Materials for Deep Submersibles

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530.352: Materials Selection Lab 4

Executive Summary

- Design Problem: choose material options for deep submersible
- Objective: minimize mass
- Constraints: effective compressibility less than that of sea water, corrosion resistant, temperature, fracture toughness, must not buckle
- Selection Process: one material index in CES software, then buckling
- Material Options: CFRP, Cobalt superalloy, Nickel alloy, Stainless steel, Titanium
- Final Selection: two options with varying cost and mass

Problem Definition

Deep Submersible

- Design a spherical submersible (small submarine)
- Must withstand hydrostatic pressure at depth of 5 km
- Radius must be 3 m
- Maintain positive buoyancy
- Buoyancy increase with depth
- Objective is to minimize the mass of the submersible

Constraint Determination

Density

- Density of seawater equal to 1027 kg/m^3
- In order to maintain positive buoyancy, average density of submersible must be less than density of seawater
- Volume of submersible:

$$V = 4/3 * \pi * [r ^ 3 - (r - t) ^ 3]$$

where *r* is the radius of the submersible, and *t* is the thickness of the Submersible (more on thickness in MBD slides)

- Submersible displaces 116,000 kg of water
- All the materials were calculated to confirm they are positively buoyant

Compressibility

- As the submersible descends, buoyancy should not decrease with depth, possibly making it negatively buoyant
- Compressibility of the submersible < compressibility of seawater, which is defined as:

$$1/K_{seawater}$$

  where $K_{seawater}$ is the bulk modulus of seawater, equal to 2.34×10^9 Pa

- $1/K_{seawater} = 4.2735 \times 10^{-10}\ Pa^{-1}$

Corrosion Resistance

- Exposure to seawater → constrained to materials with excellent resistance to salt water
- Exposure to the sun during submersion→ constrained to materials with good or excellent resistance to UV radiation
- Possible exposure to sea life and microbes → constrained to materials with acceptable and excellent resistance to organic solvents

More Constraints

- Form of material must be bulk:
  - Solid materials that can be forged, cast, extruded, or molded
  - Material must be readily available in quantities large enough for a 6m wide sphere
- Service temperature:
  - Must operate down to -2C (coldest that seawater can get)
- Fracture Toughness:
  - > 15 $MPa.m^{1/2}$
  - Ashby's rule of thumb for mechanical design

Mechanics Based Design

Thin Walled Vessel vs. Thick Walled

- Pressure vessels can be approximated as thin-walled if their wall thickness is significantly smaller than their radius ($r > 10t$)
  - Preliminary calculations established that this condition should hold true for designs based on most common materials such as steel. Subsequently used thin wall equations for all calculations and confirmed the thickness condition for end materials.

Mechanics-Based Design

- Must not yield due to radial or tangential components of wall stress
  - σ_θ = pr/2t (where p is pressure difference, r is the radius, t is thickness)
  - σ_r = -p/2
- Must not buckle

$$p_{CL} = \frac{2E}{\sqrt{3(1-v^2)}}\left(\frac{t}{r}\right)^2$$

Where E is Young's modulus and v is poisson's ratio

- Mass must be less than the mass of displaced seawater to maintain buoyancy (116,200 kg)

$$m = \rho\left(\frac{4}{3}\pi r^3 - \frac{4}{3}\pi(r-t)^3\right)$$

https://rules.dnvgl.com/docs/pdf/DNVGL/CG/2015-10/DNVGL-CG-0128.pdf

FGM Equation and Materials Index

- Solve for thickness in terms of all other values in MBD equations, then use this thickness to solve for mass
- Materials index to minimize mass while ensuring vessel does not yield from tangential stress: $M_I = \rho/(\sigma_y)^3$
- Constraint to ensure vessel does not yield due to radial stress component: $\sigma_y >$ 50MPa/2 = 25 MPa
- Materials index to minimize mass while ensuring vessel does not buckle from external pressure: $M_I = (\rho * v^{3/2})/(E^3)$

Materials Search: CES

Applying Constraints

Strength and Form Properties

- $K_{mat} > 2.34*10^9$ Pa
- $\sigma_y > 25$ MPa
- $K_{IC} > 15$ MPa*$m^{1/2}$
- Must be available in bulk or sheet form

Environmental Factors

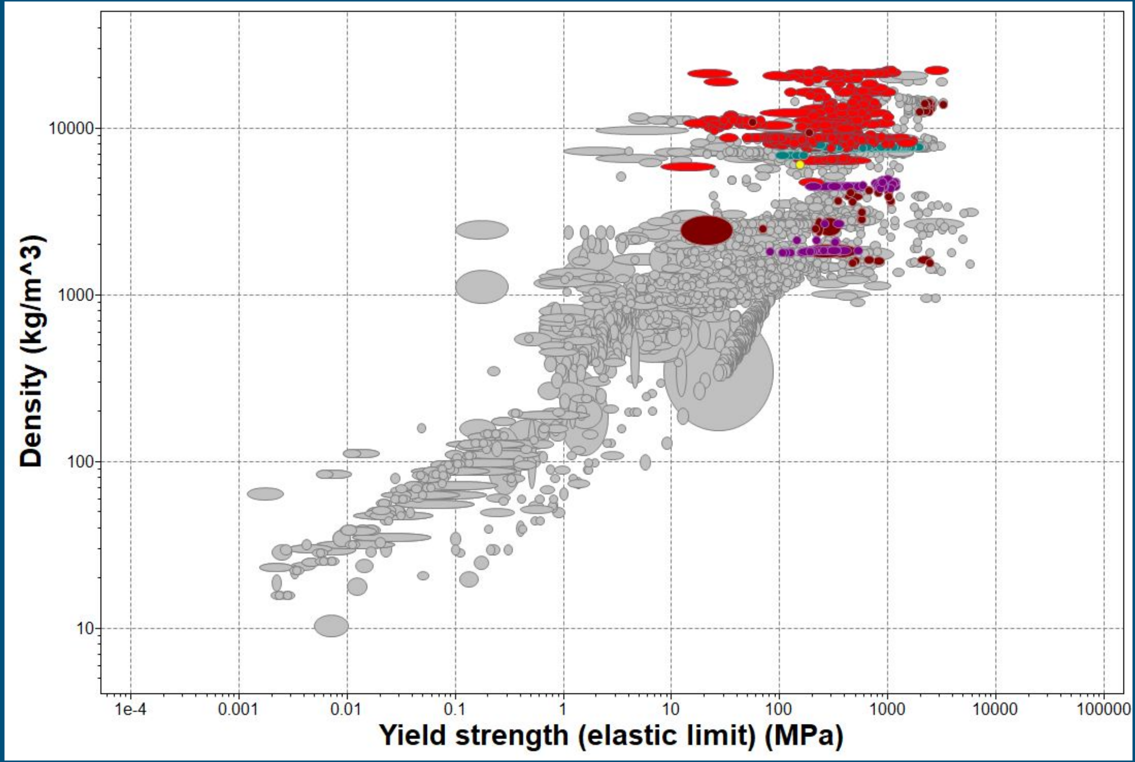
- Excellent resistance to corrosion in salt water
- Excellent resistance to organic solvents
- Good durability in UV radiation

55 Materials Left

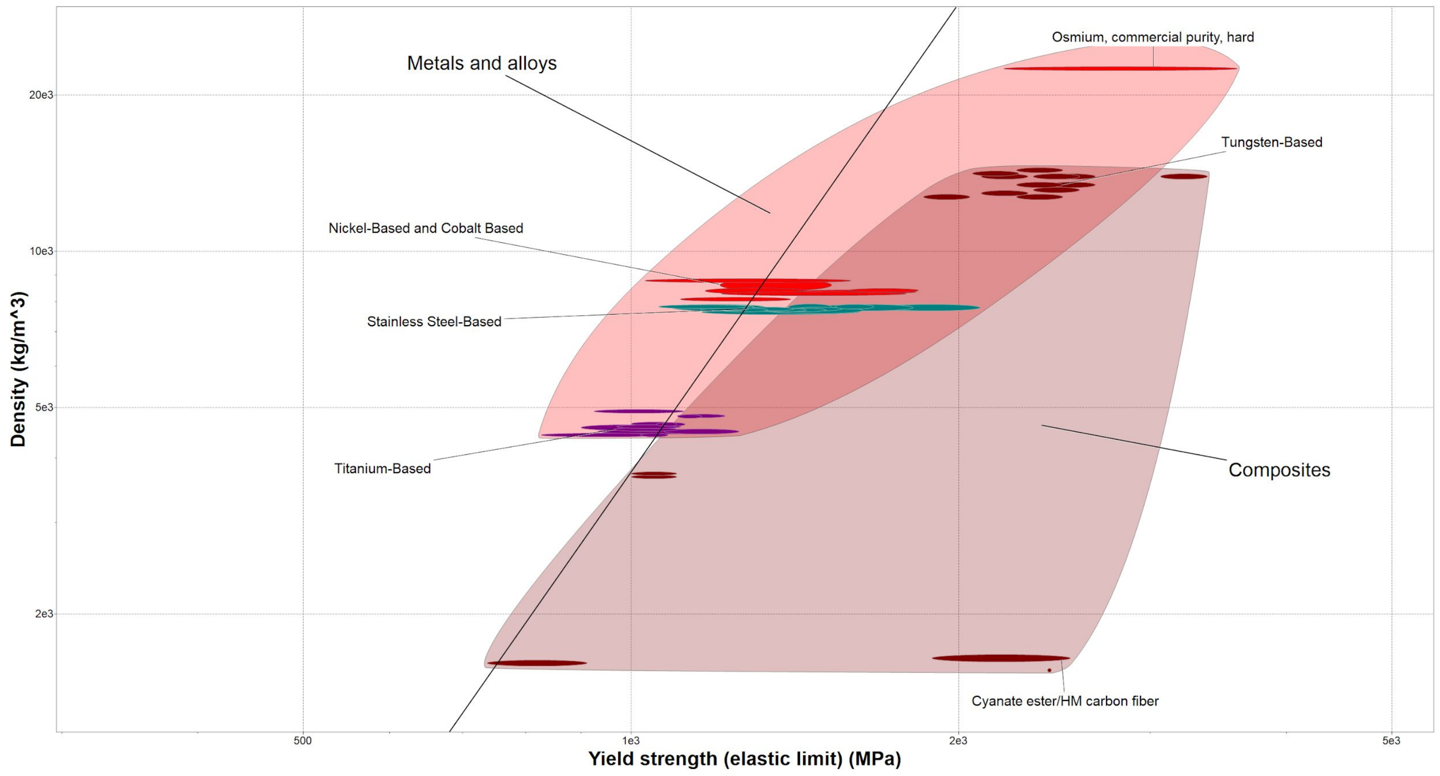
7 Different Groups

- Osmium
- Tungsten carbides
- Carbon Fibers
- Nickel alloys
- Cobalt alloys
- Stainless Steel
- Titanium

All Materials after Constraints (showing 814)



Hoop Stress Material Index (showing top 55)



Material	Yield Strength (MPa)	Density (kg/m^3)	Total Mass (kg)	Thickness (cm)	Fracture Toughness ($MPa*m^{1/2}$)	Bulk Modulus (GPa)	Unit Price (USD/kg)	Total Price (thousands USD)
Cyanate Ester/HM Carbon Fiber	2210	1645	2100	5.86*	55	44	225	470
Cobalt Based Super-Alloy	865	7850	74770	8.67	135	210	50	3740
Ni-Co-Cr Alloy	850	8000	77480	8.82	95	175	35	2710
Stainless Steel	1090	7640	58100	6.88	42	156	6.5	380
Ti-8Al-1Mo -1V	798	4375	45060	9.40	70	114	22	1020

Note: Values shown are the median values of each range provided by the CES software

Material Selection

Cyanate ester/HM carbon fiber

- Approximately 65% carbon and 35% cyanate ester polymer
- Requires intensive manufacturing process with autoclave cure
- Not easily available for purchase, must be custom made
- Material that will produce the lightest submersible: 2000kg
- Very cheap compared to other materials on our list (< $500,000)

Cobalt-base-superalloy, CCM (hot worked, high carbon)

- 60-70% cobalt alloyed with primarily chromium and molybdenum
- Cobalt is listed on both the US and EU critical metals list, indicating its difficulty in obtaining in certain resource scarce areas
- Good weldability for joining during manufacturing
- Excellent resistance to almost all corrosive substances
- Not readily available for purchase
- Most expensive material in final selection (>$3M)

Nickel-Co-Cr alloy, NIMONIC 115 (heat treated)

- Approximately 60% Nickel, 20% Cobalt, and 15% Chromium
- Good fatigue performance at low cycles
- Cobalt is listed on both the US and EU critical metals list, indicating its difficulty in obtaining in certain resource scarce areas
- Excellent resistance to almost all corrosive substances
- Known as a toxic material in large quantities and can cause cancer if in contact with humans
- Available for purchase online: https://www.americanelements.com/nickel-cobalt-chromium-alloy

Stainless steel, semi-austenitic (17-7PH, TH1050)

- Typically used in offshore installations, including undersea pipes and cables
- Approximately 75% iron and 17% chromium
- Excellent corrosion resistance
- Known as a formable metal that is easy to manufacture and heat treat
- Least expensive material in final selection: $377,000 for entire submersible
- Readily available in various dimensioned sheets and plates: https://www.upmet.com/products/stainless-steel/17-7-ph

Ti, near-alpha alloy, Ti-8al-1Mo-1V (Duplex annealed)

- Approximately 90% titanium and 8% aluminum
- Typically used commercially for extreme heat applications, such as high performance engines
- Weldable for ease of manufacturing
- Excellent corrosion resistance
- Compared to other materials in final selection, moderately priced and moderate total mass of submersible
- Available from: https://continentalsteel.com/titanium/grades/8al-1mo-1v/

Elimination

- Cobalt-base-superalloy is eliminated because of its high price compared to other materials with no mass gain
- Nickel-Co-Cr eliminate due to its toxicity, causing difficulty in use and manufacturing
- Titanium removed because it is significantly more expensive than stainless steel, with little mass benefits

The other two materials allow for varying price and mass options.

Final Selection: Multiple Options

Expensive, Lighter ⟷ *Cheaper, Heavier*

Cyanate Ester / HM Carbon Fiber

Total price: $470,000
Total mass: 2100kg

Considerations:

- Extremely lightweight
- Evidence of previous use for underwater submersibles

Stainless Steel (17-7PH, TH1050)

Total price: $380,000
Total mass: 58,100kg

Considerations:

- Cheaper than other options
- Excellent corrosion resistance to expected environments

What if we had a depth wish?

- The bottom of the Mariana Trench is approximately 11,000m deep.
- Pressure approximately 110 MPa
- Wall thickness and subsequent weight would need to be increased
- The weight-saving benefits of using carbon fiber (rather than steel) would increase
  - > 81,800 kg for steel
  - > 13,600 kg for carbon fiber

Questions?