Materials Selection Project

Project Title: Connecting Rods

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Part A:

Q1. Identify a component/equipment for your project.

A1. Connecting Rod is a mechanical device that acts as a linkage between piston and crankshaft.It has both linear (reciprocating up and down) and rotational (rotary) motion.

The connecting rod in its simplest form is a beam with two pin joints at either end. One end sees relatively low rotation speeds as it is connected to the piston, while the other sees high rotation speeds as it is attached to the crankshaft. The connecting rod will typically support the bearings or bushings for both ends of its application. It is one of the most stressed components in the engine and subjected to high tensile, compressive, and bending stress. It can be cast, forged, or sintered from powdered metal.

Fig1: Connecting Rod

Q2. Describe briefly the functions of the component/equipment and the environment to which it is exposed (temperature, pressure, the loading patterns) (2)

A2.

Functions of Connecting Rod:

- The connecting rod converts the reciprocating motion of the piston into the rotation of the crankshaft.
- It is required to transmit the compressive and tensile motion of the piston and rotate at both ends.
- It also is used to convey cooling oil to the pistons which demands for quite a large diameter passage.

OPERATIONAL PARAMETERS OF A CONNECTING ROD OF A
FOUR-STROKE SPARK-IGNITION INTERNAL COMBUSTION ENGINE
(Length = 100 mm)

Operational Parameter	Value
Maximum Load	40 kN (compressive), 25 kN (tensile)
Maximum extension	160 μm (compressive), 100 μm (tensile)
Maximum distortion of big- and small-end eyes	10 μm
Minimum durability	3000 h
Minimum number of load cycles	3 x 108
Minimum temperature range	-30°C to 180°C (small-end eye). -30°C to 140°C (big-end eye)

Q3. Identify the primary set of properties of the material of construction that should be taken into account for the mechanical design of the equipment. (Example: strength, service temperature, type of loading, corrosion or creep resistance,…)(3)

If 'A' denotes the area of cross-section of the connecting rod and 'L' is length and ρ denote the density of the material of which it is made then the mass 'm' is:

$$m = AL\rho \quad (1)$$

If the applied force on the connecting rod is 'F' and the endurance limit of the material is 'σ', the fatigue constraint requires that,

$$\frac{F}{A} \leq \sigma \qquad (2)$$

The mass from equation (1) by eliminating 'A' is then given by,

$$M \geq FL\frac{\rho}{\sigma} \quad (3)$$

In order that the mass is minimized we need to maximize σ and minimize ρ.

Thus we know,

$$Specific\ Stiffness = \frac{E}{\rho}$$

And,

$$Specific\ Compressive\ Strength = \frac{\sigma_c}{\rho}$$

Thus for the mechanical design specific stiffness and specific compressive strength is required.

E = Tensile Modulus of the material

ρ = Density of the material

The material also should have a high temperature resistance since the maximum temperature connecting rods have to go through can be upto 180° C.

Thus temperature is an important factor which should be taken care of when designing a material.

Q4. Identify the candidate materials that may have the properties identified. (Essential mechanical properties and other desirable attributes)(3)

Material	Tensile Modulus E (GPa)	Maximum Compressive Strength, σ (MPa)	Density, p (kg m^{-3})	Maximum Service Temperature (°C)	Unit Cost ($ t^{-1})	Specific Stiffness, E/p (10^6 m)	Specific Compressive Strength, σ_c/p (10^3 m)
Steel	210	1000	7890	800	880	2.71	12.92
Aluminumalloy	71	280	2700	350	1200	2.68	10.57
Silicon carbideceramic	310	490	3200	1000	5700	9.88	15.61
S glass fiber reinforced polymer laminate	56	540	1997	220	5000	2.86	27.56
Carbon fiber reinforced polymer laminate	138	600	1661	220	130,000	8.47	36.82

Q5. Workout a procedure for the comparison of the suitability of the materials giving relative weightage to different property levels taking into account the importance in the design and performance in service. (5)

A5. Connecting Rods are subjected to huge amount of force, thus the materials with higher compressive stress are preferred.
The crankpin end of the connecting rod is primarily designed for stiffness and not strength, as the connecting rod needs to support the crankpin journal bearing and maintain roundness. As the engine progresses through its cycle, tensile inertia forces attempt to stretch the rod and deform the crankpin end of the connecting rod, as shown in Fig 2. Stretching of the connecting rod along the cylinder bore causes the connecting rod to pinch in along the cap split due to the Poisson effect, which may lead to the oil film breaking down and the bearing contacting the crankshaft.

Fig2:Deformed shape of crankpin bearing bore

Operating temperatures of the connecting rod are typically oil operating temperature of between 80-110ºC, but peak oil temperatures can rise to 150ºC. Connecting rod crankpin bore temps are similar, but piston pin end temperatures are higher as they are exposed to the bottom side of the piston. The connecting rod piston pin end typically sees 150-180ºC.

From the above points it can be concluded that temperature, stiffness and maximum compressive stress play a huge role in the selection of material.
Also the cost of the material also has to come under considerations because the cost per unit can go upto $130,000.

Relative weightages:

- Stiffness can be given a weightage of 0.3.
- Compressive strength can be given a weightage of 0.3
- Cost can be given a weightage of 0.2
- Survival temperature can be of weightage 0.2

Also we know that,
Weightage index (for quantities where maximum is preferable),

$$W_i = w_i \frac{M_i}{(M_i)_{max}}$$

In this case quantities are: stiffness, compressive strength, cost, survival temperature.

Weightage index (for quantities where minimum is preferable),

$$W_i = w_i \frac{(M_i)_{min}}{M_i}$$

In this case quantity is cost.

M is the value of the properties.
w is the weightage factor.
Thus the best selection is the material with largest value of the sum

$$W = \sum_i W_i = \sum_i w_i \frac{M_i}{(M_i)_{max}}$$

Material	W
Steel	0.57
Aluminum alloy	0.38
Silicon carbide ceramic	0.64
S glass fiber reinforced polymer laminate	0.39
Carbon fiber reinforced polymer laminate	0.6

Thus the materials can now be compared based on the weightage index.

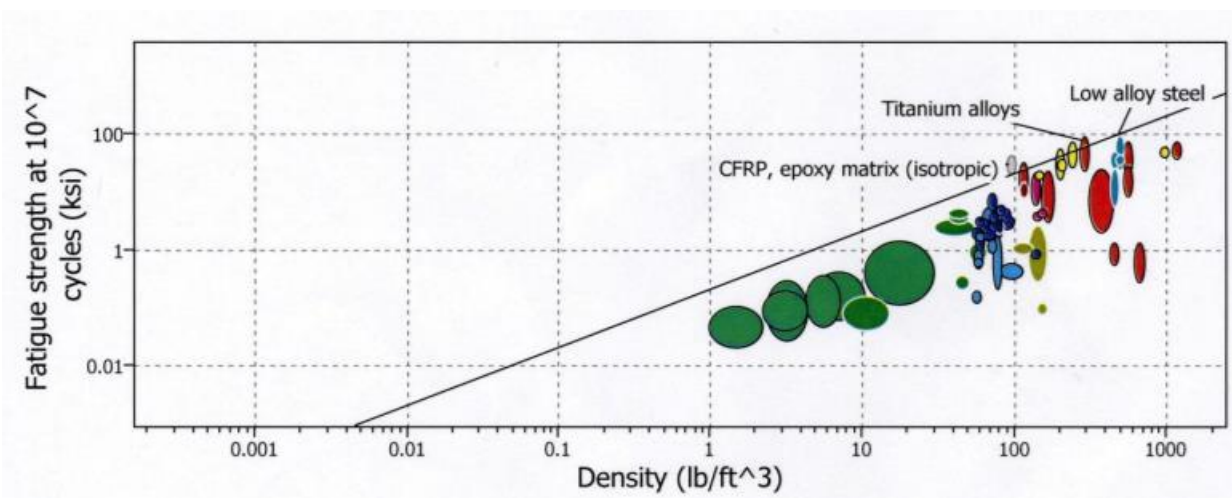
Q6. Select the best material based on your analysis taking into account the properties, cost, etc. (3)

A6.
Steel according to me is the best possible material that can be used.

Though two materials have weightage index greater than that of steel the cost per unit of the two materials is very high and thus is not preferable.Also steel can be easily made into an alloy which would not be expensive and also perform better.

Steel has the maximum compressive strength of about 1000 MPa. Also the maximum temperature steel can withstand is second highest (800^{o} C). An added benefit of using steel is the cost per unit which is the lowest. Thus steel is the best material that can be used. Steel is also used because of its high strength durability.

Steel has a disadvantage of having a high density and thus exerting excessive stress on the crank shaft of high speed engines.
High speed engines sometimes use aluminum and titanium however they suffer relatively low strength and fatigue life. Thus steel is preferred.



Fatigue Strength vs. Density

The prominent one in the above graph is low alloy steel.Thus it is extensively used for engines running at high rotational speeds.

Q7. For the material identified, outline briefly the metallurgical processes for the conversion of the material into finished product. (5)

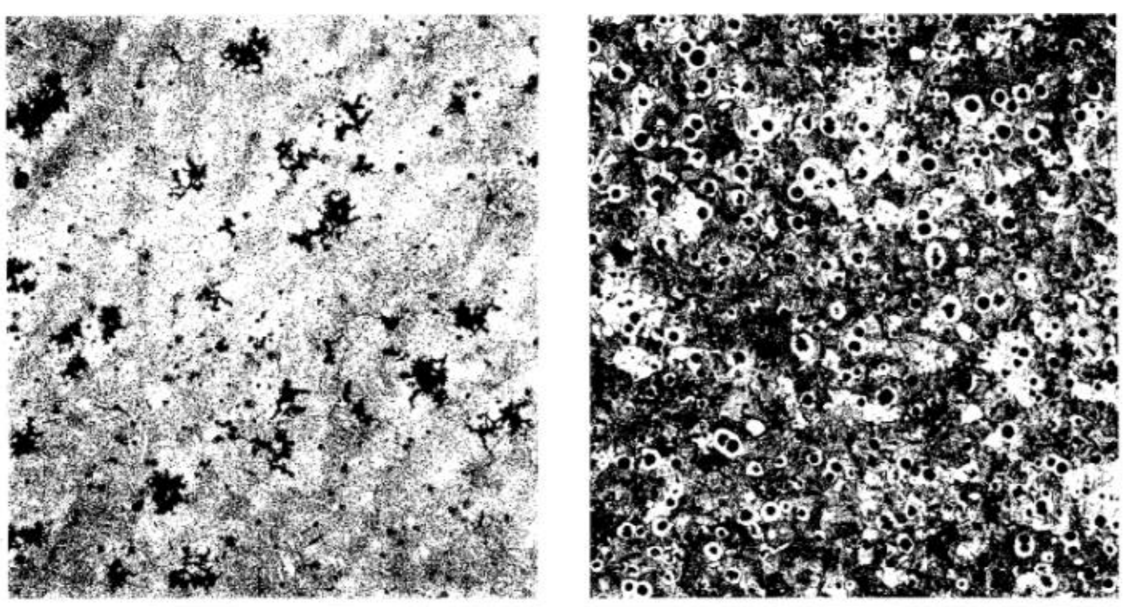
A7. Processes that can be used are:

- Forging
- Casting
- Powder Metallurgy

Casting:

- Green sand molds are used.
- They are first annealed at 1750° F for 18 hours and air cooled.
- After air cooling they are reheated a second time at 1600° F.
- Then the mold is quenched in oil to form a martensitic microstructure and then tempered for 3 to 4 hours at $1150\text{-}1180^{\circ}$ F.
- The cast connecting rod was reported 7 to be economically competitive with its forged counterpart with savings coming from the extended machine tool life associated with the excellent machining qualities of the pearlitic malleable iron from which it is cast.

It was later found out that ductile iron connecting rods outperformed the malleable iron connecting rods in push-pull fatigue tests.



Left- Metallurgical structure of malleable iron con-rod (x50). Right-Metallurgical structure of ductile iron con rod (x50)

Additionally, since the nodular form of the graphite is created upon solidification of the connecting rod in the ductile iron rod (as opposed to the malleable iron connecting rod which has to be heat treated for the graphite to obtain the nodular form) there is an elimination of a thermal treatment for the ductile iron rods. Finally, with malleable iron connecting rods, there is a risk of causing cracks during handling of the untreated castings because of the extremely brittle structure in the cast condition. This risk is eliminated with ductile iron rods. Today, cast iron is seen as too heavy, labor intensive, and not economical for production in automotive engines. Additionally, it does not have the mechanical property requirements for the modern automotive engine and is no longer being used as a major method of manufacture for connecting rods.

Forging:

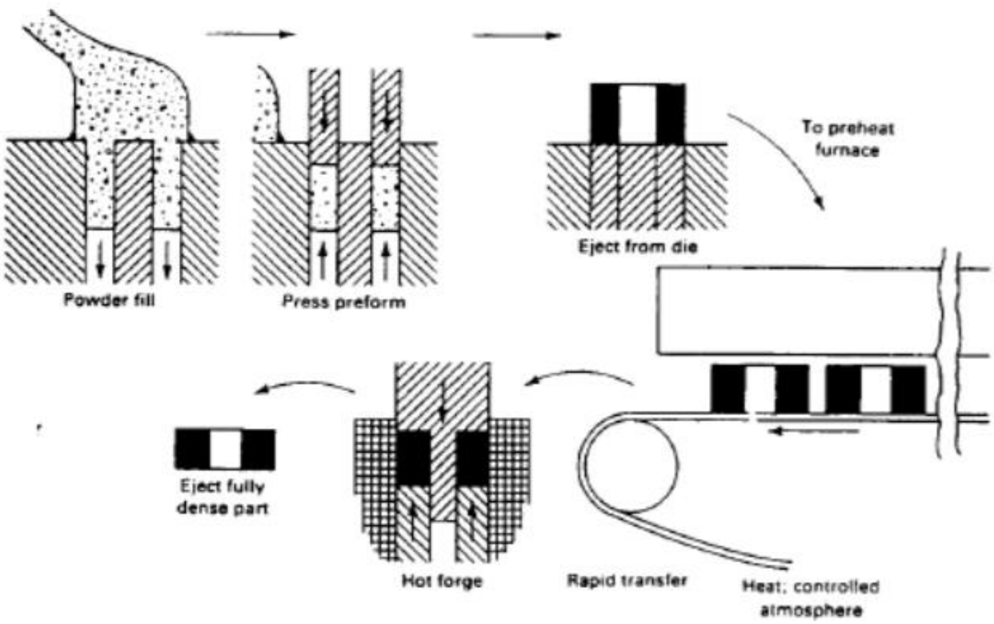
- Cutting the material: The material is cut a little greater than the required due to further process.
- Heating Billets: Billet is heated in the furnace at 500-600^{o} C.
- Hot Forging: Hot forging is defined as working the metal above it recrystallization temperature (for steel it is typically 400-700^{o} C). The main advantage of hot forging is that the metal is deformed and the strain-hardening effects are negated by the recrystallization process.
- Then mechanical processes like piercing, trimming and shot/blast peening is done.
- To ensure proper weight and balance of the finished rod, the rod is forged with extra weight in the form of balancing pads on both ends of the rod. These balancing pads are then machined during 10 the finishing operation to obtain a well-balanced connecting rod.
- The rod and cap are finish machined using several operations including broaching, milling, boring, honing, fringing and other finishing steps. A substantial quantity of metal is removed to get the final dimensions and finish. The quantity of metal removed during the machining process is typically around 25-30% of the drop forged rough stock cap and rod.

Nakamura et al. developed a high fatigue strength, free machining micro alloyed steel specifically for connecting rods. This steel, a 0.3 wt.% carbon steel with additions of vanadium, sulfur, phosphorus and/or calcium, displayed a 26% higher fatigue strength than the traditional connecting rods and displayed equal machine tool life as traditional connecting rods. Because the desired mechanical properties could be achieved in the as-cooled condition, this eliminated the need for any post forging heat-treatment. In addition, the weight of the connecting rod could be reduced by 15% without any reduction in mechanical properties.

C-70, a crack able steel developed in Europe in the early 2000s, has become widely adopted as the standard alloy for crack able wrought forged connecting rods in the United States. It is a steel with a ~0.7 wt.% C level and an essentially fully pearlitic microstructure to allow for cleavage fracture of the rod and cap at room temperature.

Powder metallurgy process:

- Metal powders are first consolidated.
- Then the metal powders are put in a preform that is sintered.
- Then it is reheated to forging temperature (or in some cases forged



subsequently to sintering)

- The metal is then fully densified to final shape.
- The rod cap end is then fractured.

Schematic of powder forging process

Comparing forging and powder metallurgy process:

			Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Density (g/cm^3)	Hardness (HB)
Wrought Hot Forged Conrod	Carbon steel (S48CM)	Specification	608 min	490	17 min	--	179-212
		Measurement	745	481	23	--	214
	Microalloyed (S45CVMn)	Specification	834 min	539 min	12 min	--	247-285
		Measurement	941	569	19	--	295
Powder Forged Conrod	Powder metal (Wedhodit 70)	Specification	696 min	441 min	10 min	7.65 min	200 min
		Measurement	794	530	14	7.71	245

Mechanical Properties of Connecting Rod Materials

Q8. Give details of the material composition, recommended process route, expected property levels for procurement. (2)

A8. Material composition:

Alloying Elements	Percentage(%)
Carbon	0.56
Silicon	0.26
Manganese	0.28
Sulphur	0.014
Phosphorus	0.313
Chromium	0.12
Nickel	0.09

Recommended process route: Forging

- Forging gives consistent and accurate dimensions.
- Reduces mass by 10%.
- Consumes less energy as compared to casting.
- Provides longer tool life.
- Forged steel connecting rods run smoother in engines.
- Less cost of production for more than 20,000 pieces as compared to casting.
- High production rate.
- It can be performed at low temperatures.

Expected Procurement Level:

- Factor of safety must be 2 or above.
- Material should have infinite fatigue life. (Forged Steel has infinite fatigue life but aluminum has a fatigue life of 10^8 cycles)
- Maximum stress developed in the connecting rod must be lower than the yield limit of the material. In case of steel it is 503 MPa.
- Maximum stress and poor fatigue cycles occurs at the fillet section of the CR, redesign at this area, by either deleting the fillet section or increase the thickness at that particular site, is highly recommended to reduce stress concentration.
- Tolerance of surface should be less than 0.025 mm.
- Tolerance of bores should be less than 0.02 mm.
- Roughness should be less than 5μm.

PART B:

Q1. Refine arguments for establishing relative merits of the materialsselected taking into account additional mechanical engineering parametersincluding shape of the object.

The connecting rod is subjected to a combination of axial and bending stresses. Furthermore the connecting rod is subjected to a large compressive load so that it is imperative that buckling does not occur. To mitigate this problem, „I‟- section is commonly used.

In order to select the proper manufacturing process, the economic, technical and quality constraints are employed. The economic constraints involve raw material cost and batch size used in production. The technical constraints consist of estimated connecting rod mass and a minimum section of the connecting rod. The quality constraints involve manufacturing tolerance Page 15.1057.2 and surface roughness. The competitive processes of powder methods and forging are carefully investigated tracking the latest developments in alloy development.

We define the shape factor in bending, ‘k’due to stiffness effects as:

$$k = \frac{s}{s_o} \qquad (1)$$

Here ‘S’ is the stiffness of cross section under consideration, and ‘S_o’ is the stiffness of reference solid square cross-section. It should be noted here that the bending stiffness ‘S’ is proportional to ‘EI’, where ‘E’ is the elastic modulus and ‘I’ is the area moment of inertia. Noting that for a square of side ‘b’ we have, comparing sections(second moment of inertia) of same area, A,

$$I_o = \frac{b^4}{12} = \frac{A^2}{12} \qquad (2)$$

$$k = \frac{s}{s_o} = \frac{EI}{EI_o} = \frac{121}{A^2} \qquad (3)$$

The other shapefactor (k_2) relates the strength-efficiency of the shaped beam, and is measured by the ratio of the section moduli (first moment of inertia) as:

$$k_2 = \frac{Z}{Z_o} \qquad (4)$$

$$Z_o = \frac{b^3}{6} = \frac{A^{3/2}}{6} \qquad (5)$$

Thus,

$$k_2 = \frac{Z}{Z_o} = \frac{6Z}{A^{3/2}} \qquad (6)$$

The failure of the connecting rod (stress exceeding the endurance limit, σ_e) if the limiting moment M_e is reached, that is when,

$$M_e = Z\sigma_e \qquad (7)$$

Replacing Z by expressions in equations (4) and (5) we have,

$$M_e = \frac{k_2}{6}\sigma_e A^{3/2} \qquad (8)$$

If 'A' denotes the area of cross-section of the connecting rod and 'L' its length and 'ρ' the density of the material of which it is made then the mass 'm' is:

$$m = Al\rho \qquad (9)$$

Substituting A from equation (8) into the equation (9) for mass of the connecting rod, we have,

$$m = (6M_e)^{2/3} L \left[\frac{\rho^{3/2}}{k_2\sigma_e}\right]^{2/3} \qquad (10)$$

The best material and shape combination (using maximum bending strength as a criterion) is that withthe greatest value of the new index M_2 , where

$$M_2 = \frac{(k_2\sigma_e)^{2/3}}{\rho} \qquad (11)$$

Similarly, the best material and shape combination (using maximum stiffness as a criterion) is that with the greatest value of the new index M3, where

$$M_3 = \frac{(kE)^{1/2}}{\rho} \qquad (12)$$

Now the material with strength σ_e and density ρ when shaped behaves in bending like a new material of strength and density,

$$\sigma^* = \frac{\sigma_e}{{k_2}^2}$$

$$\rho^* = \frac{\rho}{{k_2}^2}$$

Thus,

Material selection based on strength at a minimum weight:

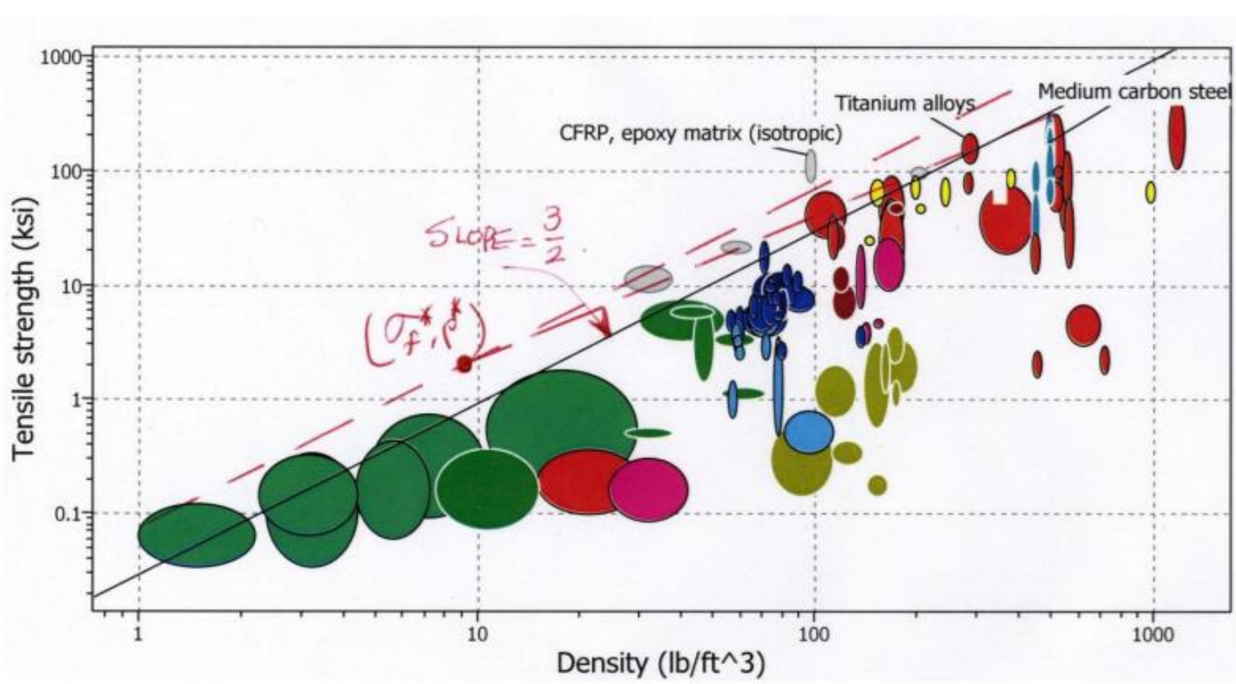
$$M_2 = \frac{{\sigma^*}^{2/3}}{\rho^*}$$

Similarly,

Material selection based on stiffness at a minimum weight:

$$M_3 = \frac{{E^*}^{1/2}}{\rho^*}$$

The co-selections based on minimizing mass for maximum strength and for



maximum stiffness is shown in the below figures.

Fig.1 Tensile Strength(σ) vs. Density(ρ)

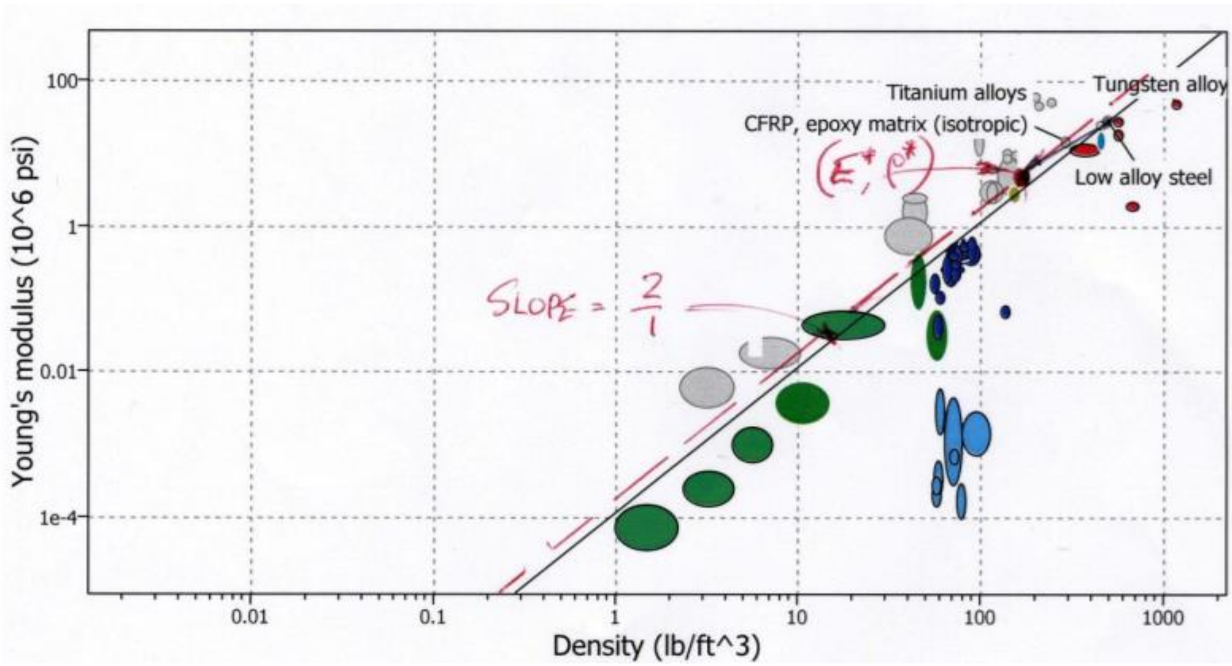


Fig.2 Young’s Modulus(E) vs. Density(ρ)

Fig.1 and 2 clearly show the effect of the section shape on the overall performance in strength and stiffness respectively.

Thus selection of the material can be done on the basis of the following parameters:

- Stiffness
- Strength
- Maximum survival temperature
- Cost per unit

The candidate materials for connecting rod are:

Material	**Tensile Modulus E (GPa)**	**Maximum Compressive Strength, σ (MPa)**	**Density, p (kg m^{-3})**	**Maximum Service Temperature (°C)**	**Unit Cost (\$ t^{-1})**	**Specific Stiffness, E/p (10^{6} m)**	**Specific Compressive Strength, σ$_c$/p (10^{3} m)**
Steel	210	1000	7890	800	880	2.71	12.92
Aluminumalloy	71	280	2700	350	1200	2.68	10.57
Silicon carbideceramic	310	490	3200	1000	5700	9.88	15.61
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Carbon fiber reinforced polymer laminate	138	600	1661	220	130,000	8.47	36.82

For selection of materials we can use the weight factor method which is a formal way of selecting the best material based on use.

Weightage index (for quantities where maximum is preferable),

$$W_i = w_i \frac{M_i}{(M_i)_{max}}$$

Weightage index (for quantities where minimum is preferable),

$$W_i = w_i \frac{(M_i)_{min}}{M_i}$$

M is the value of the properties.
w is the weightage factor.
Thus the best selection is the material with largest value of the sum

$$W = \sum_i W_i = \sum_i w_i \frac{M_i}{(M_i)_{max}}$$

For w_i we can give,

- Stiffness: 0.3
- Strength: 0.3
- Cost: 0.2
- Temperature:0.2

After calculating weightage index we get the following table,

Material	W
Steel	0.57
Aluminum alloy	0.38
Silicon carbide ceramic	0.64
S glass fiber reinforced polymer laminate	0.39
Carbon fiber reinforced polymer laminate	0.6

Since the weightage factor method can just give pointers but not the ideal choice we selection should be based on analytic judgement also.

In this case, though steel has a lower weightage factor than silicon carbide ceramic and carbon fiber reinforced polymer laminate, the cost of steel is much less than the rest.

Also several alloys of steel have been recognized in which the cost of manufacturing is less as well as the stiffness and strength also have increased significantly. For e.g. C-70

SUMMARY:

Manufacturing connecting rods require a lot of analysis related to materials science. I learned that forged steel will perform better than aluminum (in most cases) because of the strength, stiffness, etc. We also know that ductile iron performs better than malleable iron based on the molecular study of the two after fatigue limit test. There are a lot of candidates for manufacturing connecting rods but after material analysis we can identify the ideal candidates and which will have a fatigue life of infinity.