MCT-241: Design of Machine Elements

CEA Problem: Analysis & Design of a Twin-Turbo v6 Engine in SolidWorks

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Domain Specification:

The project falls under the domain of automotive and mechanical engineering design, focusing on the development and analysis of high-performance internal combustion engines.

Nature of CEA:

This project involves mechanical component design, computer-aided engineering (CAE)

analysis, and the study of the thermodynamic, structural, and fluid dynamics aspects of an engine assembly.

Where Does the Assembly Come From / What Machinery Are We Taking the Assembly From:

The twin-turbo V6 engine assembly is inspired by modern automotive designs found in high-performance sports cars such as the **Nissan GT-R** and **Ford GT**, as well as in luxury SUVs like the **Porsche Cayenne**. These engines deliver high power outputs while maintaining a compact size, making them ideal for vehicles prioritizing performance and efficiency.

Application Area:

- **Automobiles:** Sports cars, luxury sedans, and high-performance SUVs.
- **Marine vessels:** High-performance speedboats.
- **Industrial machinery:** High-output generators and pumps (as a compact power source).

Expected Parts to Design:

The assembly will include the following major components:

1. **Cylinder Block:** Houses the six cylinders arranged in a "V" configuration.
2. **Pistons and Connecting Rods:** Transfer energy from combustion to the crankshaft. 3. Crankshaft: Converts reciprocating motion into rotational motion.
3. **Camshafts and Valves:** Control the intake of air/fuel mixture and exhaust gases.
4. **Turbochargers:** Two units to compress air for increased engine performance.
5. **Intake and Exhaust Manifolds:** Channel air and exhaust gases.
6. **Cooling System:** Radiators and coolant channels for thermal management.
7. **Oil System:** For lubrication and cooling of moving parts.
8. **Flywheel:** For smooth engine operation.

Design Consideration:

- **Performance:** Achieving high power output while maintaining efficiency.
- **Compactness:** Ensuring the design fits into standard automotive engine bays.
- **Material Selection:** Aluminum alloys for weight reduction and thermal properties; steel for components requiring high strength.
- **Thermal Management:** Designing cooling channels and intercoolers for the twin turbos.
- **Stress Analysis:** Accounting for high pressures in the combustion chamber and forces on moving components.
- **Manufacturability:** Ensuring realistic tolerance and assembly methods.

Problem Explanation:

The main challenge is designing a twin-turbo V6 engine that balances performance, efficiency, and durability while being manufacturable and suitable for real-world applications. Specific issues include:

- **Complex Assembly:** Coordinating multiple moving parts and subsystems like
- turbochargers and cooling.
- **Structural Analysis:** Ensuring components can withstand stresses from combustion and high-speed rotation.
- **Heat Dissipation:** Managing the heat generated by both the engine and the
- Turbochargers.

Overall Working of the Project (Brief Explanation):

The twin-turbo V6 engine operates by drawing in air through the turbochargers, which compress the air to increase its density. This compressed air enters the combustion chamber, where it mixes with fuel. After ignition, the resulting expansion of gases drives the pistons, which in turn rotate the crankshaft to generate mechanical power. Turbochargers further enhance performance by utilizing exhaust gases to boost air intake, leading to higher power output for the same engine displacement.

Objectives:

- **Design:**
    a. Create a 3D model of the twin-turbo V6 engine in SolidWorks.
    b. Ensure all components are dimensionally accurate and fit together in the assembly.
- **Analysis:**
    a. Perform structural analysis of the cylinder block, pistons, and crankshaft. b. Conduct thermal analysis to evaluate the cooling system's effectiveness. c. Simulate fluid dynamics for intake and exhaust flow.
- **Deriving Equations:**
    a. Calculate thermodynamic efficiencies using air-standard assumptions. b. Analyze force and torque equations for crankshaft operation. c. Determine stress and strain values for high-stress components.

Conceptual Design of the Twin-Turbo V6 Engine Assembly:

The following illustration represents a conceptual design for the proposed twin-turbo V6 engine. While it does not depict the exact final design to be implemented, it serves as a visual guide to understand the working principles and overall functionality of the engine.

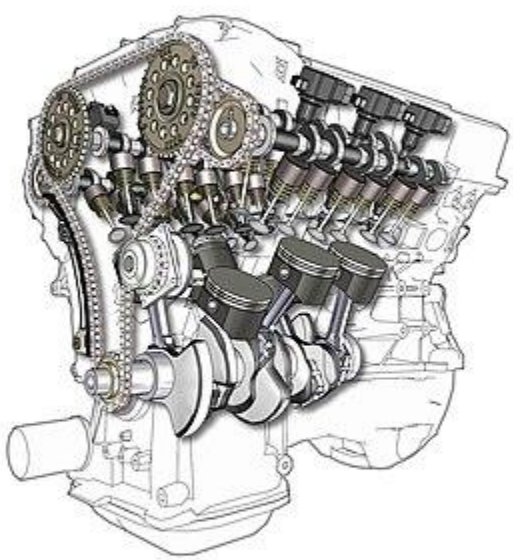


Fig1.1: Cutaway view of a V6 engine with double overhead camshafts (Wikipedia)

Mathematical Equations for Twin-Turbo v6 Engine:

Designing a twin-turbo V6 engine involves several interconnected mathematical models, focusing on thermodynamics, fluid dynamics, and mechanical aspects. Below is a step-by-step breakdown of the essential equations for each component.

Engine Basics:

Engine Displacement

The displacement of the engine is calculated as:

$$V_{\text{disp}} = \frac{\pi}{4} \cdot B^2 \cdot S \cdot N$$

Where:

- V_{disp}: Engine displacement (m^3 or L)
- B: Bore diameter (m)
- S: Stroke length (m)
- N: Number of cylinders (6 for a V6)

Compression Ratio (CR)

$$CR = \frac{V_{\text{cyl}} + V_{\text{clearance}}}{V_{\text{clearance}}}$$

Where:

- $V_{\text{cyl}} = \frac{V_{\text{disp}}}{N}$: Volume of one cylinder (m^3)
- $V_{\text{clearance}}$: Clearance volume at TDC (m^3)

Air-Fuel Ratio (AFR)

The stoichiometric AFR for gasoline is:

$$AFR = \frac{\text{Mass of air}}{\text{Mass of fuel}}$$

For turbocharging, the AFR is slightly adjusted for boosted air intake:

$$\dot{m}_{\text{air}} = \frac{\eta_{\text{vol}} \cdot V_{\text{disp}} \cdot \rho_{\text{air}}}{2 \cdot n}$$

Where:

- $\dot{m}_{\text{air}}$: Mass flow rate of air (kg/s)
- η_{vol}: Volumetric efficiency (dimensionless, typically 0.85–0.95)
- n: Engine speed in revolutions per second (rps)
- ρ_{air}: Air density (kg/m³, adjusted for pressure/temperature)

Turbocharging System:

Boost Pressure

The boost pressure generated by the turbocharger is:

$$P_{\text{boost}} = P_{\text{manifold}} - P_{\text{ambient}}$$

Where:

- P_{boost}: Boost pressure (Pa)
- $P_{\text{manifold}} = P_{\text{ambient}} \cdot \Pi_{\text{c}}$: Intake manifold pressure (Pa)
- Π_{c}: Pressure ratio of the turbocharger

Compressor Power

The power required by the compressor is:

$$P_{\text{comp}} = \frac{\dot{m}_{\text{air}} \cdot C_p \cdot T_{\text{in}}}{\eta_{\text{comp}}} \cdot \left[(\Pi_{\text{c}})^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

Where:

- C_p: Specific heat capacity of air at constant pressure (J/kg·K)
- T_{in}: Intake air temperature (K)
- η_{comp}: Compressor efficiency (dimensionless, 0.7–0.9)
- γ: Ratio of specific heats ($\gamma = 1.4$ for air)

Turbine Power

The power extracted by the turbine is:

$$P_{\text{turb}} = \eta_{\text{turb}} \cdot \dot{m}_{\text{exh}} \cdot C_p \cdot T_{\text{exh}} \cdot \left[1 - \left(\frac{P_{\text{turb-out}}}{P_{\text{exh}}}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

Where:

- $\dot{m}_{\text{exh}}$: Mass flow rate of exhaust gases (kg/s)
- T_{exh}: Exhaust gas temperature (K)
- $P_{\text{turb-out}}$: Pressure at turbine outlet (Pa)
- P_{exh}: Exhaust manifold pressure (Pa)

Matching Compressor and Turbine

For a balanced design:

$$P_{\text{comp}} = P_{\text{turb}}$$

This ensures that the turbine can power the compressor effectively.

Engine Performance:

Brake Mean Effective Pressure (BMEP)

$$BMEP = \frac{2 \cdot \pi \cdot T_{\text{eng}}}{V_{\text{disp}}}$$

Where:

- T_{eng}: Engine torque (Nm)

Power Output:

Brake Power:

The brake power is:

$$P_{\text{brake}} = 2 \cdot \pi \cdot n \cdot T_{\text{eng}}$$

Thermal Efficiency

$$\eta_{\text{thermal}} = \frac{\dot{W}_{\text{out}}}{\dot{Q}_{\text{in}}} = \frac{P_{\text{brake}}}{\dot{m}_{\text{fuel}} \cdot LHV}$$

Where:

- $\dot{W}_{\text{out}}$: Brake power output (W)
- $\dot{Q}_{\text{in}}$: Energy input from fuel combustion (W)
- LHV: Lower heating value of the fuel (J/kg)

Volumetric Efficiency

$$\eta_{\text{vol}} = \frac{\text{Actual air intake mass flow rate}}{\text{Theoretical air intake mass flow rate}}$$

Twin-Turbo Configuration:

In a twin-turbo V6, the two turbochargers split the exhaust gases. For a parallel configuration:

$$\dot{m}_{\text{air},1} = \dot{m}_{\text{air},2} = \frac{\dot{m}_{\text{air}}}{2}$$

$$P_{\text{boost},1} = P_{\text{boost},2}$$

The compressor maps for both turbos must match the engine's flow requirements.

Input:

The engine requires the following inputs to function:

Energy Input:

The primary source of energy for the engine comes from:

- **Fuel:** Typically, gasoline or another hydrocarbon fuel.

- **Mass flow rate of fuel:**

$$\dot{m}_{\text{fuel}} = \frac{\dot{m}_{\text{air}}}{AFR}$$

Where AFR is the air-fuel ratio.

- **Chemical energy in fuel:**

$$\dot{Q}_{\text{in}} = \dot{m}_{\text{fuel}} \cdot LHV$$

LHV: Lower heating value of the fuel (J/kg).

Air Input:

Air is required for combustion:

- **Mass flow rate of air**

$$\dot{m}_{\text{air}} = \frac{\eta_{\text{vol}} \cdot V_{\text{disp}} \cdot \rho_{\text{air}}}{2 \cdot n}$$

Adjusted for turbocharged intake:

$$\rho_{\text{air}} = \frac{P_{\text{boost}}}{R \cdot T_{\text{intake}}}$$

P_{boost}: Boost pressure (Pa), R: Gas constant (J/kg·K), T_{intake}: Intake air temperature (K).

Mechanical Inputs

- **Crankshaft rotation:** Initial rotation (via starter motor) to begin the cycle.
- **Lubrication system:** Ensures reduced friction and longevity of moving parts.
- **Cooling system:** Prevents overheating by dissipating excess heat.

Output:

The outputs of the engine include energy, mechanical work, and by-products.

Useful Output:

- ***Mechanical Power (Brake Power)***

This is the **usable power** delivered to the wheels:

$$P_{\text{brake}} = 2 \cdot \pi \cdot n \cdot T_{\text{eng}}$$

- n: Engine speed (rps)
- T_{eng}: Torque output of the engine (Nm)

- ***Exhaust Flow (Drives Turbocharger)***

The exhaust gases provide the energy to spin the turbochargers:

Exhaust mass flow rate

$$\dot{m}_{\text{exh}} = \dot{m}_{\text{fuel}} + \dot{m}_{\text{air}}$$

- **Exhaust temperature (*Texh*):** Calculated using energy balance in the combustion chamber.

Performance Metrics:

- **Torque (T_{eng})**
- **Horsepower (P_{brake})**
- **Thermal efficiency (η_{thermal})**

By-products:

Heat

A significant portion of the fuel's energy is lost as heat:

$$\dot{Q}_{\text{loss}} = \dot{Q}_{\text{in}} - \dot{W}_{\text{out}} - \dot{Q}_{\text{exhaust}}$$

Where:

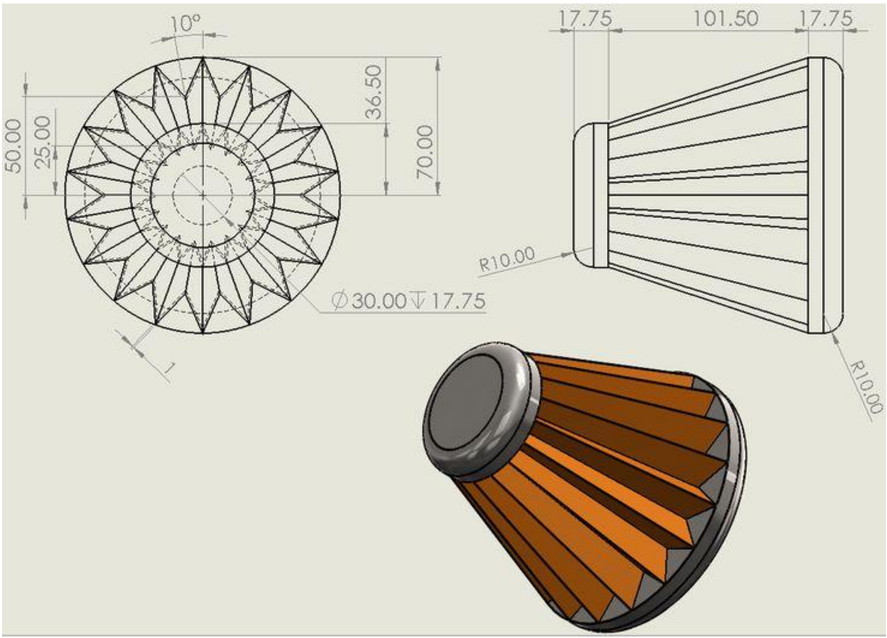
- $\dot{Q}_{\text{loss}}$: Heat dissipated to the cooling system and surroundings.
- $\dot{Q}_{\text{exhaust}}$: Heat carried by exhaust gases.

Exhaust Gases

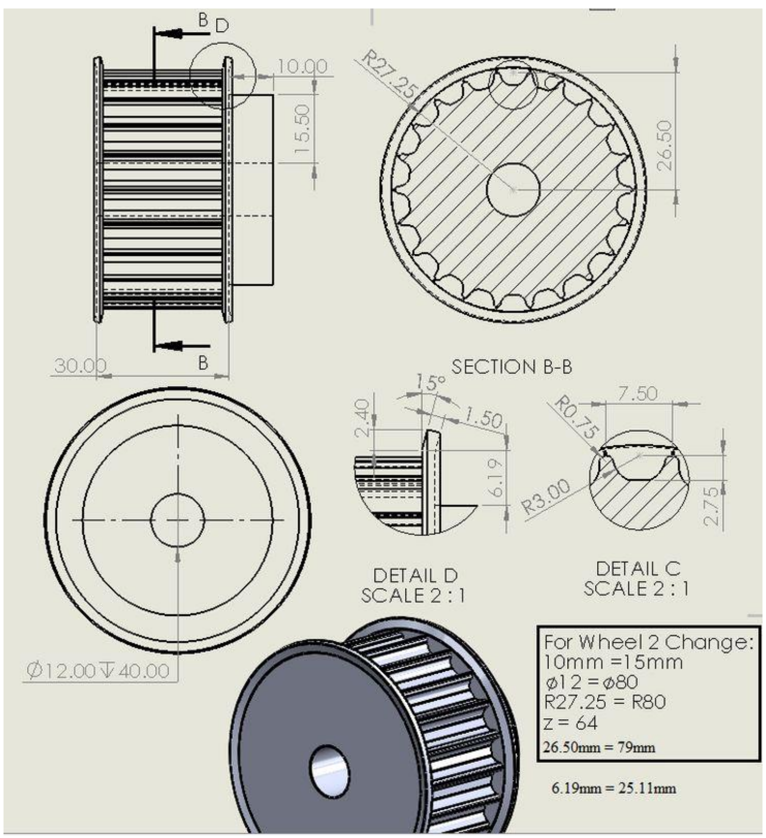
Combustion produces:

- CO2 ,H2O,NOx ,CO,HC,PM (particulate matter).

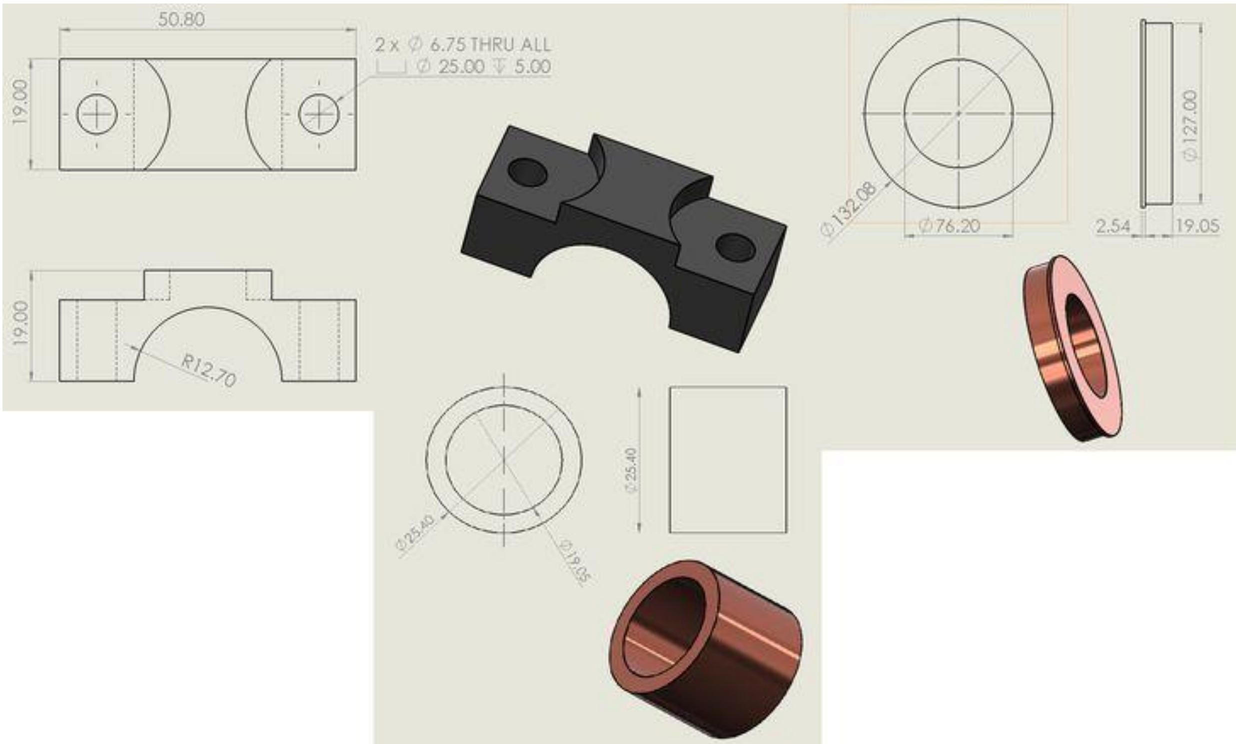
Design Sketches:



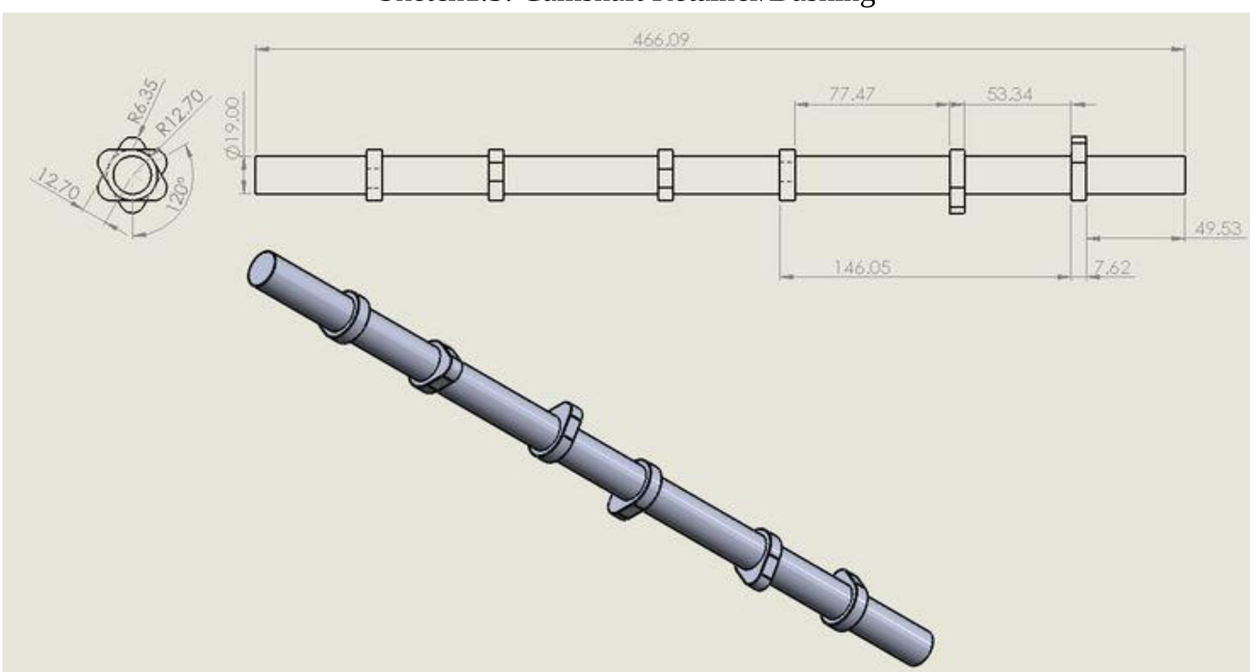
Sketch1.1: Air Filter



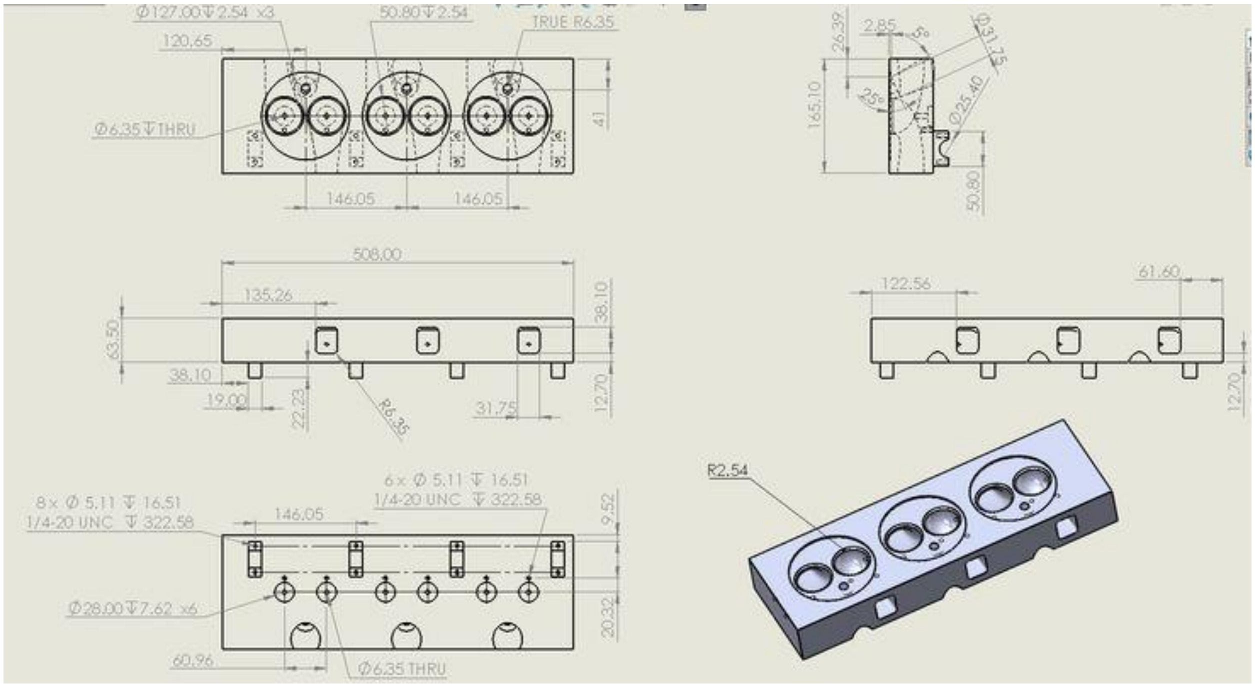
Sketch1.2: Belt Wheels



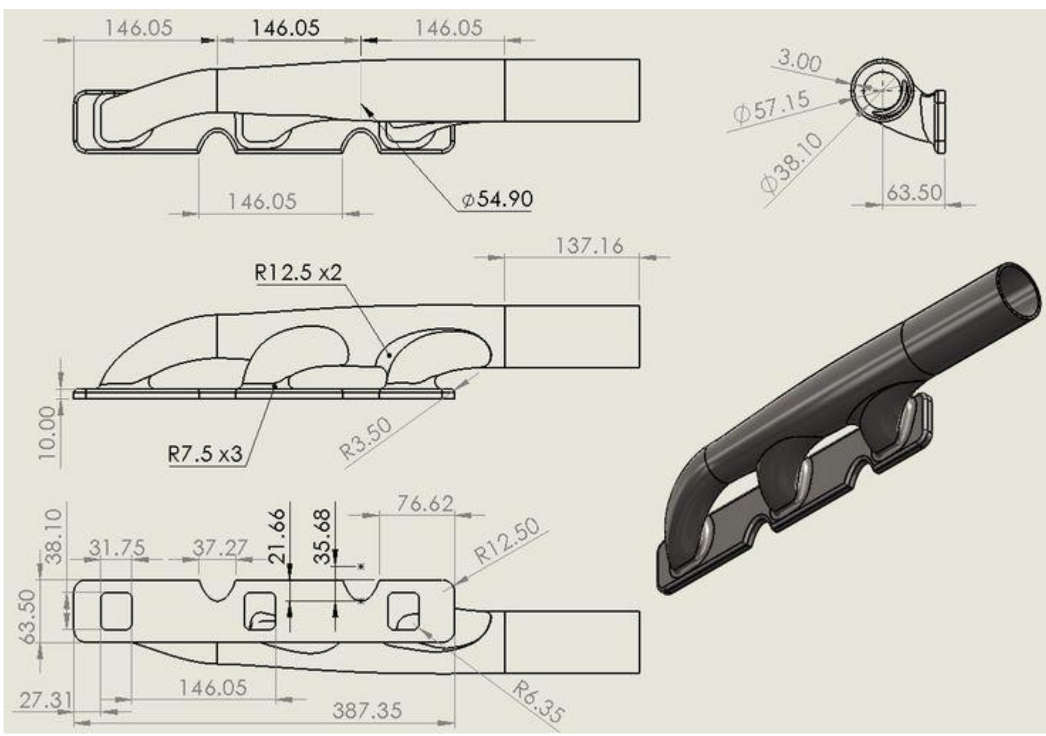
Sketch1.3: Camshaft Retainer/Bushing



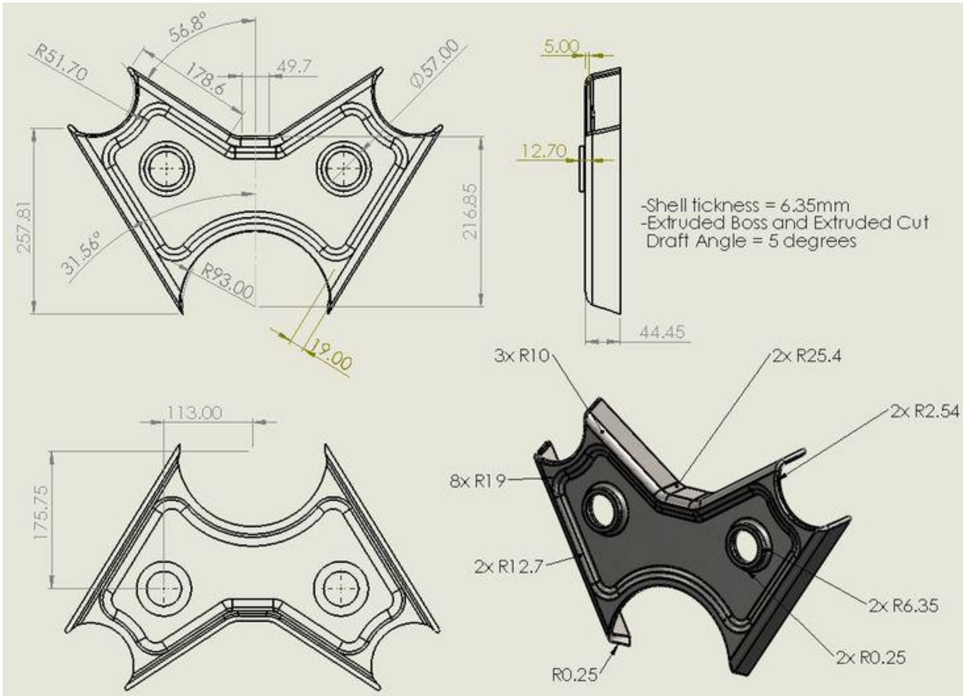
Sketch1.4: Camshaft



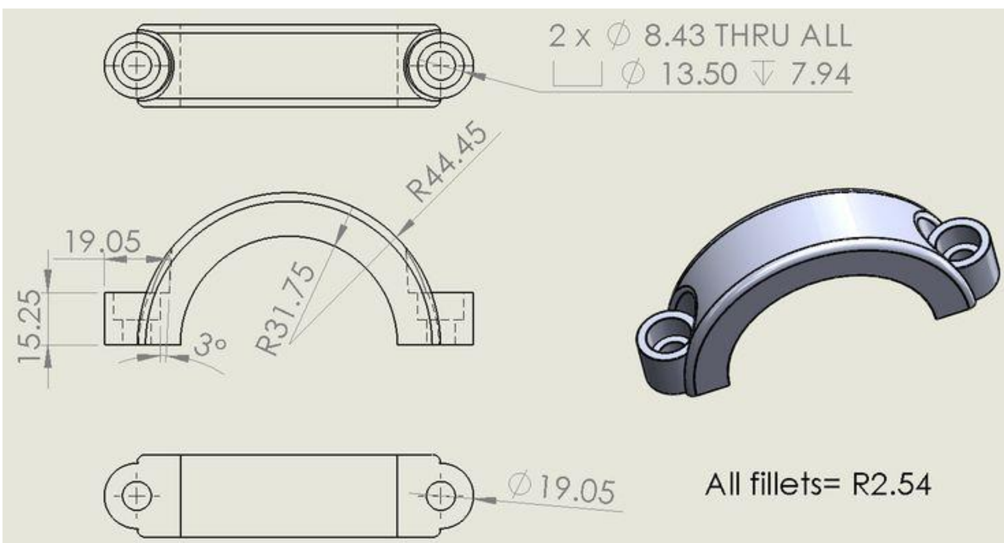
Sketch1.5: Cylinder Head



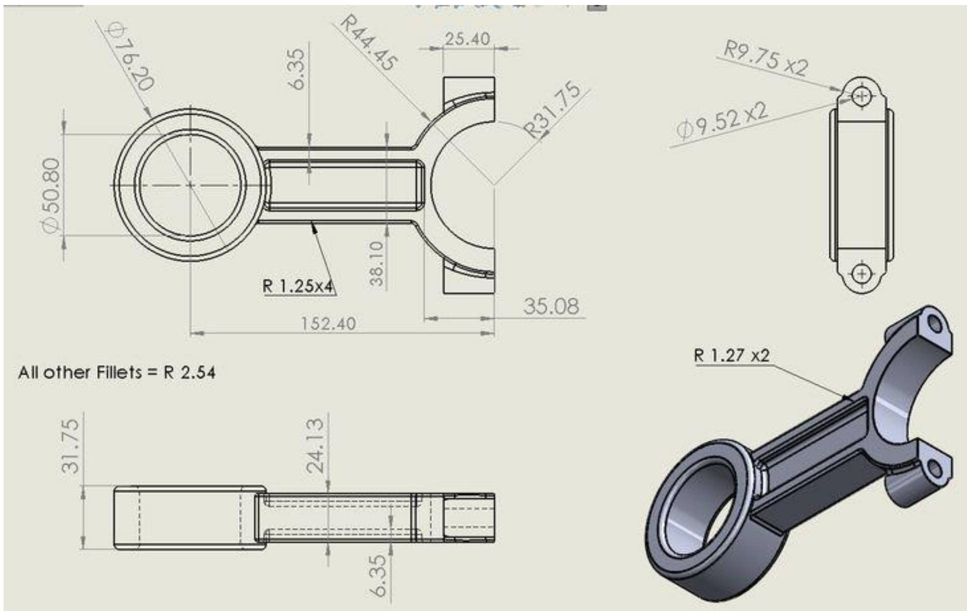
Sketch1.6: Exhaust Manifold



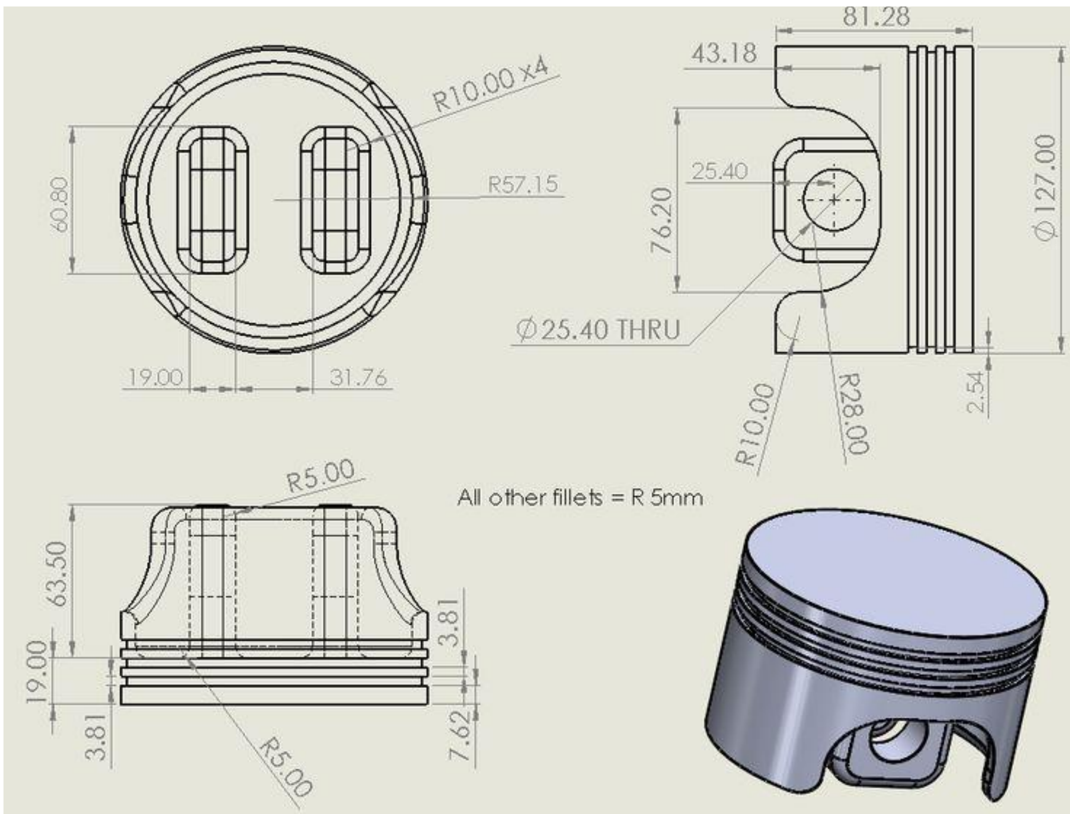
Sketch1.7: Front Cover



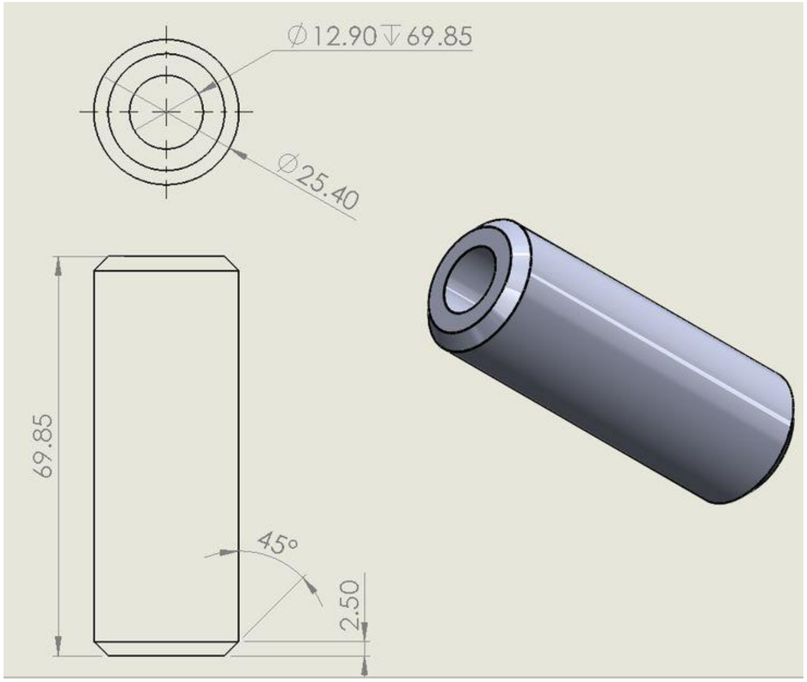
Sketch1.8: Piston Holder



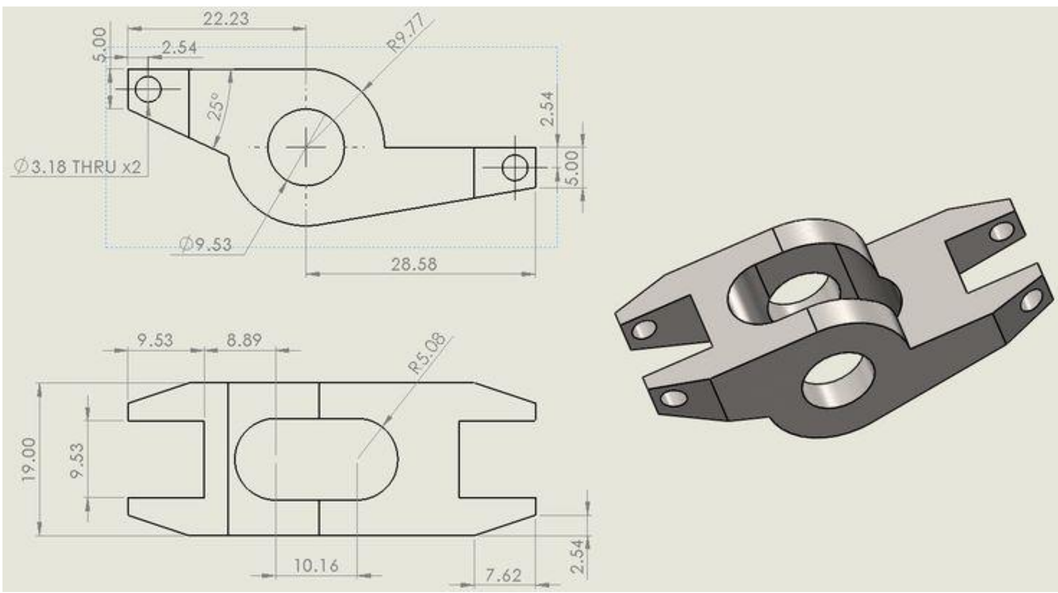
Sketch1.9: Piston Arm



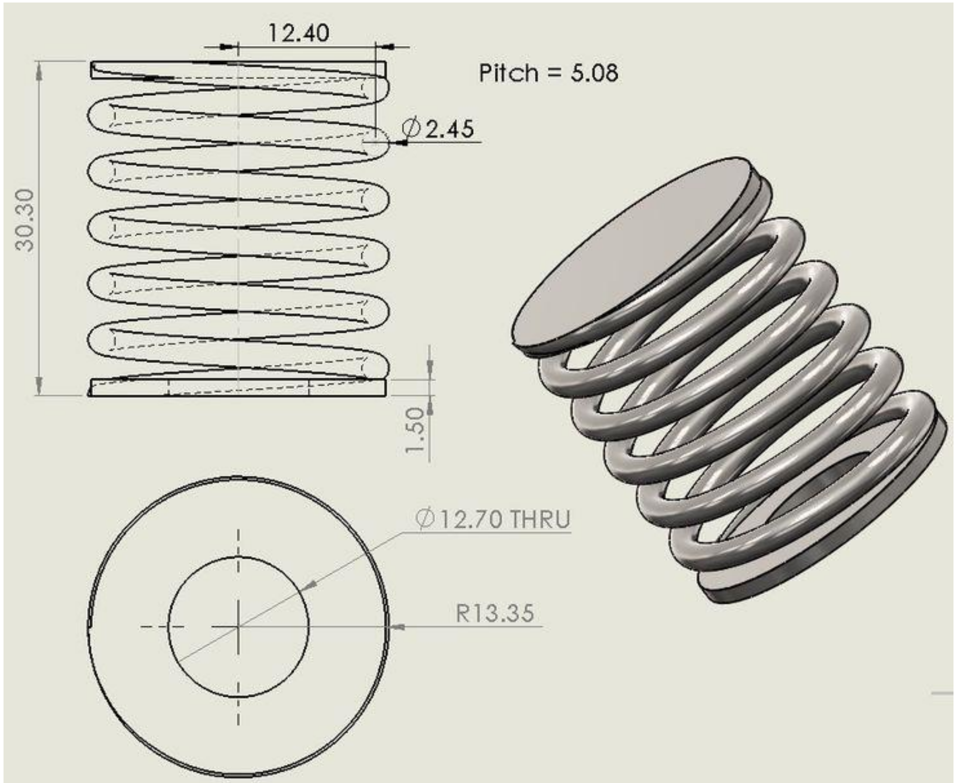
Sketch2.0: Piston Head



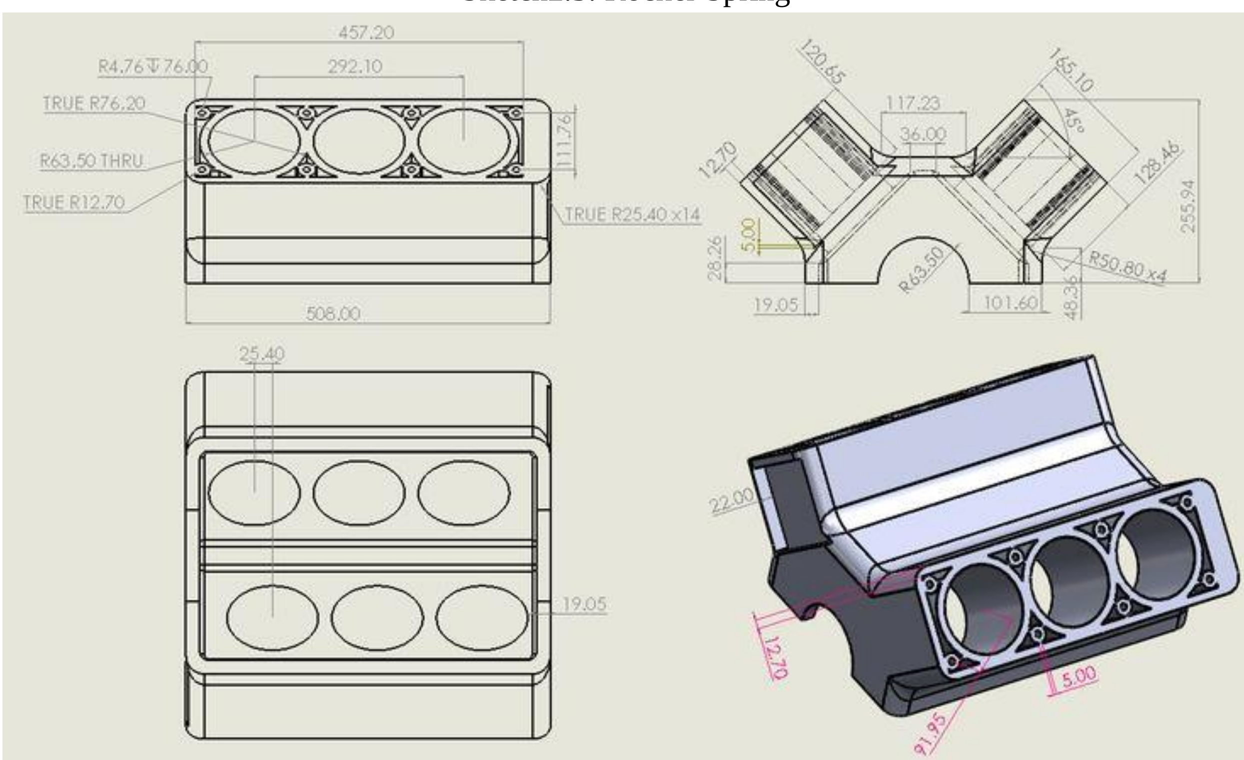
Sketch2.1: Piston Pin



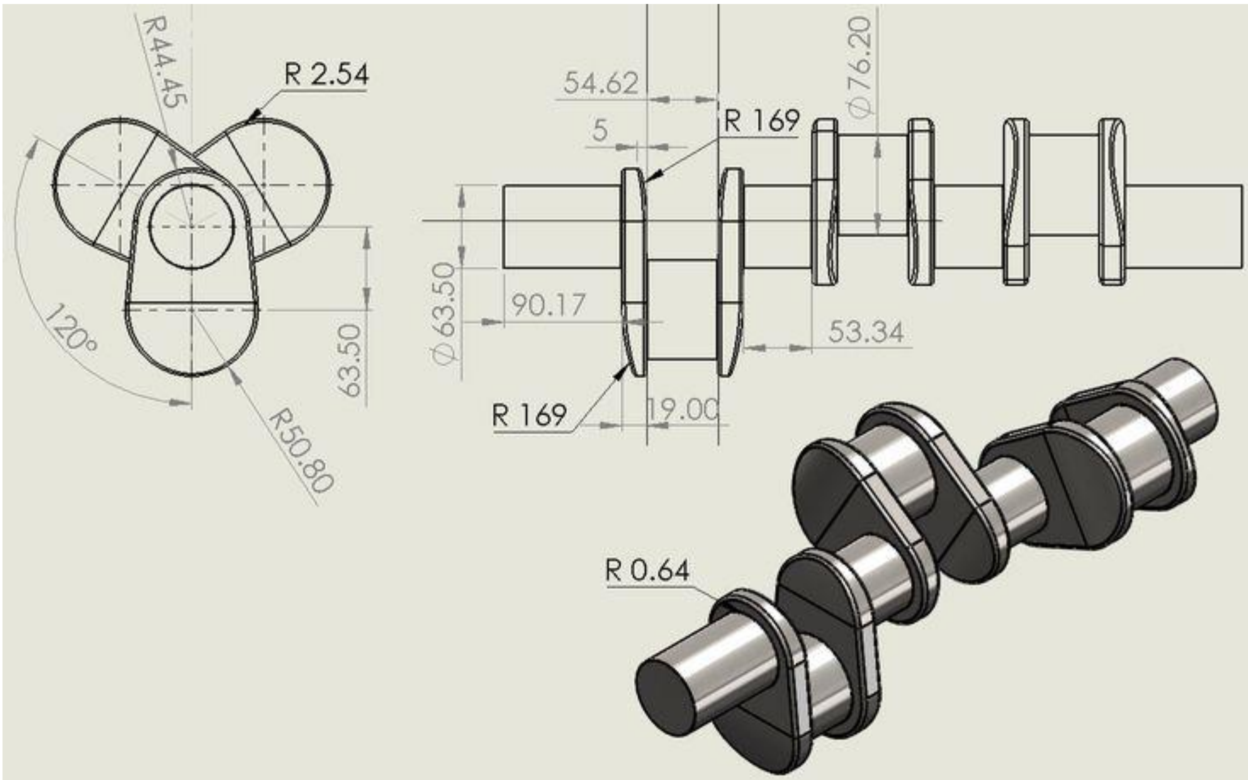
Sketch2.2: Rocker Arm



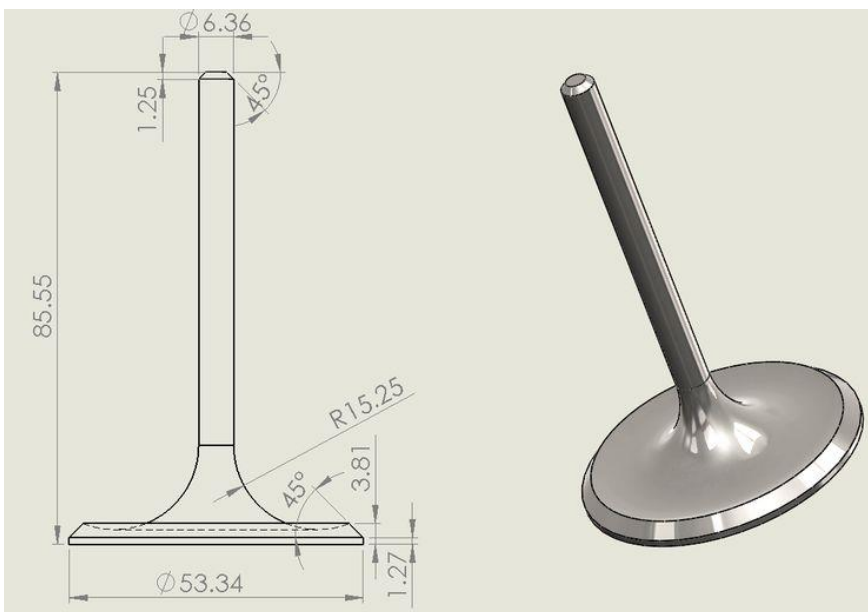
Sketch2.3: Rocker Spring



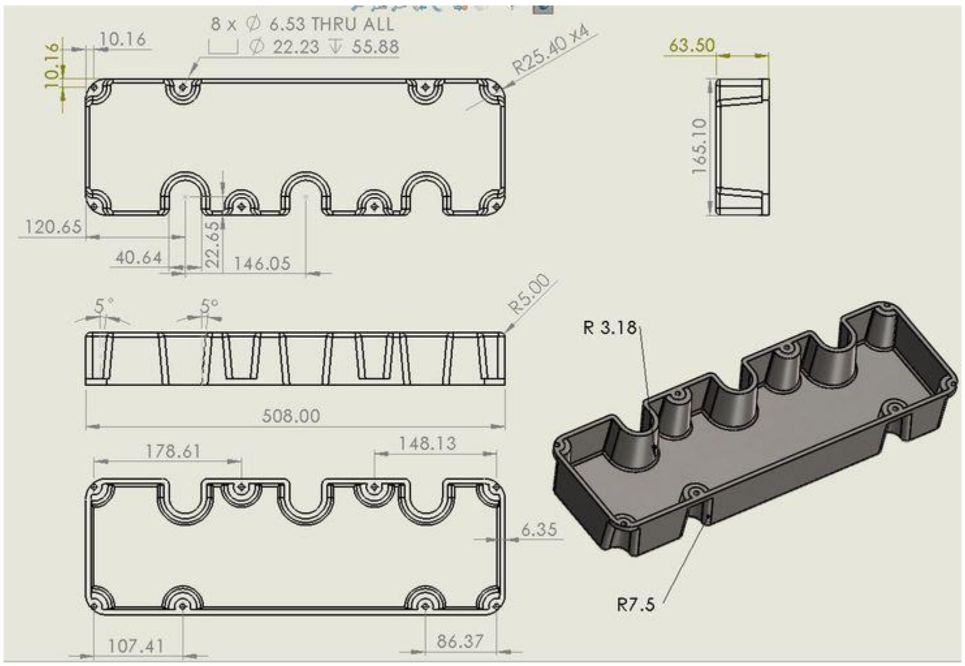
Sketch2.4: Engine Block



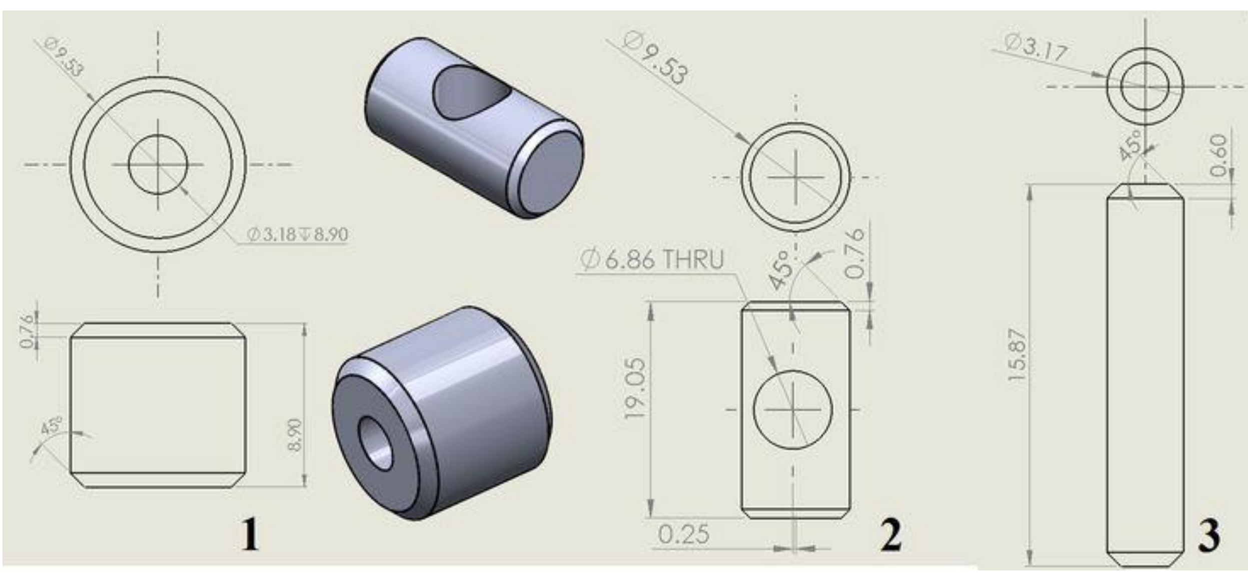
Sketch2.5: Crank Shaft



Sketch2.6: Valve

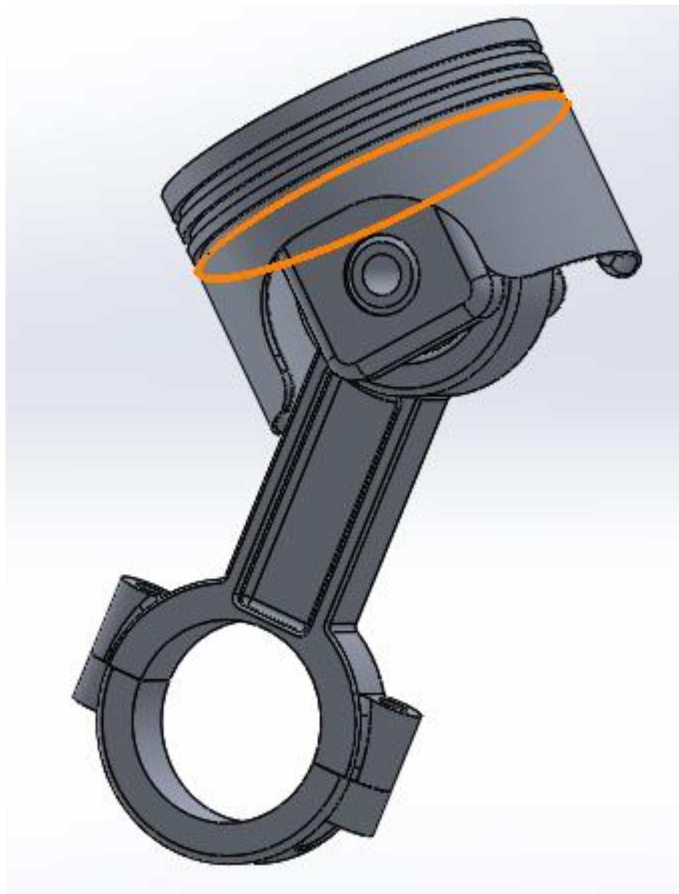


Sketch2.7: Valves Cover

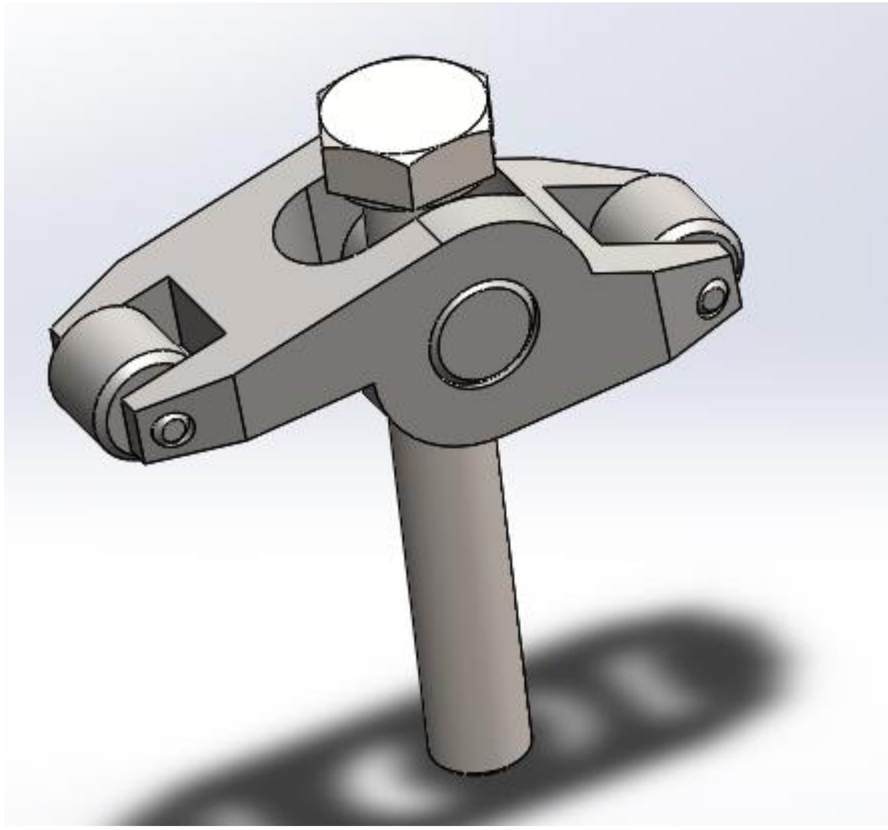


Sketch2.8: Rocker Wheels/Pins

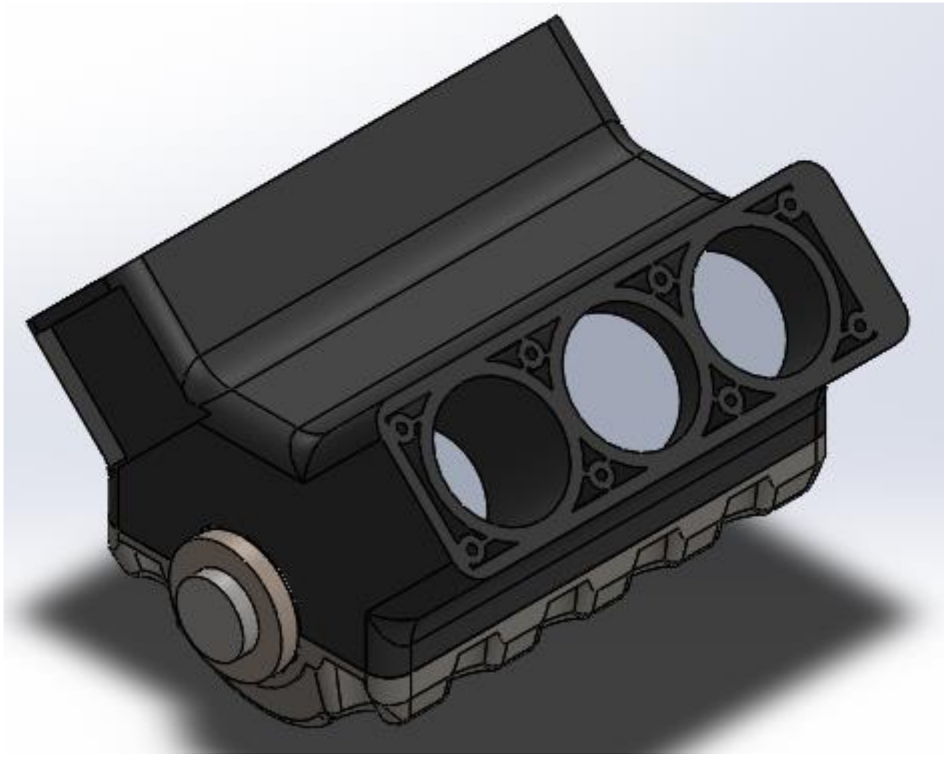
Machine Assemblies:



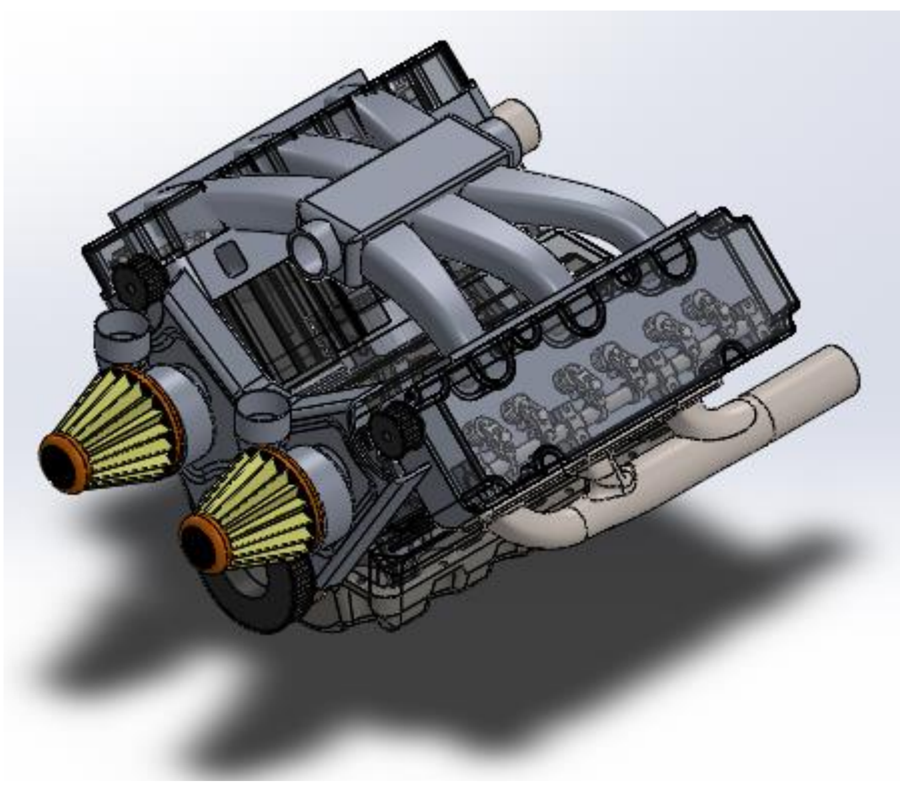
Assem1.1: Piston Assembly



Assem1.2: Rocker Arm Assembly



Assem1.3: Lower Engine Block Assembly



Assem1.4: Upper Engine Block Assembly

Materials Selected for Required Parts:

Air Filter:

Material: Polypropylene (SAE J1647 compliant)

Lightweight, corrosion-resistant, and suitable for filtering air efficiently.

Air Turbo:

Material: Aluminum Alloy 2618 (ASMA B209 compliant)

High strength-to-weight ratio and excellent thermal conductivity for turbo applications.

Belt Wheel:

Material: Cast Iron (ASTM A48 Grade 30)

Provides durability and wear resistance for high-stress operations.

Camshaft:

Material: Steel AISI 8620 (SAE J404 compliant)

Offers high fatigue resistance and wear properties for continuous motion.

Camshaft Bushings:

Material: Bronze SAE 660 (ASTM B505)

Excellent low-friction properties for rotating components.

Camshaft Retainer:

Material: Steel AISI 4140 (SAE J404 compliant)

Durable and capable of withstanding high stress.

Crank Shaft:

Material: Forged Steel AISI 4340 (SAE AMS 6415)

High tensile strength and toughness for dynamic loads.

Cylinder Head:

Material: Aluminum Alloy A356-T6 (ASTM B26)

Lightweight with superior heat dissipation properties.

Engine Block:

Material: Cast Iron ASTM A536 Grade 65-45-12

Durable and wear-resistant for structural integrity, or Aluminum Alloy 319 for lightweight applications.

Exhaust Manifold:

Material: Stainless Steel AISI 321 (SAE J405 compliant)

High corrosion and temperature resistance for exhaust gases.

Front Cover:

Material: Aluminum Alloy 319 (ASTM B85)

Lightweight and durable for heat dissipation.

Intake Manifold:

Material: Glass-Reinforced Nylon (ASTM D4065 compliant)

Cost-effective and lightweight alternative for improved airflow.

Oil Pan:

Material: Aluminum Alloy A356-T6 (ASTM B26)

Corrosion-resistant and lightweight for oil containment.

Piston Arm / Piston Cap:

Material: Aluminum Alloy 2618 (ASMA B209 compliant)

High thermal stability and strength-to-weight ratio for piston components.

Piston Holder:

Material: Steel AISI 4140 (SAE J404 compliant)

Ensures toughness and strength under load.

Piston Ring:

Material: High-Alloy Steel AISI 50110 (SAE AMS 2303)

Provides wear resistance and thermal stability under high pressures.

Rocker Arm / Rocker Arm Wheel:

Material: Hardened Steel AISI 4140 (SAE J404 compliant)

Durable and wear-resistant for dynamic motion components.

Rocker Arm Pins:

Material: Case-Hardened Steel AISI 8620 (SAE J404 compliant)

Excellent for components requiring low friction and high durability.

Rocker Spring:

Material: Spring Steel AISI 9260 (SAE J403 compliant)

High elasticity and fatigue resistance for consistent performance.

Valve:

Material: Hardened Steel AISI 410 (SAE J405 compliant)

Provides heat resistance and durability against wear.

Valves Cover:

Material: Aluminum Alloy 319 (ASTM B85)

Lightweight and corrosion-resistant, or Glass-Reinforced Nylon for cost savings.

Conclusion:

This project provided an invaluable opportunity to design, analyze, and conceptualize a twin-turbo V6 engine, demonstrating a comprehensive understanding of mechanical engineering principles and SolidWorks CAD modeling. By systematically breaking down the engine into its individual components, selecting appropriate SAE/ASTM-certified materials, and considering manufacturing constraints, the project aligned theoretical knowledge with practical applications. The design's emphasis on efficiency, performance, and sustainability showcased how modern engineering can address real-world challenges in automotive industries.

Improvements That Could Be Made:

1. **Enhanced Thermal Analysis**: Integrating advanced thermal simulations would better predict heat dissipation and thermal stresses in critical components like the cylinder head and exhaust manifold.
2. **Weight Optimization**: Further refinements in material selection, such as using composite materials in non-critical components, could improve the engine's weight-to-power ratio.
3. **Noise and Vibration Analysis**: Incorporating acoustic and vibrational analysis tools would ensure better engine performance and user experience.
4. **Simulation of Real-Life Conditions**: Performing full-cycle dynamic simulations for combustion and turbocharger efficiency would enhance the validation process.
5. **Additive Manufacturing Exploration**: Investigating 3D printing methods for prototyping or even manufacturing certain parts could reduce costs and time.

Benefits of the Engine:

The twin-turbo V6 engine is a testament to advanced engineering, offering significant advantages:

- **Improved Power-to-Weight Ratio**: The twin-turbo setup enhances engine efficiency, delivering high power outputs while maintaining a compact design.
- **Reduced Environmental Impact**: Incorporating lightweight materials and optimizing fuel combustion ensures lower emissions and higher fuel efficiency.
- **Versatility**: This engine design is suitable for a wide range of vehicles, from high-performance sports cars to robust trucks.
- **Cost-Effectiveness**: The design leverages modern manufacturing techniques and materials to reduce production costs without compromising quality.

In conclusion, this project serves as a foundation for creating efficient, sustainable, and high-performance engines. It bridges the gap between academic learning and industrial application, inspiring further research and innovation in engine design.