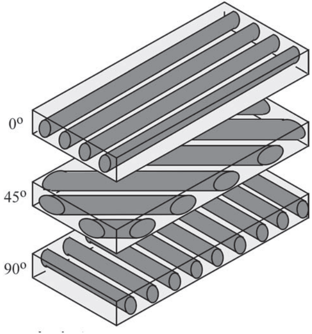


Outline

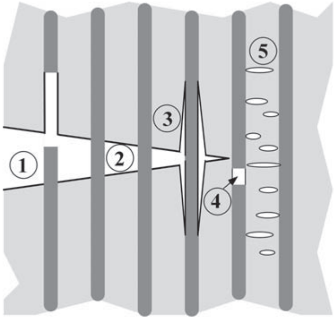
Fibre-reinforced composites

Carbon fibre reinforced composites are replacing metals in multiple lightweight applications. They exhibit very different fracture mechanisms than metals.





In-plane mechanisms



The most important mechanisms in plane are:

1. Fibre pull-out
2. Fibre bridging
3. Fibre/matrix debonding
4. Fibre failure
5. Matrix cracking

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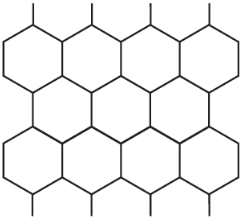
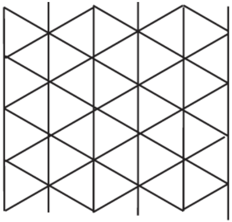
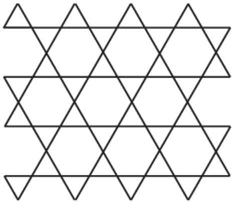
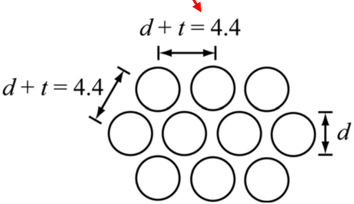
Lattice materials

- Lattices are interconnected arrays of beams.
- They can be made from any existing material.
- Combine high stiffness and high strength at low densities.

Geometry



Dimensions in mm

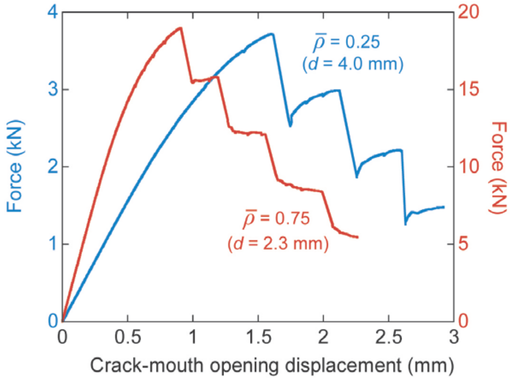
Relative density: $\bar{\rho} = 1 - \dfrac{\sqrt{3}\pi d^2}{6(d+t)^2}$

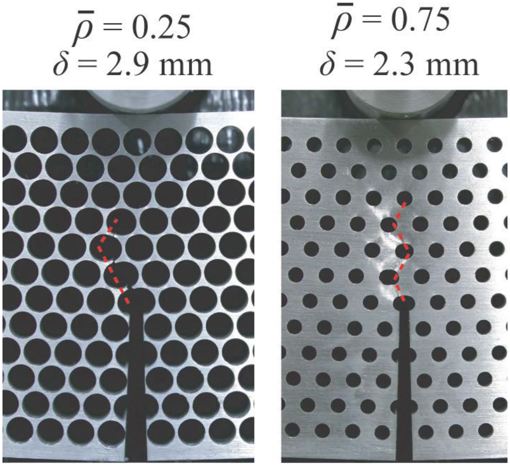
Dimensions of the specimens tested:

d (mm)	4.2	4.0	3.2	2.3	1.0
$\bar{\rho}$	0.17	0.25	0.52	0.75	0.95

Made by drilling holes in aluminum.

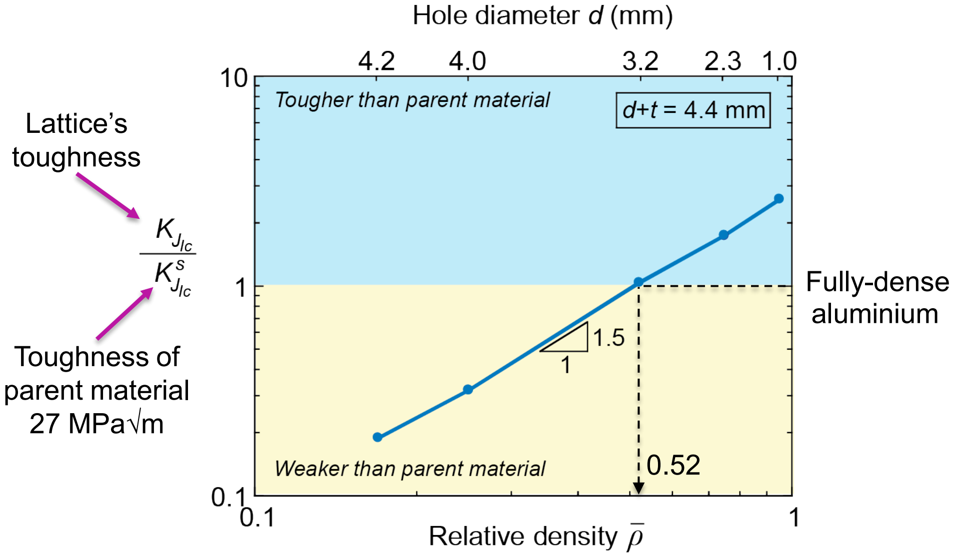
Toughness test





Each step in the load-displacement curve corresponds to a cell wall breaking.

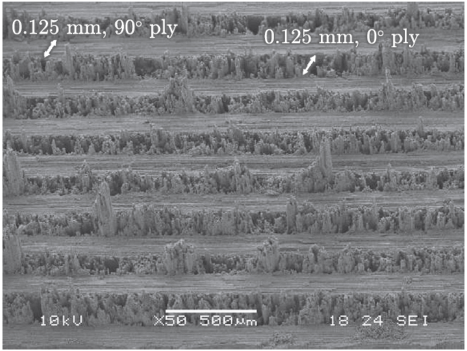
Results



- The lattice can be 50% lighter than aluminum and maintain the same toughness.

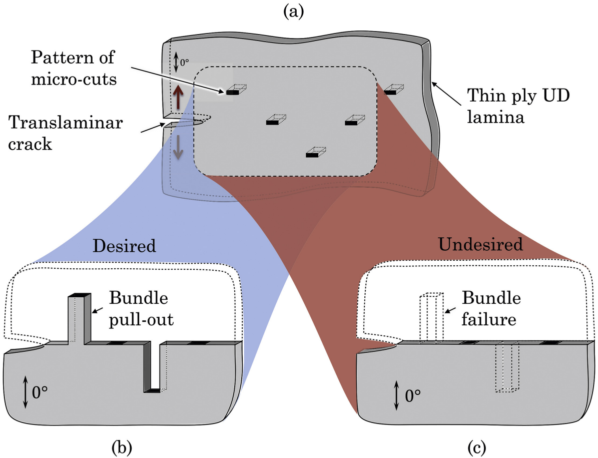
Outline

Motivation

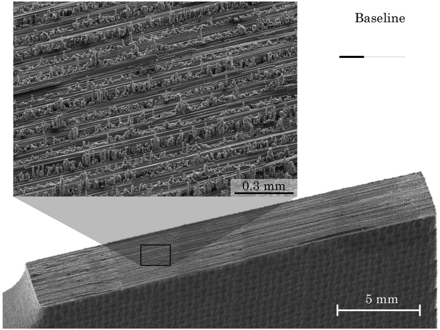


- A lot of energy is dissipated by fibre pull-out.
- Can we increase the pull-out length?

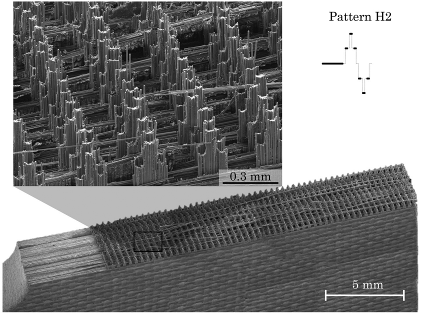
Method



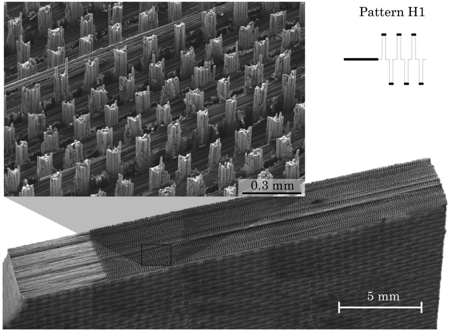
Provide a pattern of laser micro-cuts to guide the crack and increase the pull-out length.


Baseline
0.3 mm
5 mm

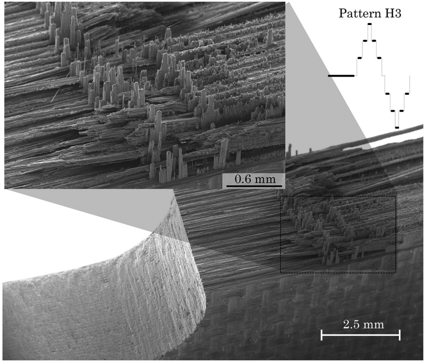
(a)


Pattern H2
0.3 mm
5 mm

(c)

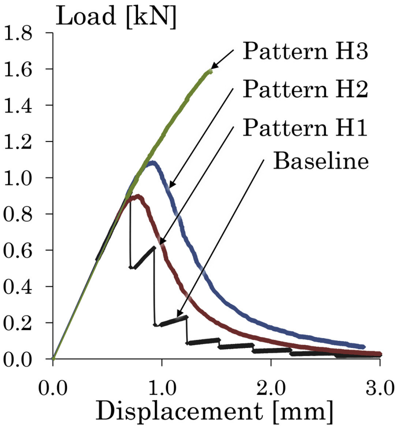

Pattern H1
0.3 mm
5 mm

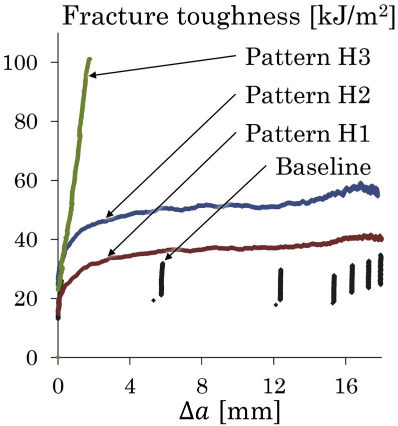
(b)


Pattern H3
0.6 mm
2.5 mm

(d)

Results





- Patterns H1 and H2 have stable crack growth while the baseline exhibit unstable crack growth.
- Increase in toughness of up to 200%.
- See Bullegas et al. (2016) Engineering the translaminar fracture behaviour of thin-ply composites.

Summary

- There is a strict protocol to measure the fracture toughness of metals: fatigue precrack, specimen geometry, and size requirements.
- Ductile fracture is the most common mechanism in metals. Cleavage and intergranular fracture can occur at low temperatures or in harsh environments.
- Several toughening mechanisms can lead to a rising R-curve: plasticity, crack tip blunting, fibre bridging, and/or fibre pull-out. These mechanisms can be exploited to design tougher materials.