5–11. The assembly consists of two sections of galvanized steel pipe connected together using a reducing coupling at B. The smaller pipe has an outer diameter of 0.75 in. and an inner diameter of 0.68 in., whereas the larger pipe has an outer diameter of 1 in. and an inner diameter of 0.86 in. If the pipe is tightly secured to the wall at C, determine the maximum shear stress developed in each section of the pipe when the couple shown is applied to the handles of the wrench.

\[
\tau_{AB} = \frac{T_c}{J} = \frac{210(0.375)}{\frac{\pi}{2}(0.375^4 - 0.34^4)} = 7.82 \text{ ksi}
\]

\[
\tau_{BC} = \frac{T_c}{J} = \frac{210(0.5)}{\frac{\pi}{2}(0.5^4 - 0.43^4)} = 2.36 \text{ ksi}
\]
5–13. If the tubular shaft is made from material having an allowable shear stress of $\tau_{allow} = 85 \text{ MPa}$, determine the required minimum wall thickness of the shaft to the nearest millimeter. The shaft has an outer diameter of 150 mm.

**Internal Loadings:** The internal torques developed in segments $AB$, $BC$, and $CD$ of the assembly are shown in their respective free-body diagrams shown in Figs. $a$, $b$, and $c$.

**Allowable Shear Stress:** Segment $BC$ is critical since it is subjected to the greatest internal torque. The polar moment of inertia of the shaft is $J = \frac{\pi}{2} (0.075^4 - c_i^4)$.

\[
\tau_{allow} = \frac{T_{BC} c_i}{J} = \frac{85(10^6)}{\frac{\pi}{2} (0.075^4 - c_i^4)}
\]

\[c_i = 0.05022 \text{ m} = 50.22 \text{ mm}\]

Thus, the minimum wall thickness is

\[t = c_o - c_i = 75 - 50.22 = 24.78 \text{ mm} = 25 \text{ mm}\]

Ans:

Use $t = 25 \text{ mm}$
5–31. The solid steel shaft $AC$ has a diameter of 25 mm and is supported by smooth bearings at $D$ and $E$. It is coupled to a motor at $C$, which delivers 3 kW of power to the shaft while it is turning at 50 rev/s. If gears $A$ and $B$ remove 1 kW and 2 kW, respectively, determine the maximum shear stress developed in the shaft within regions $AB$ and $BC$. The shaft is free to turn in its support bearings $D$ and $E$.

\[
T_C = \frac{P}{\omega} = \frac{3 \times 10^3}{50(2\pi)} = 9.549 \text{ N} \cdot \text{m}
\]

\[
T_A = \frac{1}{3} T_C = 3.183 \text{ N} \cdot \text{m}
\]

\[
(\tau_{AB})_{\text{max}} = \frac{T_C}{\frac{J}{2(0.0125^4)}} = 3.183 (0.0125) = 1.04 \text{ MPa}
\]

\[
(\tau_{BC})_{\text{max}} = \frac{T_C}{\frac{J}{2(0.0125^4)}} = 9.549 (0.0125) = 3.11 \text{ MPa}
\]

Ans:

\[
(\tau_{AB})_{\text{max}} = 1.04 \text{ MPa}, \quad (\tau_{BC})_{\text{max}} = 3.11 \text{ MPa}
\]
5–38. The motor \( A \) develops a power of 300 W and turns its connected pulley at 90 rev/min. Determine the required diameters of the steel shafts on the pulleys at \( A \) and \( B \) if the allowable shear stress is \( \tau_{\text{allow}} = 85 \text{ MPa} \).

**Internal Torque:** For shafts \( A \) and \( B \)

\[
\omega_A = \frac{90 \text{ rev}}{\text{min}} \left( \frac{2\pi \text{ rad}}{\text{rev}} \right) \frac{1 \text{ min}}{60 \text{ s}} = 3.00\pi \text{ rad/s}
\]

\[
P = 300 \text{ W} = 300 \text{ N} \cdot \text{m/s}
\]

\[
T_A = \frac{P}{\omega_A} = \frac{300}{3.00\pi} = 31.83 \text{ N} \cdot \text{m}
\]

\[
\omega_B = \omega_A \left( \frac{r_A}{r_B} \right) = 3.00\pi \left( \frac{0.06}{0.15} \right) = 1.20\pi \text{ rad/s}
\]

\[
P = 300 \text{ W} = 300 \text{ N} \cdot \text{m/s}
\]

\[
T_B = \frac{P}{\omega_B} = \frac{300}{1.20\pi} = 79.58 \text{ N} \cdot \text{m}
\]

**Allowable Shear Stress:** For shaft \( A \)

\[
\tau_{\max} = \tau_{\text{allow}} = \frac{T_A c}{J}
\]

\[
85 \left( 10^6 \right) = \frac{31.83 \left( \frac{d_A}{2} \right)}{\pi \left( \frac{d_A}{2} \right)^4}
\]

\[
d_A = 0.01240 \text{ m} = 12.4 \text{ mm} \quad \text{Ans.}
\]

For shaft \( B \)

\[
\tau_{\max} = \tau_{\text{allow}} = \frac{T_B c}{J}
\]

\[
85 \left( 10^6 \right) = \frac{79.58 \left( \frac{d_B}{2} \right)}{\pi \left( \frac{d_B}{2} \right)^4}
\]

\[
d_B = 0.01683 \text{ m} = 16.8 \text{ mm} \quad \text{Ans.}
\]

**Ans:**

\[
d_A = 12.4 \text{ mm}, \quad d_B = 16.8 \text{ mm}
\]
5-46. A motor delivers 500 hp to the shaft, which is tubular and has an outer diameter of 2 in. If it is rotating at 200 rad/s, determine its largest inner diameter to the nearest 1/8 in. if the allowable shear stress for the material is $\tau_{\text{allow}} = 25$ ksi.

\[ P = 500 \text{ hp} \left[ \frac{550 \text{ ft} \cdot \text{lb/s}}{1 \text{ hp}} \right] = 275000 \text{ ft} \cdot \text{lb/s} \]

\[ T = \frac{P}{\omega} = \frac{275000}{200} = 1375 \text{ lb} \cdot \text{ft} \]

\[ \tau_{\text{max}} = \tau_{\text{allow}} = \frac{Tc}{J} \]

\[ 25(10^3) = \frac{1375(12)(1)}{\frac{\pi}{2}(d_{i}^4 - (\frac{d_{o}}{2})^4)} \]

\[ d_{i} = 1.745 \text{ in.} \]

Use $d_{i} = \frac{5}{8} \text{ in.}$  

Ans:

Use $d_{i} = \frac{5}{8} \text{ in.}$
5–49. The A-36 steel axle is made from tubes $AB$ and $CD$ and a solid section $BC$. It is supported on smooth bearings that allow it to rotate freely. If the gears, fixed to its ends, are subjected to 85-N m torques, determine the angle of twist of gear $A$ relative to gear $D$. The tubes have an outer diameter of 30 mm and an inner diameter of 20 mm. The solid section has a diameter of 40 mm.

\[
\phi_{A/D} = \sum \frac{T L}{JG}
\]

\[
= \frac{2(85)(0.4)}{\frac{1}{2}(0.015^4 - 0.01^4)(75)(10^9)} + \frac{(85)(0.25)}{\frac{1}{2}(0.02^4)(75)(10^9)}
\]

\[
= 0.01534 \text{ rad} = 0.879^\circ
\]

Ans: $\phi_{A/D} = 0.879^\circ$
5–62. The two shafts are made of A992 steel. Each has a diameter of 1 in., and they are supported by bearings at A, B, and C, which allow free rotation. If the support at D is fixed, determine the angle of twist of end A when the torques are applied to the assembly as shown.

**Internal Torque:** As shown on FBD.

**Angle of Twist:**

\[
\phi_E = \sum \frac{TL}{JG}
\]

\[
= \frac{1}{\frac{\pi}{2} (0.5^4)(11.0)(10^6)} \left[ -60.0(12)(30) + 20.0(12)(10) \right]
\]

\[
= -0.01778 \text{ rad} = 0.01778 \text{ rad}
\]

\[
\phi_F = \frac{6}{4} \phi_E = \frac{6}{4} (0.01778) = 0.02667 \text{ rad}
\]

\[
\phi_{A/F} = \frac{T_{GF} L_{GF}}{JG}
\]

\[
= \frac{-40(12)(10)}{\frac{\pi}{2} (0.5^5)(11.0)(10^6)}
\]

\[
= -0.004445 \text{ rad} = 0.004445 \text{ rad}
\]

\[
\phi_A = \phi_F + \phi_{A/F}
\]

\[
= 0.02667 + 0.004445
\]

\[
= 0.03111 \text{ rad} = 1.78^\circ
\]

**Ans:**

\[
\phi_A = 1.78^\circ
\]
5–66. The A-36 hollow steel shaft is 2 m long and has an outer diameter of 40 mm. When it is rotating at 80 rad/s, it transmits 32 kW of power from the engine $E$ to the generator $G$. Determine the smallest thickness of the shaft if the allowable shear stress is $\tau_{\text{allow}} = 140 \text{ MPa}$ and the shaft is restricted not to twist more than 0.05 rad.

\[
P = T \omega
\]
\[
32(10^3) = T(80)
\]
\[
T = 400 \text{ N} \cdot \text{m}
\]

Shear stress failure
\[
\tau = \frac{Tc}{J}
\]
\[
\tau_{\text{allow}} = 140(10^6) = \frac{400(0.02)}{\frac{\pi}{2}(0.02^4 - r_i^4)} \quad r_i = 0.01875 \text{ m}
\]

Angle of twist limitation:
\[
\phi = \frac{TL}{JG}
\]
\[
0.05 = \frac{400(2)}{\frac{\pi}{2}(0.02^4 - r_i^4)(75)(10^9)}
\]
\[
r_i = 0.01247 \text{ m} \quad \text{(controls)}
\]
\[
t = r_o - r_i = 0.02 - 0.01247 = 0.00753 \text{ m} = 7.53 \text{ mm}
\]

\textbf{Ans.}

\textbf{Ans:}

\( t = 7.53 \text{ mm} \)
The steel shaft is made from two segments: AC has a diameter of 0.5 in., and CB has a diameter of 1 in. If the shaft is fixed at its ends A and B and subjected to a torque of 500 lb·ft, determine the maximum shear stress in the shaft. \( G_{\text{st}} = 10.8 \times 10^3 \) ksi.

**Equilibrium:**

\[ T_A + T_B - 500 = 0 \]  
(1)

**Compatibility condition:**

\[ \phi_{DA} = \phi_{DB} \]

\[ \frac{T_A(5)}{\frac{1}{2}(0.25^4)G} + \frac{T_A(8)}{\frac{1}{2}(0.5^4)G} = \frac{T_B(12)}{\frac{1}{2}(0.5^4)G} \]

\[ 1408 T_A = 192 T_B \]  
(2)

Solving Eqs. (1) and (2) yields

\[ T_A = 60 \text{ lb} \cdot \text{ft} \quad T_B = 440 \text{ lb} \cdot \text{ft} \]

\[ \tau_{AC} = \frac{T_C}{J} = \frac{60(12)(0.25)}{\frac{1}{2}(0.25^4)} = 29.3 \text{ ksi} \quad \text{(max)} \]

\[ \tau_{DB} = \frac{T_C}{J} = \frac{440(12)(0.5)}{\frac{1}{2}(0.5^4)} = 26.9 \text{ ksi} \]

**Ans:**

\[ \tau_{\text{max}} = 29.3 \text{ ksi} \]
5–87. Determine the rotation of the gear at $E$ in Prob. 5–86.

**Equilibrium:**

\[ T_A + F(0.1) - 500 = 0 \]  \[ T_B - F(0.05) = 0 \]

From Eqs. [1] and [2]

\[ T_A + 2T_B - 500 = 0 \]

**Compatibility:**

\[ 0.1\phi_E = 0.05\phi_F \]

\[ \phi_E = 0.5\phi_F \]

\[ \frac{T_A(1.5)}{JG} = 0.5 \left[ \frac{T_B(0.75)}{JG} \right] \]

\[ T_A = 0.250T_B \]

Solving Eqs. [3] and [4] yields:

\[ T_B = 222.22 \text{ N} \cdot \text{m} \quad T_A = 55.56 \text{ N} \cdot \text{m} \]

**Angle of Twist:**

\[ \phi_E = \frac{T_A L}{JG} = \frac{55.56(1.5)}{\frac{\pi}{2}(0.0125^4)(75.0)(10^3)} \]

\[ = 0.02897 \text{ rad} = 1.66^\circ \]

Ans: \[ \phi_E = 1.66^\circ \]