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of ENGINEERING

Material for Jet Engine Fan Blades

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Introductions

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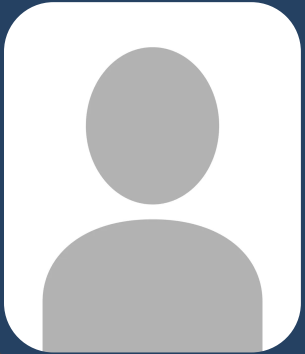

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Agenda

Material for Jet Engine Fan Blades

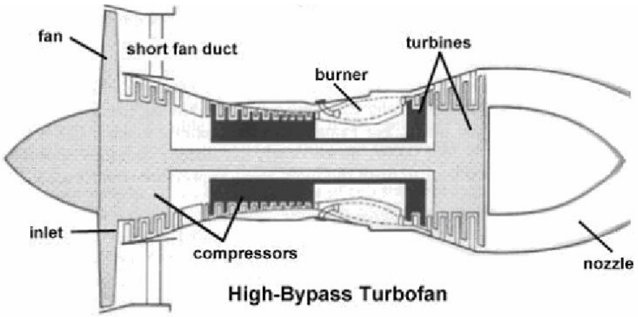
1. Problem Definition
2. Functions, Objectives, Constraints
3. Material Indices
4. Ashby Plots
5. Material Candidates
6. Material Selection
7. Considerations
8. Summary

Materials for Jet Fan Blades

Goal: Select a material for the jet engine fan blades

Function: High speed rotating fan blades that pump air

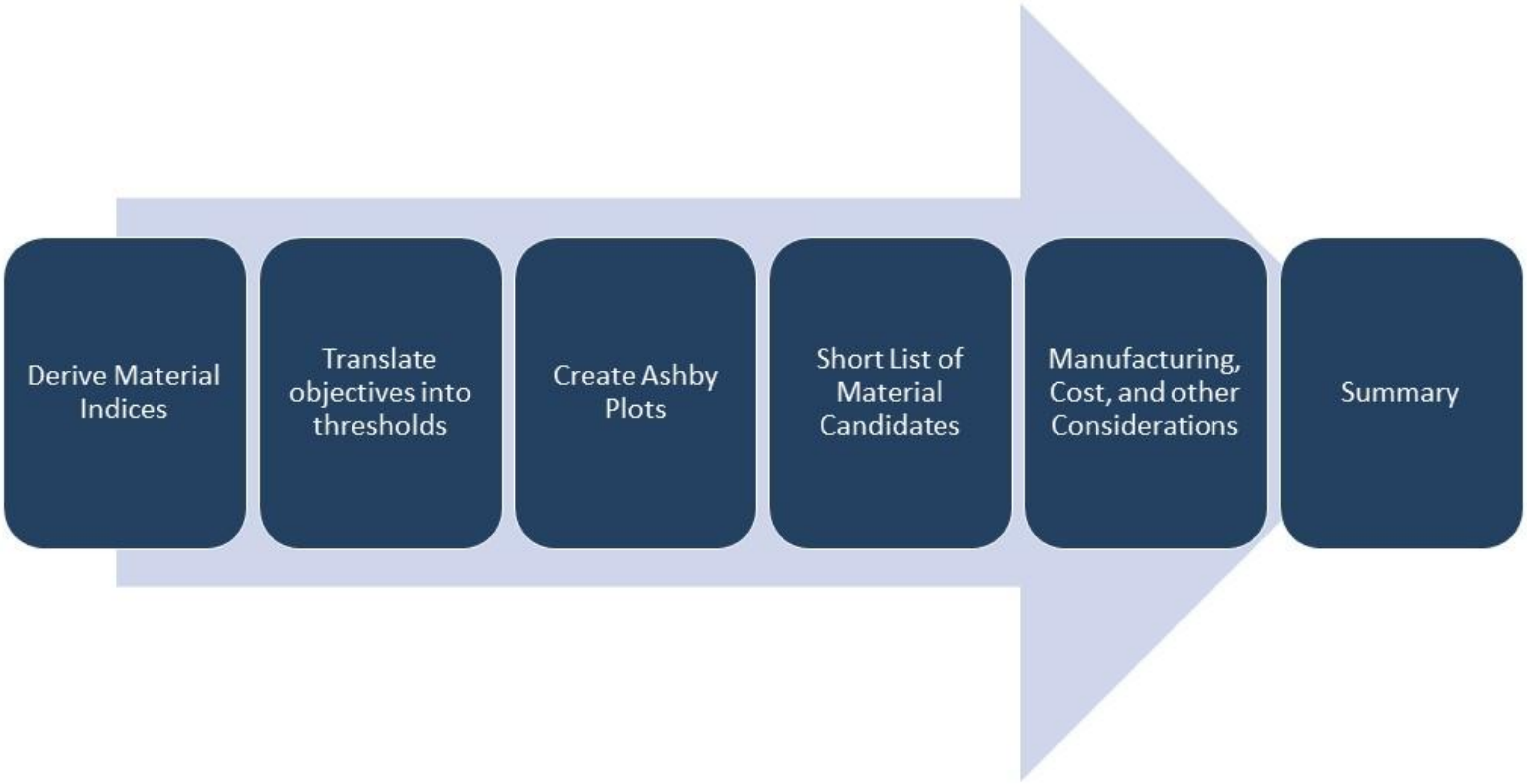
Assumptions: Model blade as a 24”x 6” x h” rectangular prism



Functions, Objectives, Constraints

Function	Jet fan blades that pump air, pushing jet
Objective	• Minimize the weight of each blade • The blade must not yield due to rotationally imposed stresses • Must bear centrifugal loads for at least 10,000 engine flights (high fatigue) • Stress intensity factor must be less than the fracture toughness (no fast fracture) • Minimize vibrational fatigue effects • Minimum operating temperature of 200℉
Constraints	• Ideally costs no more than $2000 • h is less than 0.80”
Free Variables	• Blade Cross Section • Material selection

Approach for Selecting Materials



Material Index 1: Temperature

Object: Operating Temperature of the Blade is 200°F

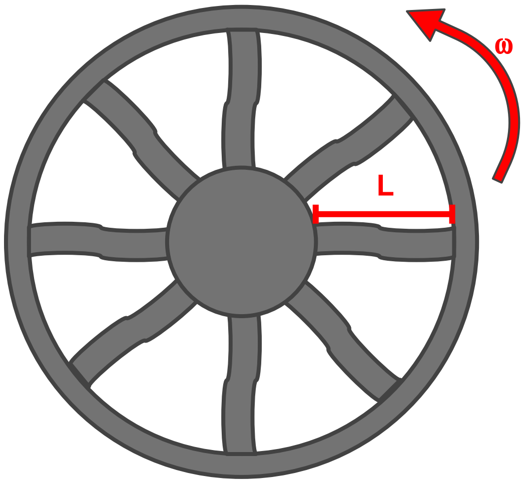
$$T_{operating} = 200^\circ F$$

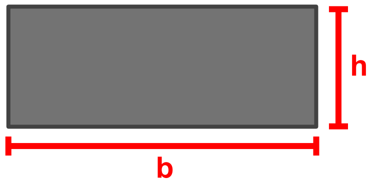
Materials must have a melting temperature above the operating, with a safety factor of 2 to minimize creep effects and enable higher engine performance.

$$\frac{T_{melt}}{2} \geq 200^\circ F \longrightarrow T_{melt} \geq 400^\circ F \longrightarrow \boxed{M_1 = T_{melt}}$$

M_1 : Materials must have a melting temperature above 400°F

Material Index 2: Yield Strength





Objects: Blade must not yield due rotational forces

- Yield stress is equal to the force divided by the area

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

- Force is variable across the blades with the radius

$$F = ma = \int \rho w h dr (\frac{v^2}{r})$$

Solving for specific yield stress:

$$\sigma_y = \frac{\frac{1}{2}\rho w h \omega^2 l^2}{wh} \longrightarrow \frac{\sigma_y}{\rho} \geq \frac{1}{2}\omega^2 l^2 \longrightarrow \boxed{M_2 = \frac{\sigma_y}{\rho}}$$

M_2 : must have a specific yield strength of 0.0184 MPa/(kg/m^3) or greater

Material Index 3: Ultimate Strength

Fatigue failure of a turbine blade

Objective: Blade must endure 10,000 engine flights

- It is assumed that if the loads are kept below half of the ultimate tensile strength of the material

$$\sigma \leq \frac{\sigma_{uts}}{2}$$

- Write the stresses in terms of the rotational loads

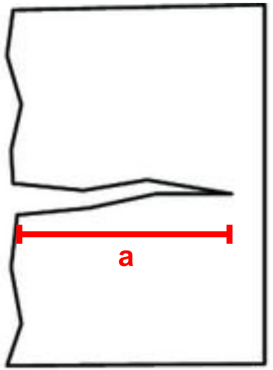
$$\sigma = \frac{1}{2}\rho\omega^2 l^2 \qquad \frac{\sigma}{\rho} \geq \frac{1}{2}\omega^2 l^2$$

Solving for specific ultimate strength:

$$\frac{\sigma_{uts}}{\rho} \geq \omega^2 l^2 \qquad M_3 = \frac{\sigma_{uts}}{\rho}$$

M_3 : Specific Ultimate strength must be at least 0.0368 MPa/(kg/m^3)

Material Index 4: Fatigue Fracture Resistance



Objective: Fracture resistance from foreign objects

- A surface crack of 0.02” crack must not propagate under cyclic loads

$$K_{IC} \geq Y\sigma\sqrt{\pi a}$$

- For a surface crack, Y=1.12 and using the same rotational loads

$$K_{IC} \geq 1.12(\frac{1}{2}\omega^2\rho l^2)\sqrt{\pi(0.02")}$$

Solving for specific fracture toughness

$$\frac{K_{IC}}{\rho} \geq 1.12(\frac{1}{2}\omega^2 l^2)\sqrt{\pi(0.02")} \longrightarrow \boxed{M_4 = \frac{K_{IC}}{\rho}}$$

M_4: specific fracture toughness must be at least 0.000823 MPa $m^{1/2}/(kg/m^3)$

Material Index 5: Vibrations

Objective : Minimize torsional vibration fatigue

- Shear modulus must be at least 25% of Young's Modulus

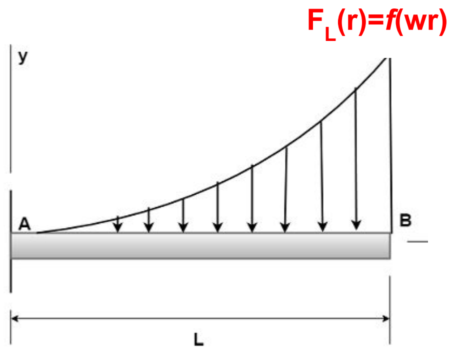
$$G \geq 0.25E$$

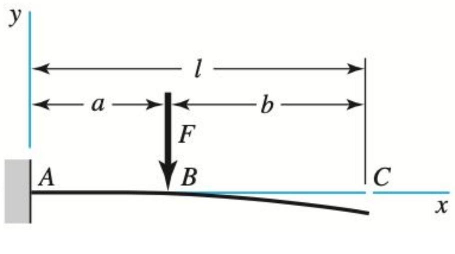
$$\frac{G}{E} \geq 0.25 \longrightarrow \boxed{M_5 = \frac{G}{E}}$$

Minimize effects of torsional vibration fatigue by keeping M_5 above 0.25

Note: The additional effect of torsional vibration will increase the cyclic stress developed in the turbine, reducing fatigue life. Thus, the blade will likely fail earlier than the predicted 10,000 cycles.

Material Index 6: Moment of Inertia





$$y_{\max} = \frac{Fa^2}{6EI}(a - 3l)$$

Objective: Minimize I (Moment of Inertia)

- The coefficient of lift can be defined as:

$$C_L = \frac{2F_L}{\rho u^2 S} \longrightarrow F_L = \frac{\rho(\omega r)^2 S C_L}{2}$$

- The total lift force due to the distributed load of the fluid on the blade:

$$F_{Tot} = \int_0^L F_L(r)dr \longrightarrow F_{Tot} = \frac{S C_L \rho \omega^2}{2}(\frac{1}{2}L^2)$$

- The maximum deflection for a cantilever beam with midspan force:

$$\delta_{max} = \frac{F_L(0.75L)^2}{6EI}(0.75L - 3L)$$

- Solving for moment of inertia:

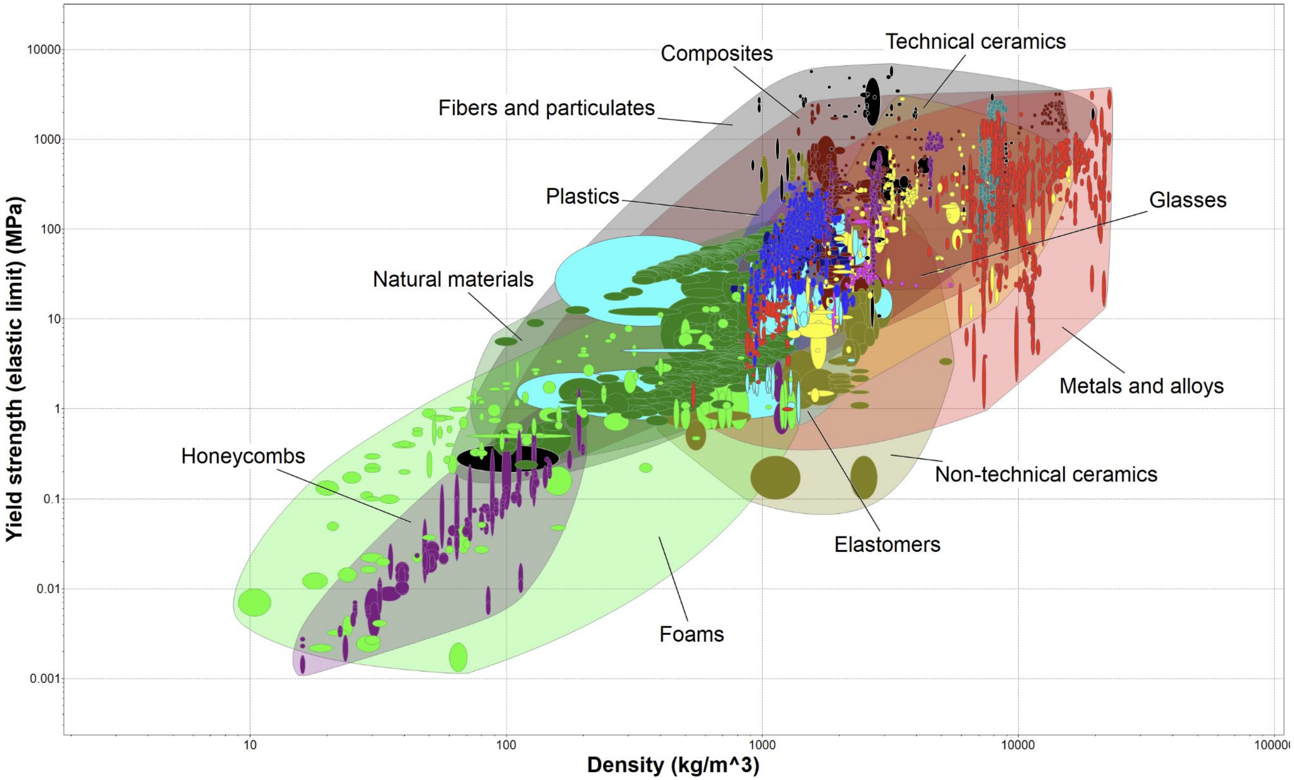
$$I \geq \frac{F_L(1.266L^3)}{6E\delta_{max}} \longrightarrow I \geq \frac{F_L(1.266)}{6\delta_{max}} L^3 (\frac{1}{E}) \longrightarrow \boxed{M_6 = E}$$

Minimize I by maximizing M_6

Material Indices Summary

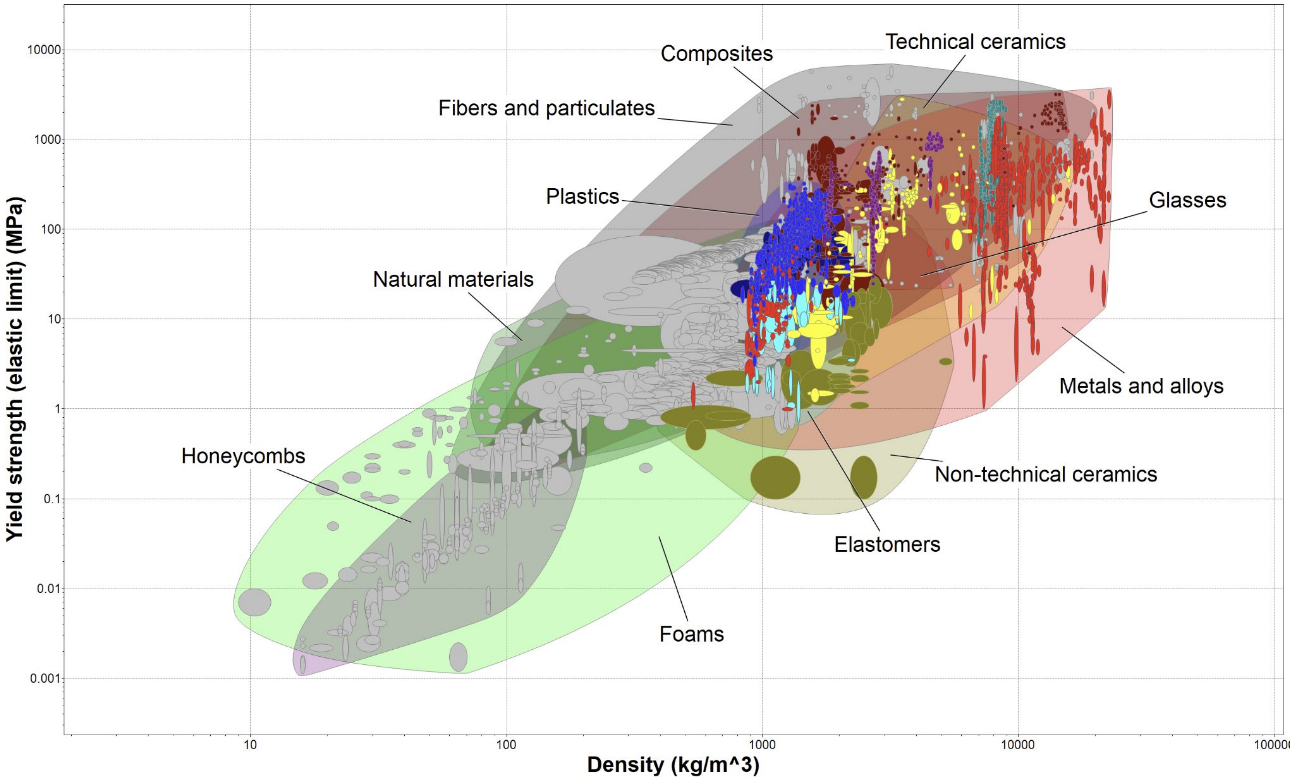
Index	Associated constraint	Equation	Threshold
M_1	Minimum operating temperature	T_{melt}	400 °F
M_2	No yield from rotationally imposed stresses	$\frac{\sigma_y}{\rho}$	0.0184 MPa/(kg/m^3)
M_3	Fatigue	$\frac{\sigma_{uts}}{\rho}$	0.0368 MPa/(kg/m^3)
M_4	Fracture resistance	$\frac{K_{IC}}{\rho}$	0.000823 MPa m$^{1/2}$/(kg/m^3)
M_5	Minimize effects of torsional vibration fatigue	$\frac{G}{E}$	0.25
M_6	Beam deflection	E	140 GPa

Ashby Plot



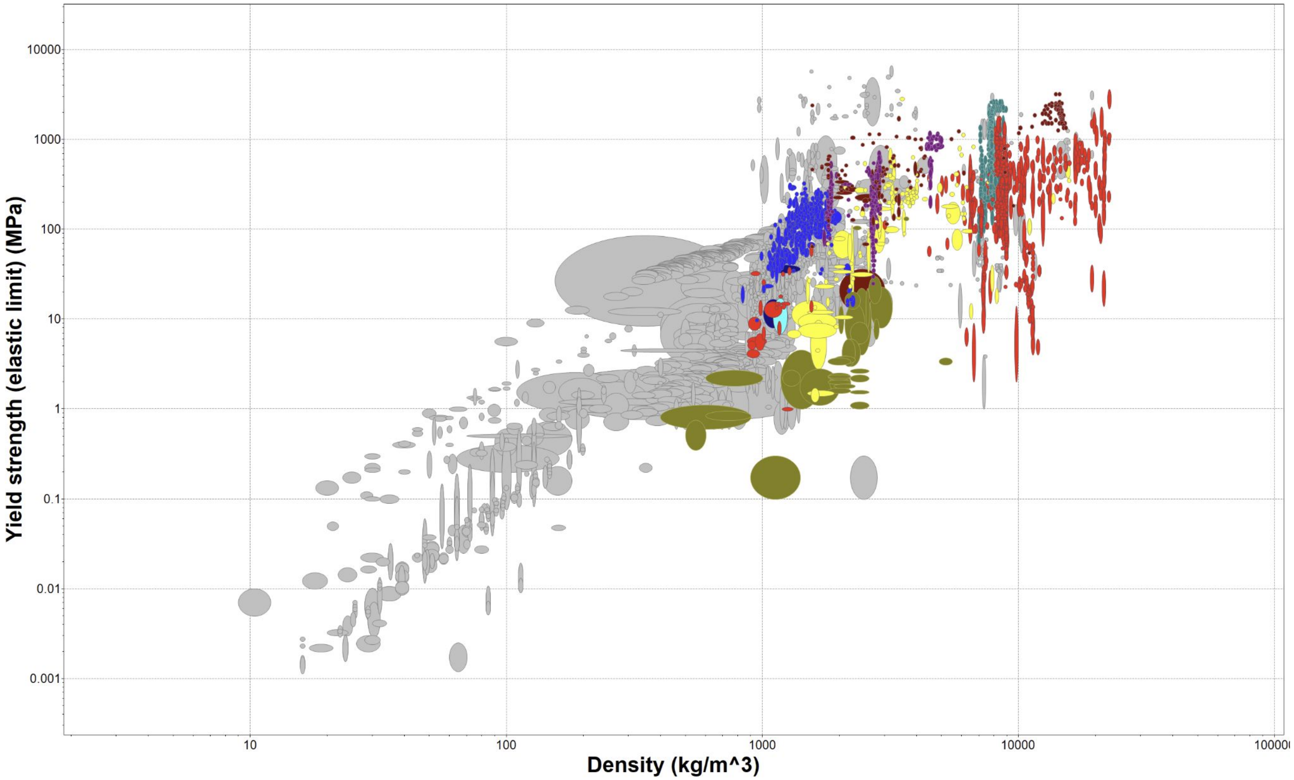
Began with all Level 3 Aerospace Materials

Ashby Plot



Eliminated obviously unhelpful materials (only come in powder form, foams, natural materials, wires, fibers)

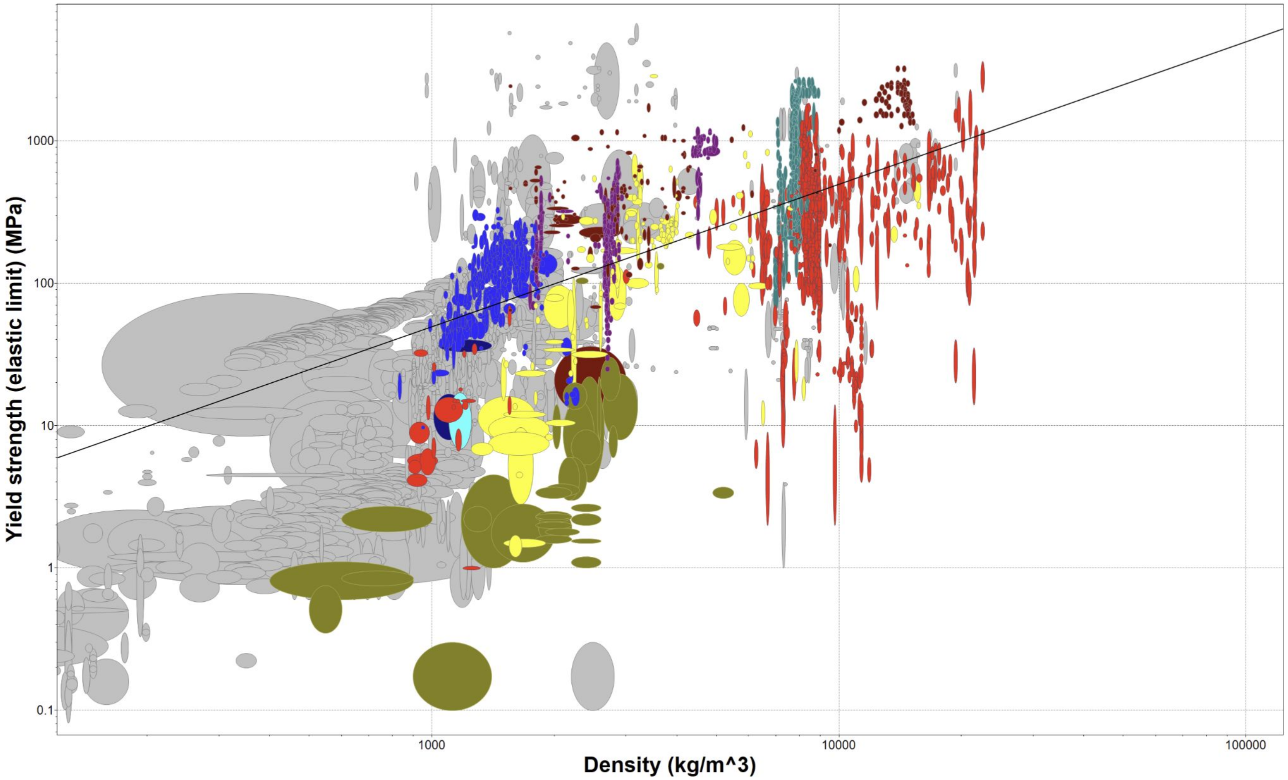
Ashby Plot



M_1 Filtering
Melting temperature > 400°F

Focus is on upper right corner

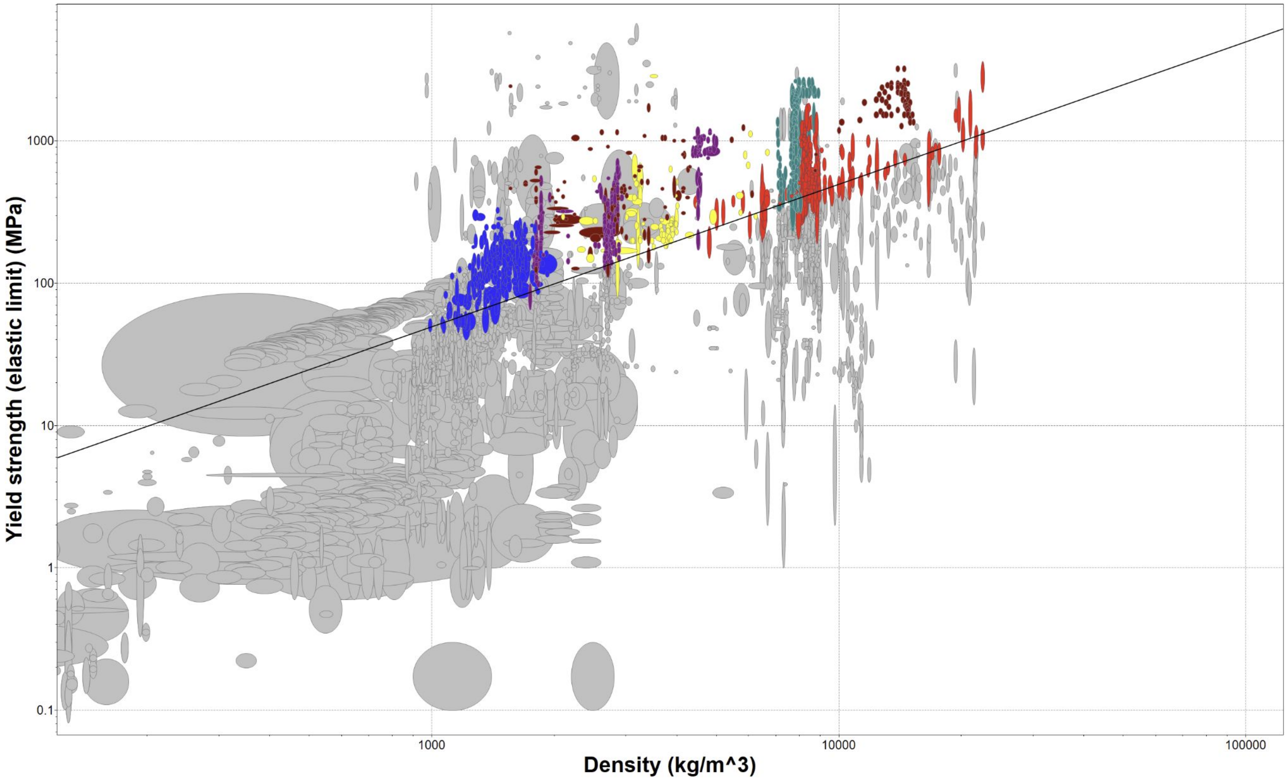
Ashby Plot



M_2 Screening - Yield Strength

Threshold Line at M_2 = 0.0184

Ashby Plot



M_2 Screening - Yield Strength

Threshold Line at M_2 = 0.0184

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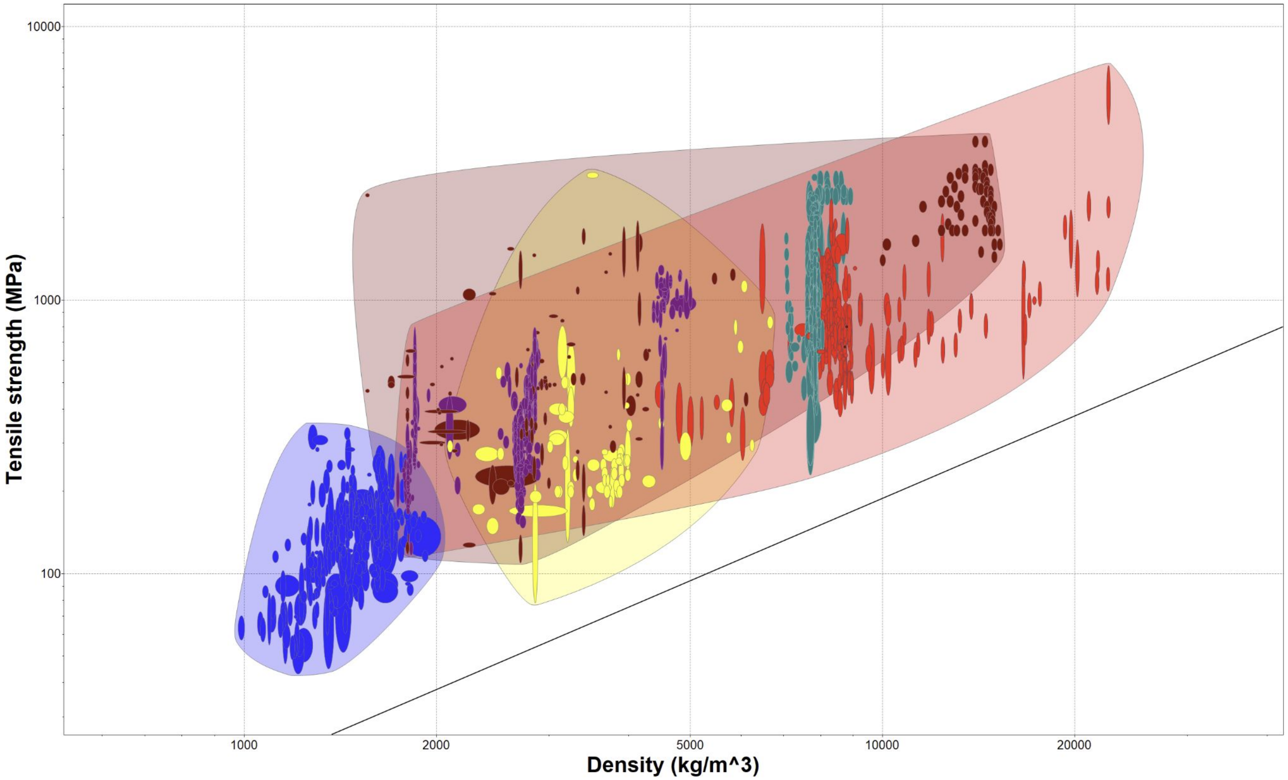
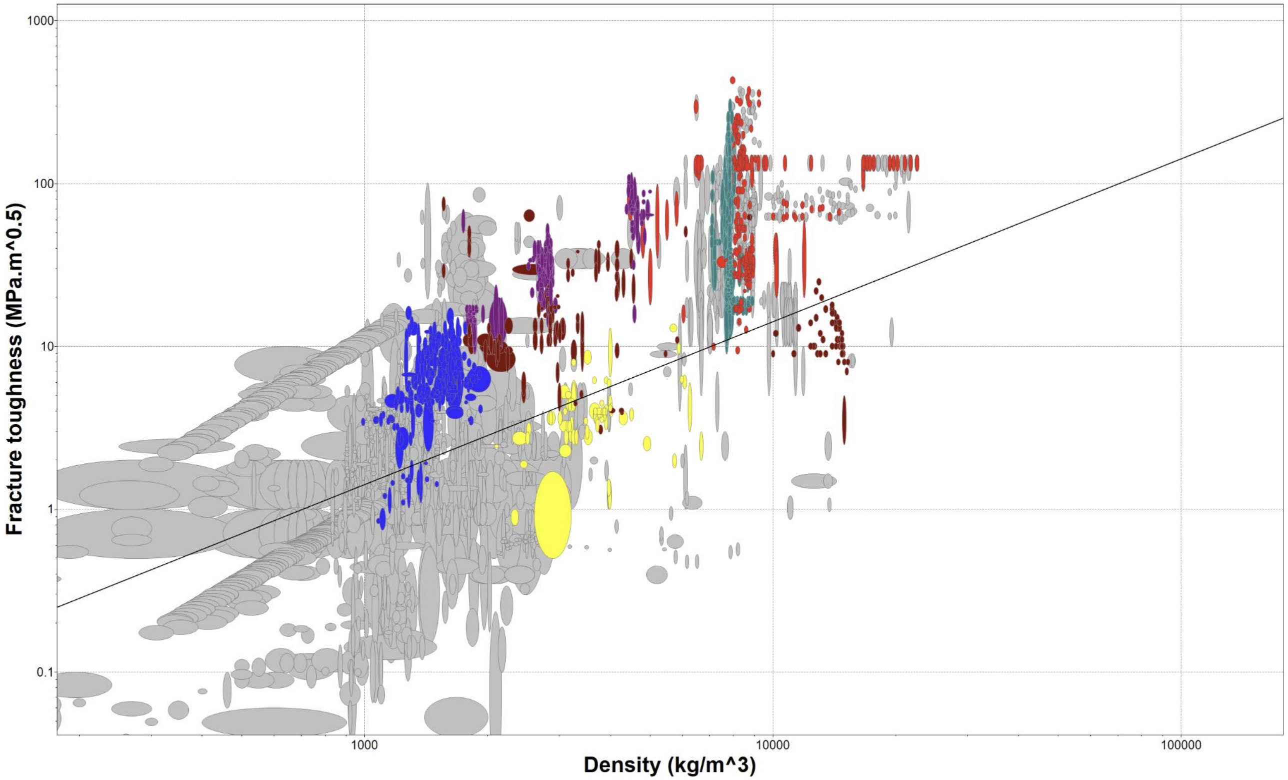


M_3 Screening - Tensile Strength

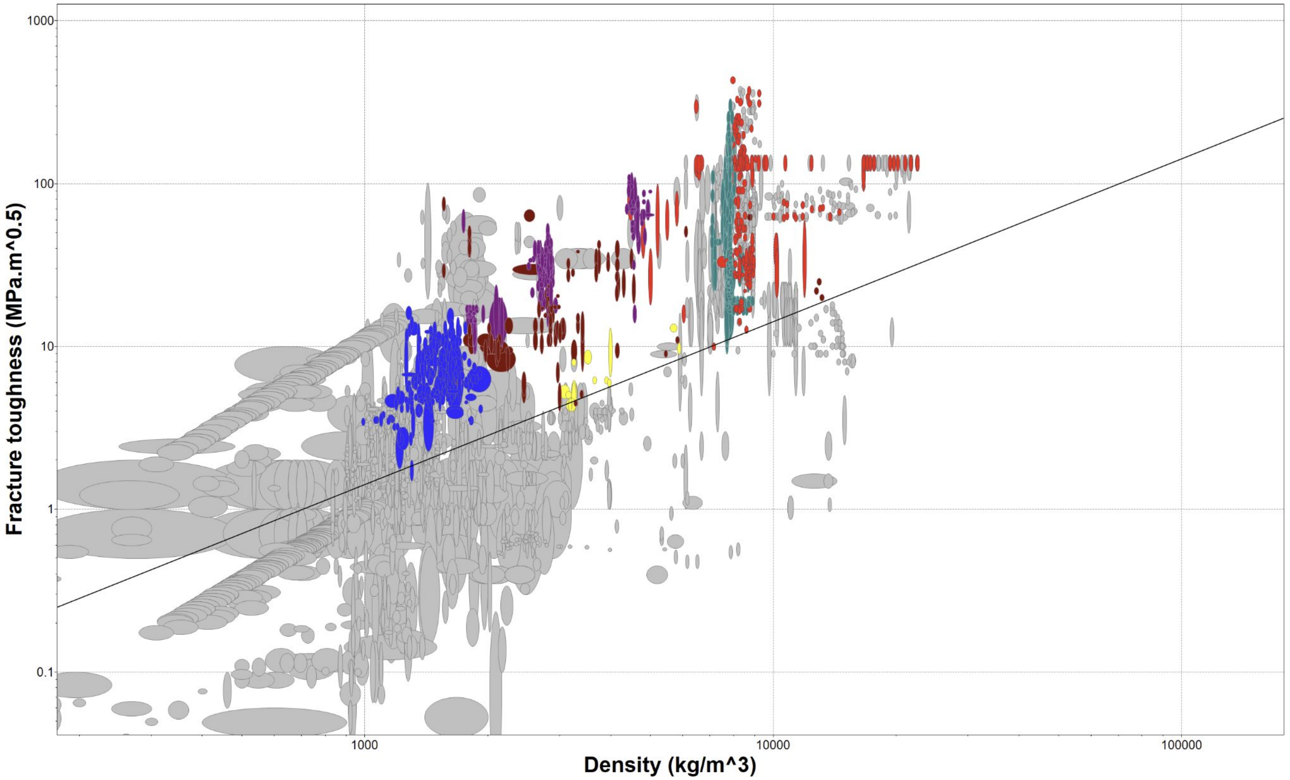
All previous materials were safely above cutoff line at M_3 = 0.0368

Ashby Plot



M_4 Screening - Fracture Toughness

Ashby Plot

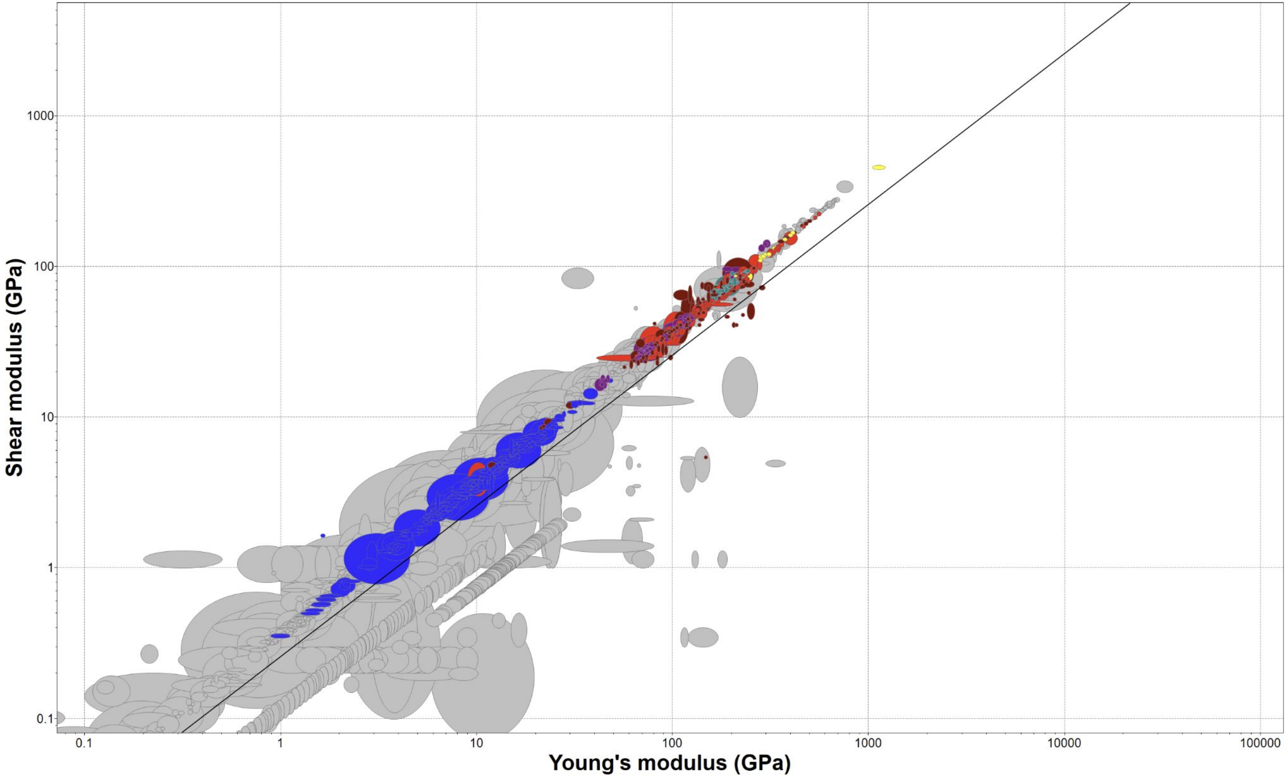


M_4 Screening - Fracture Toughness

Threshold Line at M_4 = 8.233E-4

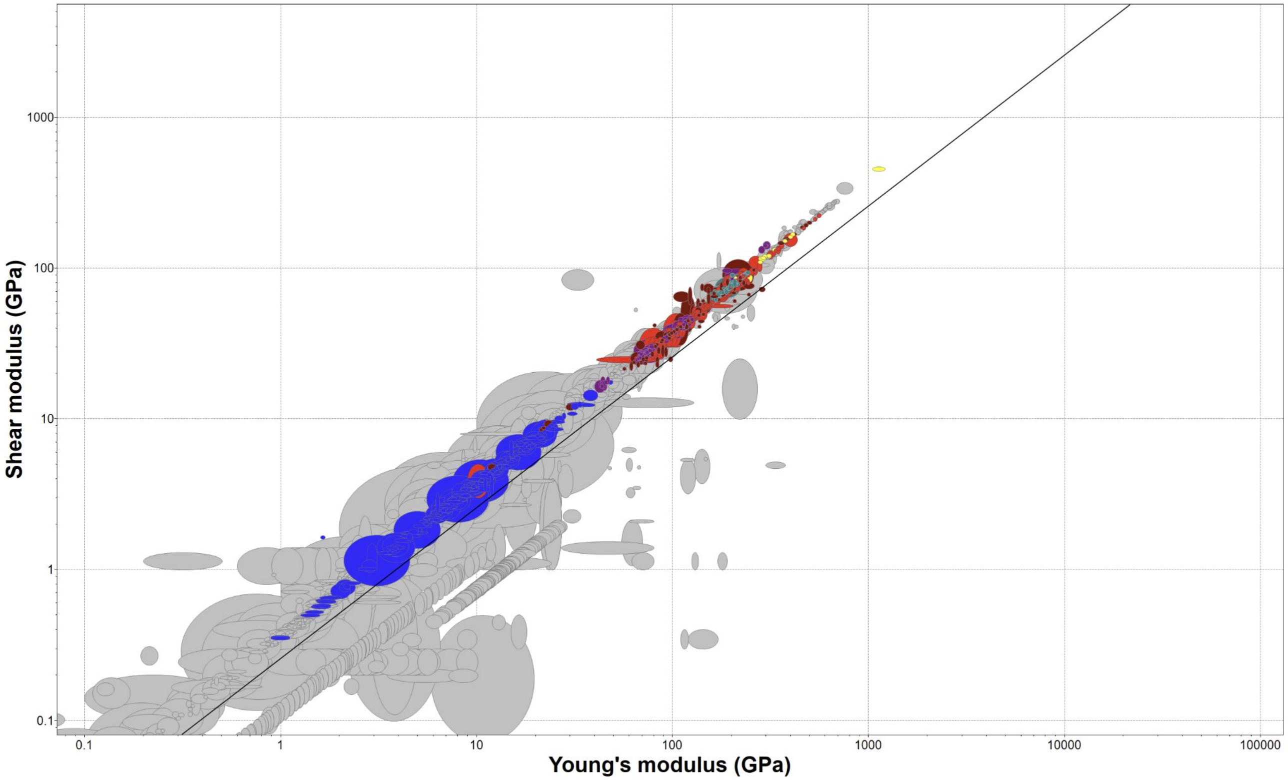
Very generous fracture toughness limit, only considers cyclic loading and not impact

Ashby Plot



M_5 Screening - Shear Modulus for torsional vibrations

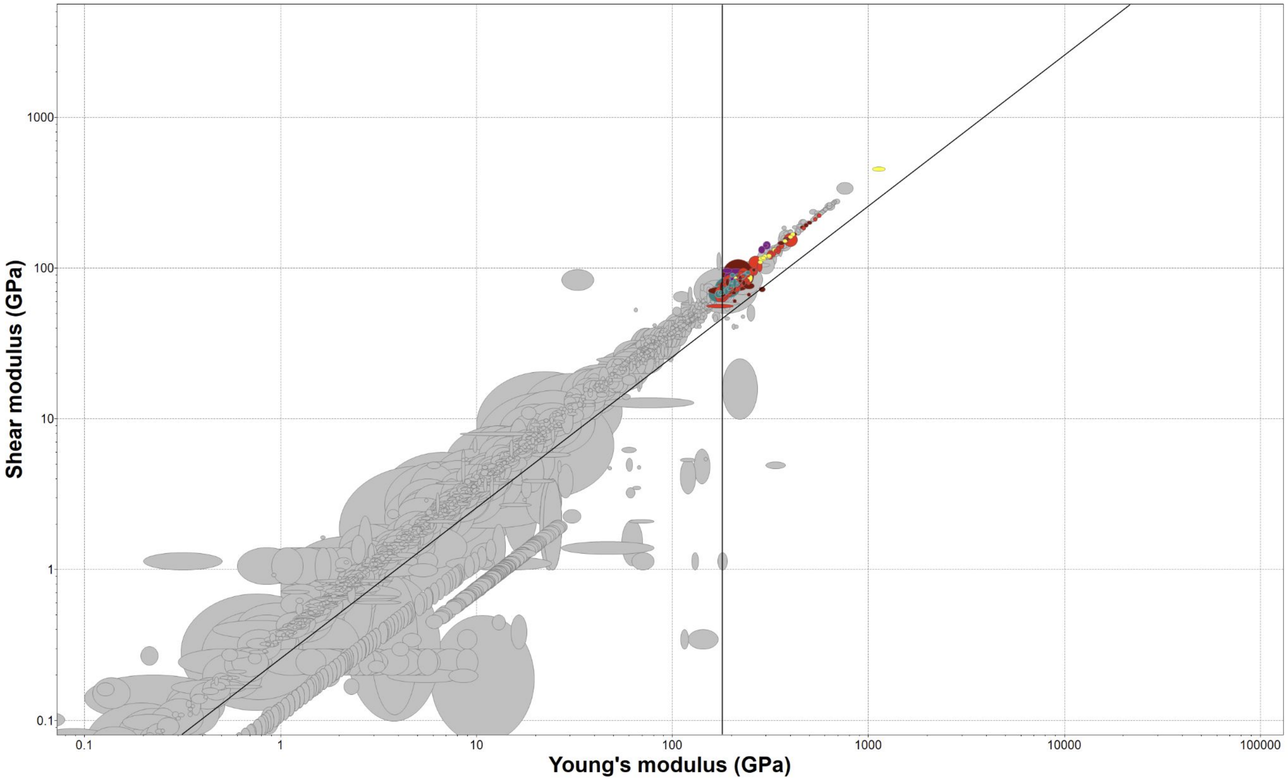
Ashby Plot



M_5 Screening - Shear Modulus for torsional vibrations

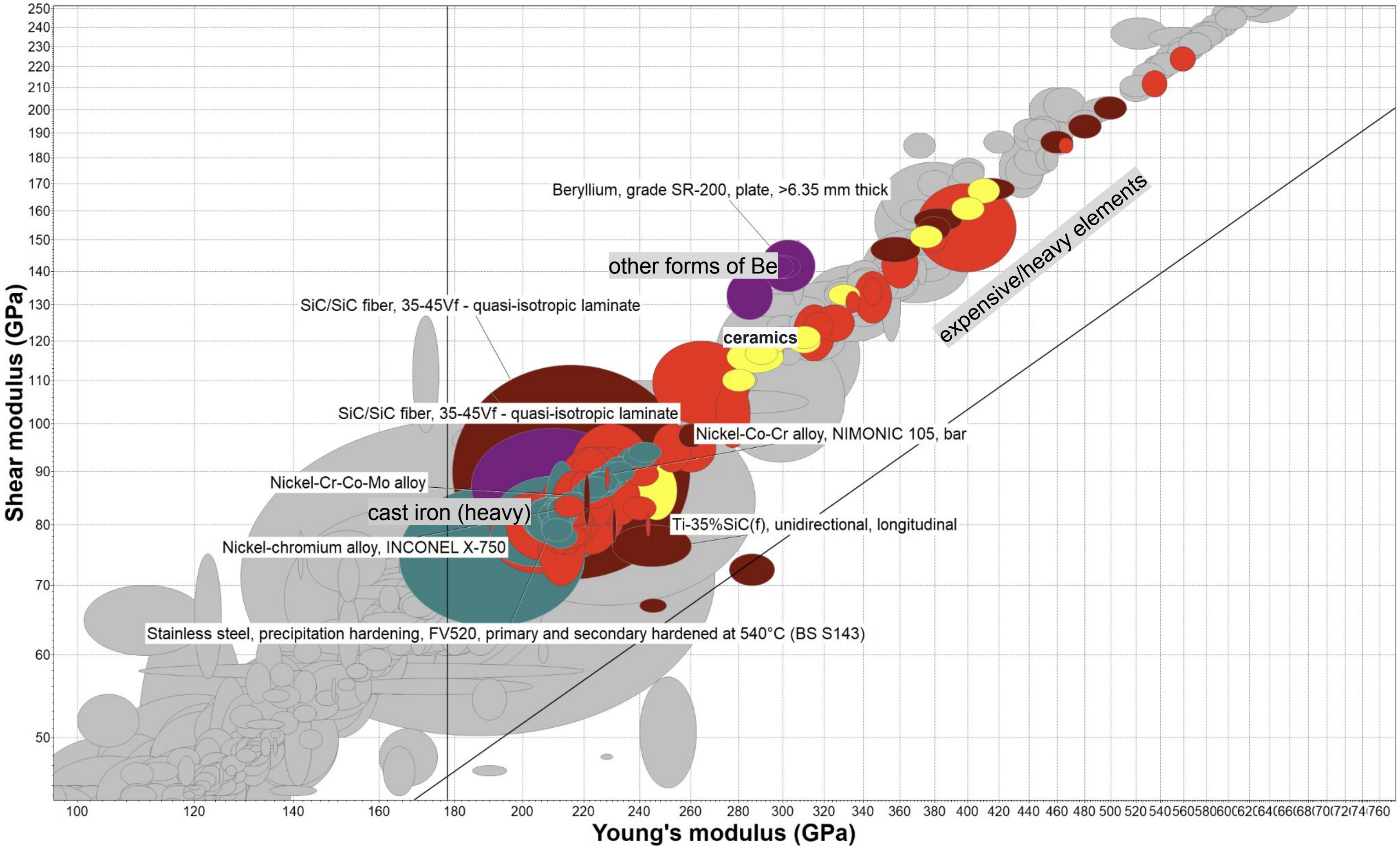
Eliminated a few materials

Ashby Plot



Assuming a solid cross section of maximum allowable thickness, we calculated a minimum Young's Modulus threshold of 140 GPa

Ashby Plot



Shear modulus (GPa)
Young's modulus (GPa)
Beryllium, grade SR-200, plate, >6.35 mm thick
other forms of Be
SiC/SiC fiber, 35-45Vf - quasi-isotropic laminate
ceramics
expensive/heavy elements
SiC/SiC fiber, 35-45Vf - quasi-isotropic laminate
Nickel-Co-Cr alloy, NIMONIC 105, bar
Nickel-Cr-Co-Mo alloy
cast iron (heavy)
Ti-35%SiC(f), unidirectional, longitudinal
Nickel-chromium alloy, INCONEL X-750
Stainless steel, precipitation hardening, FV520, primary and secondary hardened at 540°C (BS S143)

Material Properties

Material	Young's Modulus (GPa)	Density (kg/m^3)	Yield Strength (GPa)	Fracture Toughness ($MPa*m^{1/2}$)
TI-35% SiC (f) (Unidirectional, Longitudinal)	245	3930	1005	33.5
Beryllium, Grade SR-200, Plate > 6.35 mm Thick	302.5	1850	337.5	12
NIckel-Mo-Cr Alloy, Hastelloy (UNS N06635)	212	8750	445	312
Stainless Steel	211	7825	867.5	161.5
Nickel Chromium Alloy, Inconel X-750	216.5	8250	713.5	110.5
Nickel-Co-Cr Alloy	220	8250	1040	91.4
Nickel-Co-Cr Alloy, Nimonic 105	222.5	8000	830	95.75

Material Performance

Material	Minimum thickness (in)	Weight (kg)	Total Cost ($)
TI-35% SiC (f) (Unidirectional, Longitudinal)	0.495	4.59	12,857
Beryllium, Grade SR-200, Plate > 6.35 mm Thick	0.461	2.01	2,199
Nickel-Mo-Cr Alloy, Hastelloy (UNS N06635)	0.520	10.73	1,079
Stainless Steel	0.520	9.61	1,020
Nickel Chromium Alloy, Inconel X-750	0.516	10.04	1,174
Nickel-Co-Cr Alloy	0.513	9.99	1,240
Nickel-Co-Cr Alloy, Nimonic 105	0.511	9.65	1,248

Material Selection

Material	Details
Beryllium, Grade SR-200, Plate > 6.35 mm Thick	Used in aerospace structures, as heat sinks
Stainless Steel (BS S143)	Blading assemblies in aviation/aerospace industries, turbine engineering

Selected based on cost, weight, and minimum thickness

Design of Cross-Section

All materials have a baseline machining cost of $960 for a minimum thickness solid part.

If we add a cross section with a 0.1” wall thickness, the additional manufacturing cost is $910.8

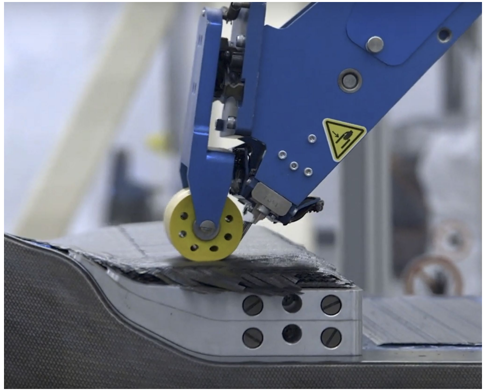
Thus, additional machining costs plus material prices will exceed our budget, and it is our best interest to design solid turbine blades

	Baseline Machining Cost: $960
	Internal Features Estimate: $911
+	Average Material Cost: $195
	Estimated final cost: $2066

Market Research

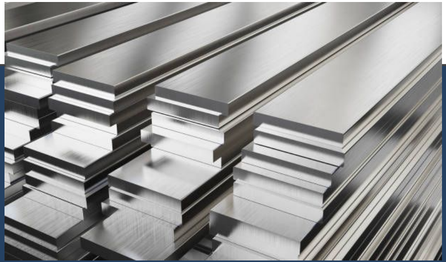
- Widely used materials
  - Nickel-based alloys
  - Titanium
  - Aluminum
  - Stainless steel
  - Sometimes CFRP

- Manufacturing
  - Mold Casting:
    - Nickel-based alloys
    - Stainless steel
    - Titanium
    - Aluminum
  - Layup: CFRP



Sources: [Materials for Aircraft Engines, Takehiro Okura](), [Engineering atoms inside the jet engine, University of Cambridge](), [How to Produce a Jet Engine Blade via Automated Fiber Placement, Duy Cao from Addcomposites]()

Final Choices



Budget friendly, reliable

Option 1: Stainless Steel (BS S143)

Weight: 9.61 kg

Total Cost per blade: $1020

Other Considerations: Easily machinable

Sourcing: Widely available

High performance, for a little extra

Option 2: Beryllium, Grade SR-200

Weight: 2.01 kg

Total Cost per blade: $2199

Other Considerations: Machinable, very low comparative fracture toughness

Sourcing: More difficult to find

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Thank You

Materials Selection Lab #4

Nickel Problem from the Statement

$$F = ma = \int (\rho w h)\,dr \left(\frac{v^2}{r}\right)$$

$$= \rho w h \omega^2 \int_0^{\ell} r\,dr$$

$$= \frac{1}{2} \rho w h \omega^2 \ell^2$$

$$\sigma_y = \frac{F}{A} = \frac{\frac{1}{2}\rho w h \omega^2 \ell^2}{wh} = \frac{1}{2}\rho \omega^2 \ell^2$$

$$\frac{\sigma_y}{\rho} \geq \frac{1}{2}\omega^2 \ell^2 \qquad (M1)$$

$$\sigma_{Ni} = \frac{1}{2}(8908)(3.14\ 1/s)^2(0.6096m)^2$$

$$\sigma_{Ni} = 164\ MPa$$

$$\sigma_{y\,Ni} = 59.0\ MPa$$

6' × 2'

$$\sigma_{Ni} = \frac{1}{2}(8908)(314.56)^2(1.8288)^2$$

$$\sigma_{Ni} = 1.47\ GPa$$

Stress is ×10 Greater

→ this stress linearly with density.

More Calculations

Cross-Section Math

All Screened Material Properties

Material	Young's Modulus (GPa)	Density (kg/m^3)	Yield Strength (GPa)	Shear Modulus (GPa)	Melting Point (℃)	Fracture Toughness ($MPa*m^{1/2}$)	Specific Young's Modulus ($MPa/kg/m^3$))
TI-35% SiC	245	3930	1005	76.5	1645	33.5	62.34
Beryllium,	302.5	1850	337.5	142	1280	12	163.5
Nickel-Mo-Cr Alloy	212	8750	445	80	1360	312	24.23
Stainless Steel	211	7825	867.5	80	1420	161.5	26.96
Inconel X-750	216.5	8250	713.5	83.1	1410	110.5	26.24
Nickel-Co-Cr Alloy	220	8250	1040	85	1345	91.4	26.67
Nickel-Co-Cr Alloy, Nimonic 105	222.5	8000	830	87.5	1300	95.75	27.81