Bike Frames

Monday, January 6, 2025 5:53 PM

Bike Frames Day 1 Learning objectives

- Understand the history of bicycle frames from a materials perspective
- Identify the key differences between metals, ceramics, composites

Bike Anatomy

https://images.contentstack.io/v3/assets/blt964243cdd7810dea/bltf91ef9d568536952/62140bd6cf85c1619ad89e26/bike -anatomy-bike.jpg

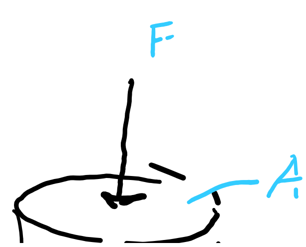
Frame: the main part of the bike that everything else is fastened onto
- Many variations, but most bikes have the "diamond frame" made up of two triangles

Group activity:

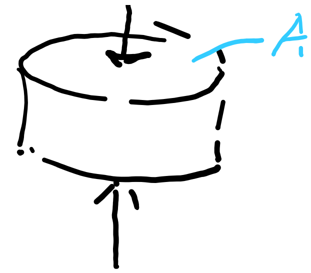
1. What is the job that the frame must fulfil?

keep it together
durable / stable / impact
lightweight
distribute weight
comfortable
corrosion resistant
fatigue resistant

stress = $\frac{\text{force}}{}$



stress = $\dfrac{\text{force}}{\text{area}}$



density = $\dfrac{\text{mass}}{\text{volume}}$

Force = mass · acceleration

strain = $\dfrac{\text{change in length}}{\text{intial length}}$

$\sigma = E\varepsilon$ $\qquad E = \dfrac{\sigma}{\varepsilon}$ (σ: stress, ε: strain)

E = elastic modulus = "stiffness"

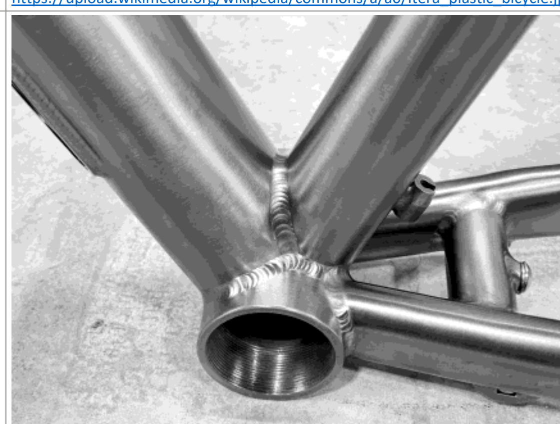
Key properties the frame should consider

- Density (weight)
- Strength (weight, crash-worthiness)
- Corrosion resistance (rust, paint)
- Vertical stiffness, lateral stiffness (comfort, energy efficiency)
- Shapes and formability (internal routing of cables, different geometries, joining)

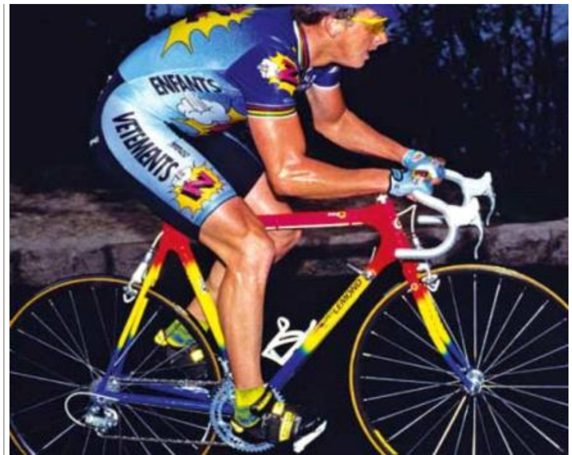
- Elongation (crash-worthiness)
- Fatigue limit and endurance limit

History of bike frames

1817: - The "Draisine" or "laufmaschine" (precursor to the modern bike) was made of wood.	 https://wide.piaggiogroup.com/articles/products/duecento-anni-in-bicicletta-dalla-draisine-alla-wi-bike/foto1-small.jpg
1820s-1850s: - 3 and 4 wheelers. - Less balance required. - Introduction of pedals, treadles, hand-cranks. - First pedal crank appears in 1853. - "Penny farthing" design with solid rubber tires and high speeds	 https://upload.wikimedia.org/wikipedia/commons/7/70/Bicycle_two_1886.jpg
Late 1800s: - Steel tubing introduced. - Wire spoke tension wheels. - Shift from expensive toy to utilitarian transportation "Safety bicycle." - Diamond frame invented by Isaac R. Johnson. - Step through frames.	 https://upload.wikimedia.org/wikipedia/commons/4/48/Whippet_Safety_Bicycle.jpg

1900 - 1940s: - Aluminum frames become popular. - Single tube with no lugs. - "Lu-Min-Num" bike model out of St. Louis Refrigerator and Gutter Co.	 https://jeffreyrubel.substack.com/p/the-aluminum-bike-frame
1970s: - plastic bikes "Itera" - Plastic everything! Chains, hubs, spokes etc - Claim: "17 lbs and stronger than steel…" - Not a commercial success	 https://upload.wikimedia.org/wikipedia/commons/a/a0/Itera_plastic_bicycle.jpg
1990s: - Titanium frames - Full suspension 1992 Gary Fischer RS-1	 https://www.unicorncycles.com/titanium-road-gravel-bike-frames

Modern era:
- Carbon fiber dominates high-performance bikes.
- 1991 first appears on the Tour de France.



Group activity:
1. What drove the changes in materials used in each case?
2. What will e-bikes do to change materials used?

How do the properties of metals vs ceramics vs composites compare?

Metals are typically…

Ceramics are typically…

Plastics are typically…

Composites are materials made up of two or more different classes of materials typically to get the "best of both worlds"

Group activity:
1. Which material would you expect to have **strongest** bonds?
2. Why is steel so heavy while aluminum is so light? Why is titanium somewhere in-between?

Bike Frames Day 2 Learning objectives

- Define basic terms and equations for mechanical properties (stress, strain, density, stiffness etc)
- Describe advantages and disadvantages of steel vs aluminum vs titanium vs carbon fiber bike frames
- Explain how atoms arrange themselves into repeating arrangements
- Identify unit cells and a draw a simple face-centered cubic cell
- Calculate theoretical density
- Differentiate alpha from beta titanium and describe their associated properties
- Describe the fundamentals of composite materials
- Compare different non-destructive testing approaches for analyzing composite bike frames

Some useful science definitions

Force (F): A push or pull on an object.

$$Force_{Net} = mass * acceleration$$
$$F = ma$$

- **On Earth**: To find the force due to weight, use $F = mg$ where $g = 9.8\, m/s^2$(Earth's gravity).
  Example: A 10 kg object has a force of F=10×9.8=98 Newtons ($N = kg\ m/s^2$)

Stress (σ): How much force is applied to a certain area.

$$\sigma = \frac{F}{A}$$

A is the area over which the force is applied
The units would be Newtons/meter squared which is a Pascal ($Pa = N/m^2$)

Strain (ϵ): How much something stretches or changes shape compared to its original size.

$$\epsilon = \frac{\Delta l}{l_{initial}} = \frac{l_{final} - l_{initial}}{l_{initial}}$$

No units! We usually report it as a percent

Stiffness (aka Elastic Modulus, E): How hard it is to stretch or bend something.

$$E = \frac{\sigma}{\epsilon}$$

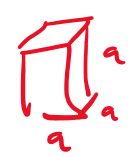
Pa
no units

Since strain is unitless, stiffness has the same units as stress. Pa
$1\ MPa = 1{,}000{,}000\ Pa = 10^6\ Pa$
$1\ GPa = 1{,}000{,}000{,}000\ Pa = 10^9\ Pa$

Density (ρ): How dense stuff (mass) is packed into a certain amount of space (volume)

$$\rho = \frac{m}{V}$$

Units are usually grams/cubic centimeter or g/cc or kg/m^3
Water has a density of 1 g/cc



a^3

Yield strength (σ_{yield}): The stress at which a material starts to deform permanently.
Before this point, the material will return to its original shape when the force is removed
After this point, when the force is removed you are left with some permanent deformation
Same units as stress (Pa)

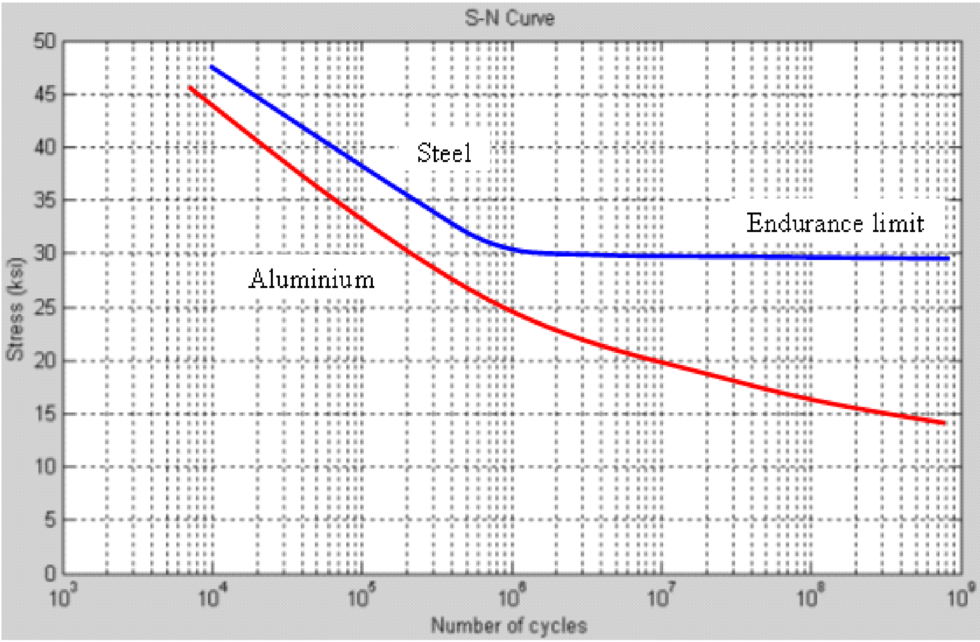
Ultimate tensile strength (σ_{UTS}): The maximum stress a material can handle before breaking.

Specific strength: A measure of how strong a material for its weight

$$\frac{\sigma}{\rho}$$

Fatigue: When a material breaks or fails after being repeatedly loaded and unloaded **even at stresses less than** the ultimate tensile strength

Fatigue Limit (Endurance limit): The maximum stress a material can endure indefinitely without breaking, even under repeated loading.



Pros and cons of specific materials

Steel:

- Pro: High strength, low cost, easy to repair. Cons: Heavy and prone to rust (unless alloyed).
- Corrosion resistant variations (chromoly 4130, "Reynolds 531")
  - If you don't know if steel is high quality or not, tap on it with fingernail and listen for ring (high-quality) or thunk (low quality).
- Decent vibration damping for good ride "feel"
- Joining tubes
  - Classically connected with lugs (thick sections the tubes slide into) where tube is brazed onto the lug. Easy to repair/replace.
  - Welding also possible. Care to ensure the welding won't weaken the steel (more on this later)
- Butted tubing can reduce weight and increase cost
- **Fatigue limits** ~0.3-0.6 of yield strength
- New super steel alloys causing a bit of a comeback for steel. For example, Reynolds 531 invented in 1935 had tensile strength of ~800MPa but Reynolds 853 released in ~2000 is air-hardened (so you can weld it) and has strength of 1200MPa, next gen Reynolds 953 has strength up to 2000MPa!
- Typical density 7.85g/cc, stiffness ~200GPa, strain 25% for 4130 (10-15% for low quality steel), strength 460MPa yield, 560MPa ultimate,

Aluminum:

- Pros: Lightweight, corrosion-resistant, affordable. Cons: Lower fatigue resistance and stiffness.
- Better overall strength to weight ratio than steel
  - Optimal is actually 200:1 diameter to wall thickness ratio but this would be like a beverage can; too fragile for impacts so larger tubes are used impacting aerodynamics but improving resistance to impacts.
- No fatigue limit, so the material gets weaker as it's cycled due to microcrack growth
- Challenging to join (TIG welding possible)
- Not always lighter than steel
- Typical density 2.7g/cc, stiffness 70GPa, strain 6-12%, strength 270MPa yield, 310MPa ultimate,

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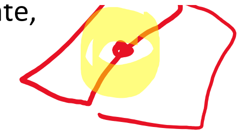
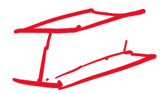


Titanium:

- Pros: Corrosion-resistant, durable, and lighter than steel. Cons: Expensive and harder to work with.
- Most common alloys is Ti-3Al-2.5V (3% Al, 2.5% V) followed by Ti-6Al-4V (6% Al, 4% V)
- Tubes can be cold-drawn and hydroformed into many complex shapes for internal cabling.
- TIG required because prone to bad welds and breakage
- Not as stiff, a bit "flexy"
- Typical density 4.58g/cc, stiffness 100GPa, strain 15-30%, strength 500MPa yield, 620MPa ultimate,

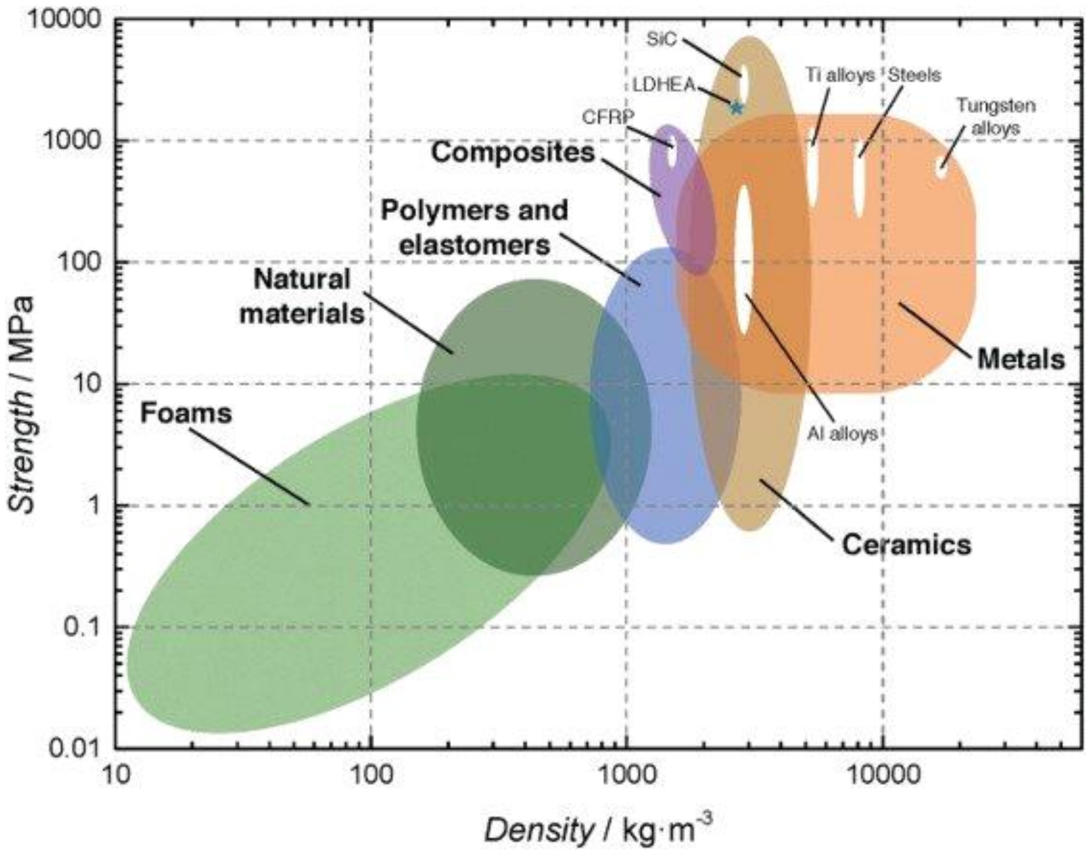


Carbon Fiber:

- Pros: Extremely lightweight, high stiffness, customizable. Cons: Expensive, less durable under impact, harder to recycle.
- **Anisotropy** possible (different properties in different directions). Can achieve low vertical stiffness, high lateral stiffness.
- Prone to damage even from overtightening or improper installation of parts
- Cracking at interlaminar regions or adhesion points
- Can add other additives like metallic boron, graphene, kevlar etc to modify properties
- Typical density 1.55g/cc, stiffness 130GPa (Very anisotropic!), strain 2% (Achilles heel), strength 2500MPa ultimate (but only along fiber direction!)

Other materials?

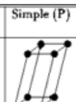
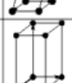
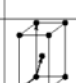
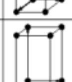
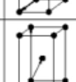
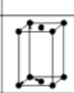
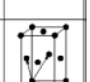
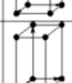
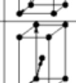
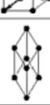
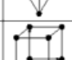
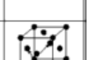
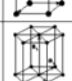
- Magnesium. A few bikes are made of this alloy. It has 64% density of Aluminum so you can get real weight savings.
  - In 1980s Frank Kirk designed a die cast one piece made of I-beams rather than tubes! Out of business 1992. Not really a popular option.
- Sc alloys. This is aluminum with a very small amount of Scandium (0.5%) so this is mostly marketing. It does improve welding characteristics and fatigue resistance allowing smaller tubes and more frame design options.
- Bamboo and wood, but these are uncommon.
- Combinations of materials for different components in the bike is very common

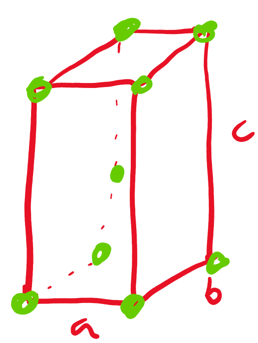


Unit cells

Most matter organizes into periodic arrangements of atoms. We call these **crystalline** materials or crystals even if they don't look like gemstones. There are a variety of different ways that we can arrange matter into repeating patterns. The smallest repeating pattern is called a **unit cell**.

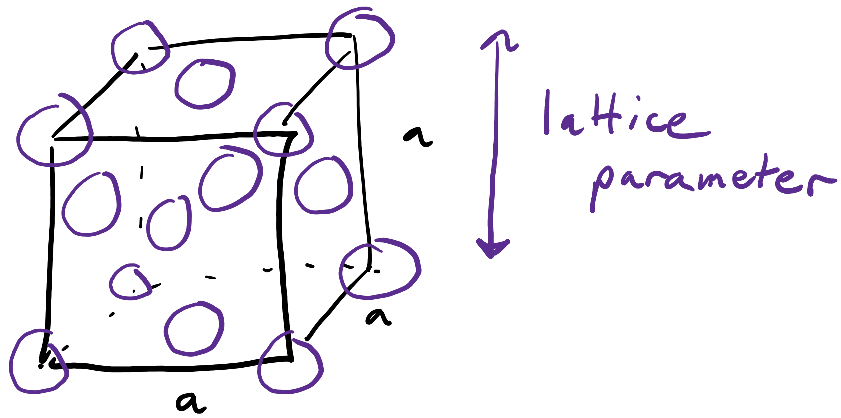
There are 14 different **Bravais Lattices** for arranging matter. The 14 Bravais lattices are found across seven different **crystal systems** by including 4 different **centering** types.

Bravais lattice	Parameters	Simple (P)	Volume centered (I)	Base centered (C)	Face centered (F)
Triclinic	$a_1 \neq a_2 \neq a_3$ $\alpha_{12} \neq \alpha_{23} \neq \alpha_{31}$				
Monoclinic	$a_1 \neq a_2 \neq a_3$ $\alpha_{23} = \alpha_{31} = 90°$ $\alpha_{12} \neq 90°$				
✓ Orthorhombic	$a_1 \neq a_2 \neq a_3$ $\alpha_{12} = \alpha_{23} = \alpha_{31} = 90°$				
Tetragonal	$a_1 = a_2 \neq a_3$ $\alpha_{12} = \alpha_{23} = \alpha_{31} = 90°$				
Trigonal	$a_1 = a_2 = a_3$ $\alpha_{12} = \alpha_{23} = \alpha_{31} < 120°$				
Cubic	$a_1 = a_2 = a_3$ $\alpha_{12} = \alpha_{23} = \alpha_{31} = 90°$				
Hexagonal	$a_1 = a_2 \neq a_3$ $\alpha_{12} = 120°$ $\alpha_{23} = \alpha_{31} = 90°$				



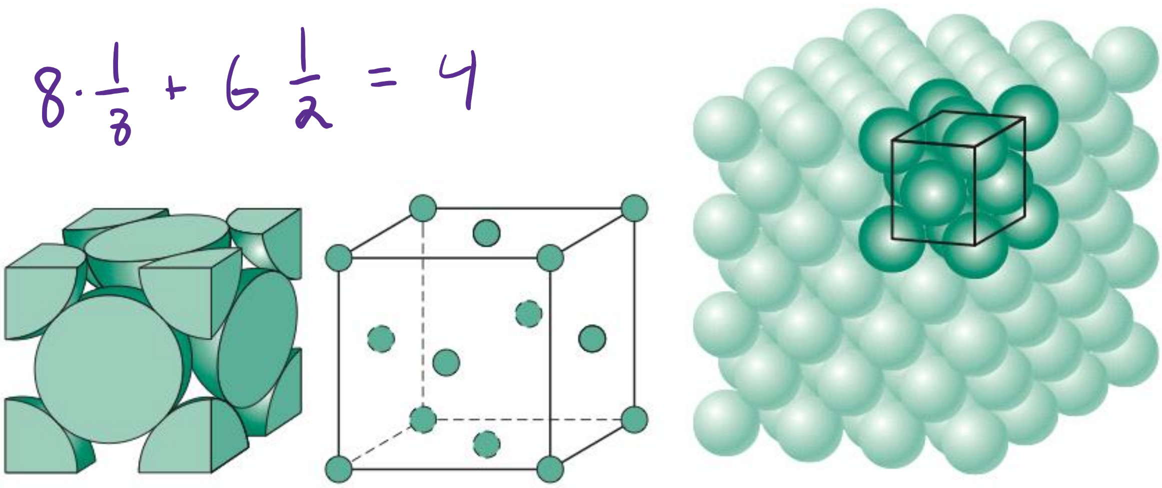
https://www.goseeko.com/blog/what-is-bravais-lattice/

Aluminum is a simple metal structure known as **Face-Centered Cubic or FCC**. It's one of the 14 Bravais Lattices.



$1 + 3$

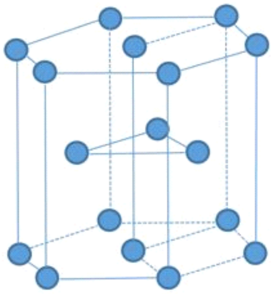
$8 \cdot \frac{1}{8} + 6 \frac{1}{2} = 4$



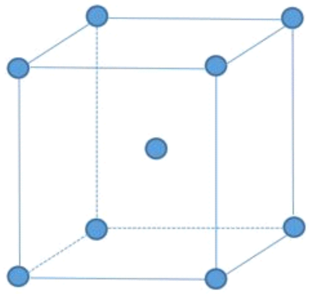
The unit cell side length is known as the **lattice parameter** and if we know the size of the metal atom and assume **close-packing** then we can estimate the lattice parameter.

There are thousands of other different **crystal structures** and these can have way different properties!

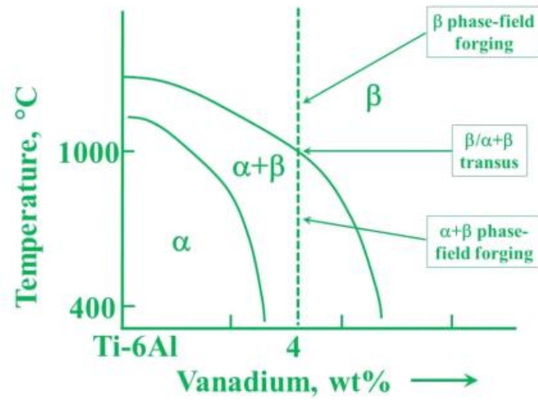
For example, titanium alloys come in two flavors the **brittle** and hard alloys or the soft and **ductile** ones



Hexagonal close-packed crystal structure (HCP)



Body-centered cubic crystal structure (BCC)



Theoretical density calculation

If we know what atoms occupy the sites in a lattice, then we can calculate the theoretical density of the crystal

Volume of cube $= a^3$

Mass of atoms $= \dfrac{\#\text{ atoms} \cdot M_w}{A_N}$

Avogadro's number: 6.023×10^{23} # of something per **mole** of substance

A mole is just a way to count very, very tiny things, like a "dozen" is used to count 12 items.

$$\rho = \frac{m}{V} = \frac{4 \text{ Al atoms} \cdot 26.98 \text{ g/mol}}{6.023 \times 10^{23} \frac{}{\text{mol}} \left(4.046 \times 10^{-8} \text{cm}\right)^3}$$

Group activity:

1. Why do materials not typically reach their theoretical density?

Alloying to achieve lightweight metals

Some metals we use in their pure form, but others we intentionally mix with other components to form an **alloy**. We alloy metals for different reasons. For solders we form alloys to lower the melting point. For "sterling silver" we add copper to silver in order to increase the hardness of the jewelry (while also reducing the cost). When we alloy materials the lattice parameter usually changes size since the atoms are different sizes. The two metals can be **randomly distributed**, or they can form an **ordered intermetallic**.

Phase diagrams help us find the limits of **solubility** so we know to what extent we can form an alloy without forming additional **phases**.

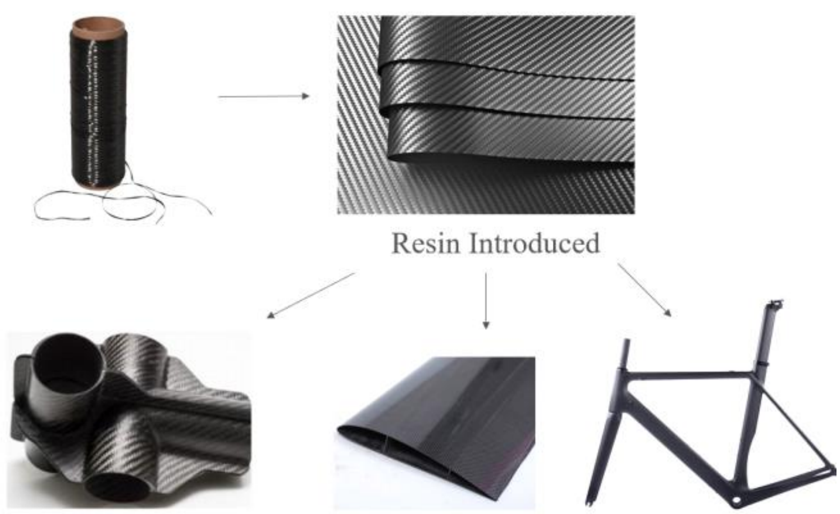
How do carbon fiber composites achieve such incredible specific strength?

Composites: A composite is a material made by combining two or more different materials to create something stronger, lighter, or better in some way.

- **Matrix (resin)**: The "glue" that holds everything together (usually a plastic, but can also be glass, metal or even ceramic!)
- **Reinforcement**: The "strengthener" that makes the composite stronger (like fibers, particles, or layers)

Carbon Fiber composites

- Matrix: **epoxy resin** (a plastic that starts as a liquid and turns into a hard, durable material when mixed with a special chemical called a **hardener**.
- Reinforcement: **carbon fibers** (super strong and light, but only in the fiber long axis direction)
  - A single carbon fiber is typically 5-10 micrometers in diameter (about 10 times thinner than a human hair, $1 micrometer = 1\mu m = 1 \times 10^{-6} m$).

- If you want strength in more than one direction, then you need fibers pointing in more than one direction, thus carbon fiber composites use weaved layers assembled into layers
- 

There is a lot more about composites that we won't cover yet, but we'll come back to them in future sports

- How are carbon fibers made?
- What options are there for epoxies?
- How do we assemble the overall carbon fiber composite?
- What other fiber options are possible?
- What about continuous vs discontinuous fibers?
- What type of layers and weaves are used?

How do we inspect composite bike frames to make sure they are safe?

Chris froome's descent.. Goooo!!!!!!!

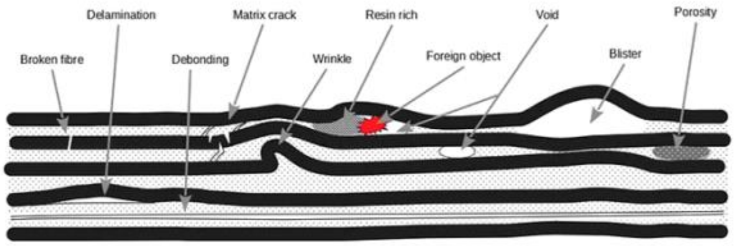
Rahul NA

Group activity:

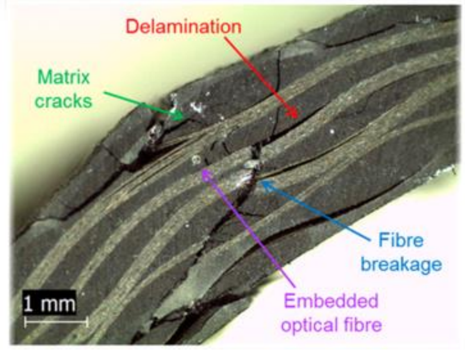
What would **you** do to give you confidence to go crazy fast on a new composite bike frame?

Sparks Research Group grad Mitch Child was passionate about carbon fiber bikes!

Many different defects can occur during fabrication of carbon fiber composites



https://www.addcomposites.com/post/defects-and-damage-in-composite-materials-and-structures



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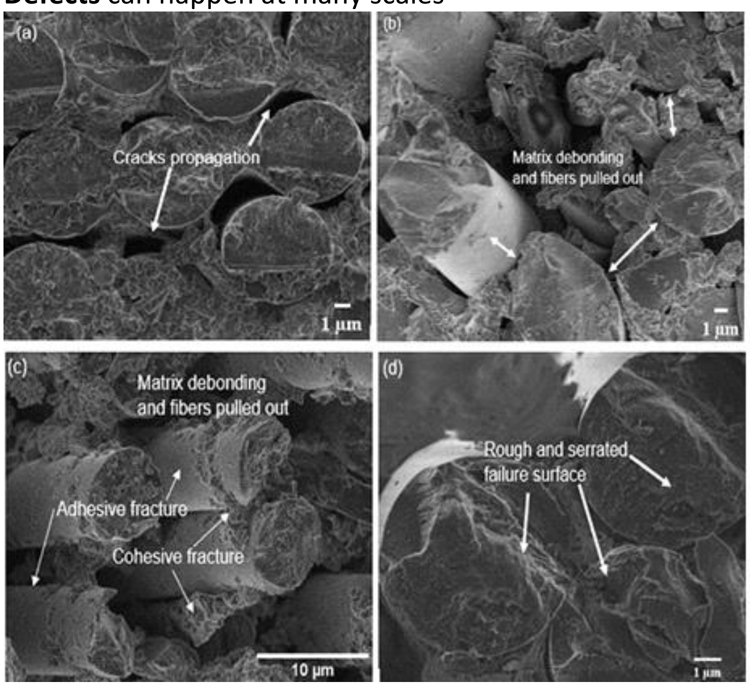
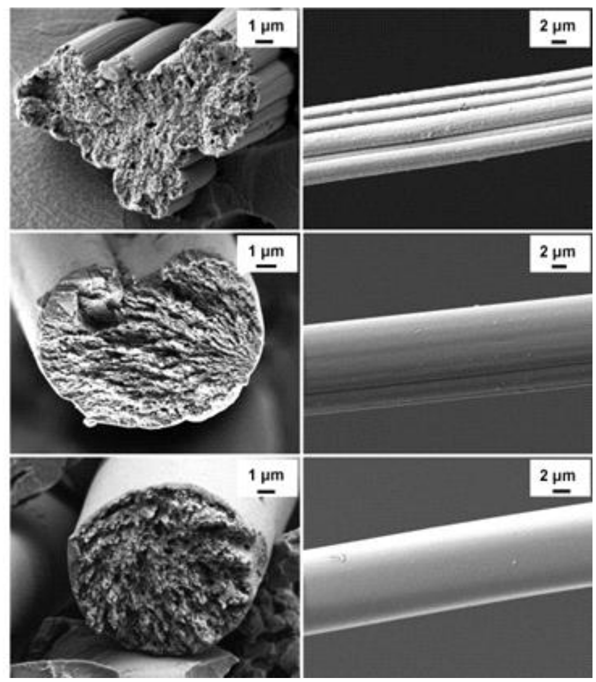
Defects can happen at many scales





How can we test for flaws inside the material?

Non-destructive testing

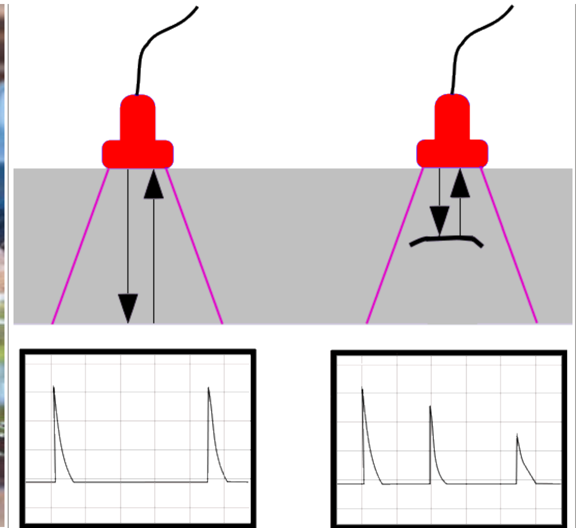
- Ultrasonic testing
- Computed tomography
- X-ray Radiography

Destructive testing

- Serial sectioning (cut the component into thin sections and examine each)
- Tensile and other strength testing

Ultrasonic testing relies on sound waves hitting a flaw and bouncing back. The time is measured between when the wave is sent and the reflection received to determine if a flaw is present


https://www.spartan.edu/wp-content/uploads/2022/01/NDT-tech-using-prob.jpg


https://www.wermac.org/others/others_img/ndt_ut1.gif

Computed tomography

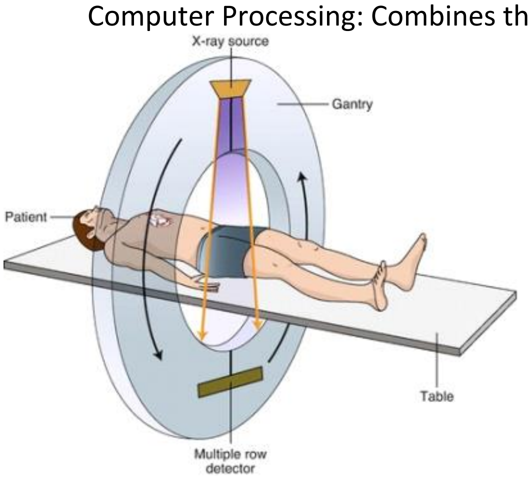
What it is: CT uses X-rays to create detailed 3D images of the inside of an object without cutting it open.

How it works:

X-ray Source: Sends X-rays through the object.

Detector: Captures the X-rays that pass through, creating 2D images from different angles as the object rotates.

Computer Processing: Combines these 2D images into a detailed 3D model of the object.



How does it identify flaws in carbon composites?

Density Variations: CT scans detect small changes in density, which show up as differences in the X-ray absorption.

Flaws: Voids (air pockets), cracks, or delaminations (layers separating) have lower density than the surrounding material.

High Resolution: CT can visualize tiny flaws, even inside thick or layered composites.

3D Mapping: Flaws are located precisely within the structure, and their size, shape, and distribution can be measured.

X-ray Radiography

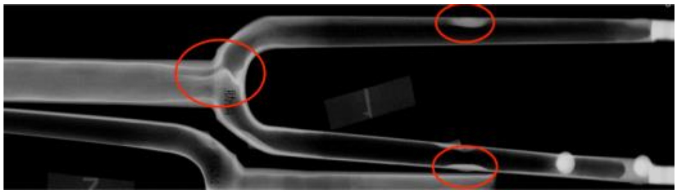
What it is: X-ray radiography uses X-rays to create 2D images of the inside of an object by showing how much the material absorbs the X-rays.

How it works:

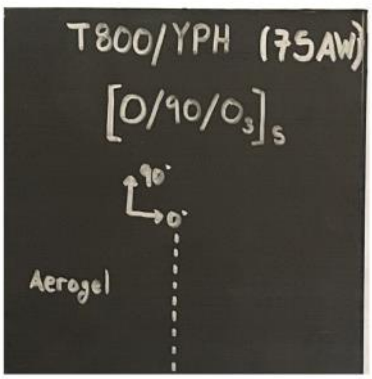
X-ray Source: Sends X-rays through the object.

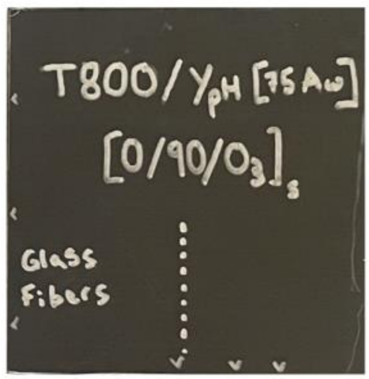
Detector/Film: Captures the X-rays that pass through, producing a shadow-like image.

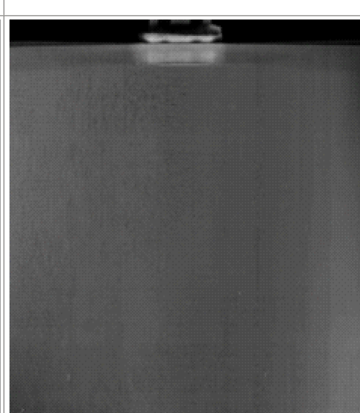
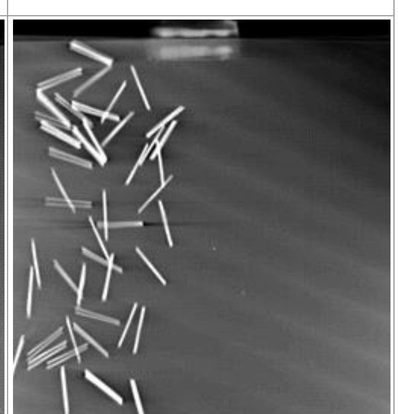
Result: The image shows areas with different densities. Dense areas (like solid fibers) block more X-rays and appear brighter, while less dense areas (like air pockets) appear darker.



Mitch was able to train **machine learning models** to identify flaws in X-ray Radiographs with much better accuracy than humans could do! Now he works for Specialized Bicycles





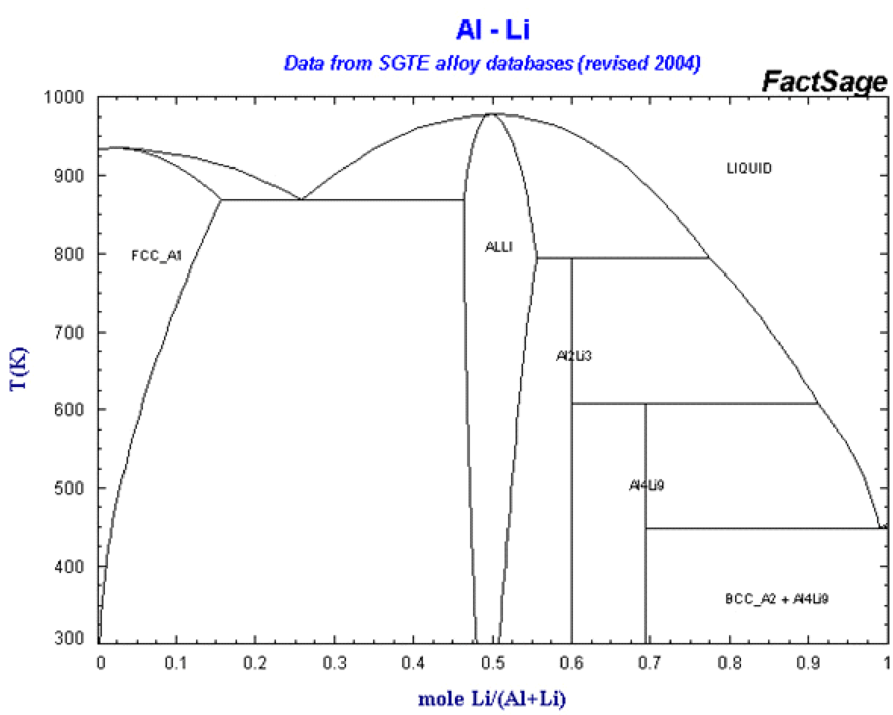
Teflon	Aerogel filler	Glass fibers
		
		

Next class:

 https://flatbike.com/wp-content/uploads/2018/06/tires-labeled.jpg	 https://static.evo.com/content/cms/guides/bike/5708_biketiregraphics_3.jpg

BONUS

Aluminum is already light, but what if we alloyed it with an even lighter element like lithium?



Lightweight alloys are extremely important for transportation applications. For example, in 2011 Polaris bought the Indian motorcycle brand and by 2015 had completely reinvented the original 1920 Indian Scout with a cast aluminum frame instead of steel. Despite having a smaller engine than a Harley Davidson Sportster (1133cc vs 1200cc) it delivers much more power (100hp vs 75hp) while weighing 100 lbs less. Ford's new F-150 has an aluminum body shaving off 15% of its weight while increasing fuel efficiency by 20% and expanding hauling capacity by 11%. Consider the Al-Li phase diagram. Li-Al alloys are important to aerospace industry largely because they are very light. For every 1% by weight of lithium added to aluminum reduces the density of the resulting alloy by 3% and increases the stiffness by 5%. This effect works up to the solubility limit of lithium in aluminum. (taken from Wikipedia page on Al-Li)