Design, analysis and optimization of 12 cylinder v-type diesel engine components

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Abstract: The designing, material selection and stress analysis are important processes in mechanical engineering design. The below brief study deals with the afore-mentioned processes conducted on the piston, connecting rod and crankshaft of a 12 cylinder V-type engine used for wood cutting application. The objective of this study was to optimize the weight of the given parts and increase their capacities to withstand different loads by means of iterative design changes as well as material selection for the three components. Pre-existing engine data and empirical relationships were used to generate a mathematical model for the design procedure and Ashby standards were followed for material selection for the above-mentioned parts. The Computer Aided Design (CAD) modelling and analysis of these parts was conducted in the Solidworks software.

Keywords: Optimization, piston, connecting rod, crankshaft, material selection.

1. Introduction

Three of the very important components of V12 engine are connecting rod, crankshaft and piston which are involved in most of the engine failure cases. Hence, we have taken these components as the focus of our study. Thus, we have made the following objectives to achieve optimized strengths for the three components.

The effect of reciprocating inertia forces and bending forces plays a vital role in the performance of a connecting rod. Connecting rod undergoes large repetitive loads of varying values and hence we need to increase its fatigue strength.

The key component of the engine that converts the reciprocating linear motion of the piston to rotational motion is the crankshaft. The cyclic changes in gas pressure inside the cylinder encourage the crankshaft torsional vibrations. In order to eliminate the leading cause responsible for part failure, it needs modification for withstanding the high torsional stress.

Engine performance is improved, if the weight of the components is reduced optimally. Weight can be reduced by changing the size, shape or material of the component. In this study, we have aimed to reduce the weight of the components through changes in their shapes and materials.

The above mentioned objectives were decided for a 12 cylinder V-type engine used in wood cutting application. The following table gives the engine specifications and operating parameters that are necessary for calculations.

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and modifications. A V12 engine is a 12-cylinder piston engine where two banks of six cylinders are arranged in a V configuration around a common crankshaft. Each bank of a V12 engine essentially functions as a straight-six engine, which itself has perfect primary and secondary engine balance. The following table gives the engine specifications and operating parameters that are necessary for calculations and modifications.

### Table 1. Engine specification and objective parameters

| Sr. No. | Parameters                                    | Symbol | Values   | Units |
|---------|-----------------------------------------------|--------|----------|-------|
| 1       | Maximum Combustion pressure                   | p<sub>za</sub> | 11.307   | MPa   |
| 2       | RPM                                           | n<sub>N</sub>  | 2600     | RPM   |
| 3       | Max Speed in idling                           | n<sub>id,max</sub> | 2700 | RPM   |
| 4       | Lambda                                        | λ       | 0.27     |       |
| 5       | Mass of connecting rod assembly               | m<sub>c.r</sub> | 3.39    | kg    |
| 6       | Length Of connecting rod                      | l<sub>s.e</sub> | 460     | mm    |
| 7       | Outer diameter of small end                   | d<sub>e</sub>  | 64       | mm    |
| 8       | Internal diameter of small end                | d        | 50       | mm    |
| 9       | Youngs modulus of Con rod grade 40X steel     | E<sub>c.r</sub> | 220000  | MPa   |
| 10      | Inner radius of big end of connecting rod     | r<sub>1</sub>  | 43       | mm    |
| 11      | Big end length                                | l<sub>c</sub>  | 33       | mm    |
| 12      | Mass of crankshaft side conrod                | m<sub>c.e</sub> | 2.458   | kg    |
| 13      | Mass of connecting rod assembly               | m<sub>cr</sub> | 3.39    | kg    |
| 14      | Length of connecting rod shank                | l<sub>cr</sub> | 222     | mm    |
| 15      | Cylinder Diameter                             | D        | 120      | mm    |
| 16      | Piston Stroke                                 | S        | 120      | mm    |
| 17      | Piston area                                   | F<sub>p</sub> | 113     | cm<sup>2</sup> |
| 18      | Maximum rated force for piston                | N<sub>max</sub> | 0.00697 | MN    |
| 19      | Mass of piston assembly                       | m<sub>p</sub>  | 2.94     | kg    |
| 20      | Piston height                                 | H        | 120      | mm    |
| 21      | Piston crown wall thickness                   | s        | 12       | mm    |
| 22      | Thickness of the top ring land                | h<sub>l</sub>  | 6        | mm    |
| 23      | Youngs modulus of piston pin                  | E        | 100000.00 | MPa |
| 24      | Outer diameter of main journal                | d<sub>mj</sub> | 90      | mm    |
| 25      | Length of journal                             | l<sub>mj</sub> | 37      | mm    |
| 26      | Crank pin inner diameter                      | d<sub>cp</sub> | 30      | mm    |
| 27      | Length of crankpin                            | l<sub>cp</sub> | 68      | mm    |
| 28      | Crank radius                                  | R        | 60       | mm    |
| 29      | Crank Pin Diameter                            | d<sub>cp</sub> | 80      | mm    |

2. Literature review

The study includes the effects of the thermal conductivity of the material of piston, piston rings, and combustion chamber wall. Results show variation of temperature, stresses, and deformation at various points on the piston [1]. With this study we came to know the designing of strong cross-sectioned parts and optimizing the material thermal conductivity.

The mechanical properties of the Titanium composites were remarkably improved by adding a small amount of carbon black at 0:070:16 mass%. The increases in the yield stress of the extruded sponge and fine Titanium matrix composite were 70.0 MPa and 291 MPa, while the tensile strength increases were 67 MPa and 231 MPa,
respectively, compared to those of extruded pure Ti with no reinforcement [2]. The TMC material has excellent mechanical properties at the same time being lightweight. Hence it has been used as a candidate for the piston.

Results show that the mechanical properties such as tensile strength of the heat-treated Al-Zn-Mg-Cu (AA7068) alloy at 210° C aging temperature has increased by 155% as compared to as cast alloy. The compressive strength and hardness of the alloy at 210° C aging temperature shows improvement of 41% and 54% respectively as compared to as cast alloy [3]. Since connecting rod undergoes significant amount of compressive forces, thus we have included Al-7068 (or AA7068) as a strong candidate material for it.

To design a new cross section of connecting rod for optimizing its weight, three cross sections: T Section, C section and hollow C section were designed and analyzed. An optimized C section was obtained with overall 14% weight reduction using response surface optimization methodology [4]. The method used in this study was understood and similar iteration were applied in the project.

Different charts compare materials on various properties such as strength, ductility, stiffness, density, thermal conductivity and cost[5]. Hence, this information about the selection of material and selection of property chart using the performance index formula has been studied from this data book and the knowledge has been applied for material selection in this project.

The author has performed the calculation of bending stress, torsional stress, stress concentration factor, fatigue strength, acceptability criteria for shrink-fits and semi-built crankshaft. These methods were applicable for both main propulsion and auxiliary purpose and being designed for continuous operation at the specified (nominal) rating [6]. Hence, through this we take away the formulas required for the calculation of crankshaft.

The author describes the process of selection of material for connecting rod where the constraints are to make light weight and yet strong enough to carry the peak load. Candidate materials has been selected using CES EduPack section chart and alloy steel comes out to be their final one [7]. Hence with this information we carry out the material selection of the connecting rod.

The webpage basically discuss the methods which has to be used in order to perform the research work [8]. This section explains us what and how do we perform the research in such a way that readers could easily evaluate the reliability and validity of the work.

The book aim to impart the advanced skills of design for analysis of mechanical components [9]. We took the generic method of designing and selection of materials for the selected engine parts.

The author in the book explained the materials to be used in industrial applications [10]. We understand the methods involved in the material selection such as digital logic method and learned how to find the performance index value.

3. Methodology

The research that has been performed regarding 12 cylinders V-type engine calculation, material selection, design and analysis comes under the quantitative method. Meanwhile during calculation of the parameters, most of the data was received from the project sponsorship company whereas some data such as maximum combustion pressure, air-fuel equivalence ratio, fuel-air equivalence ratio, etc. was more generic.

Data collection has been done primarily from the respective source [6,7,9]. The inputs and objectives of the project are largely based on customer specifications. While as a project-based learning initiative our team has done research at the ARAI library, Pune and as a result we understood the design methodologies of various engine parts and the generic procedure of material selection in automobile engine.

Before the calculation of the engine, the data sheet was thoroughly observed and the useful and necessary data was identified. Data related to piston, connecting rod and crankshaft was preferred over that of the carburetor and other engine components. Using empirical relations, a mathematical model was constructed for calculating various dimensions of the three components. When it comes to material selection process the performance index has been characterized differently according to the load applied and shape of the parts used in it. Iterative structural and thermal analysis were conducted to verify the results of the design calculations and material selection.

The tools and techniques that were used for design calculations, material selection, and analysis are: We used the MS-excel software for performing various calculations, the Granta software was used for material screening, the digital logic method was used for determining various weighing factors in the material selection process and the CAD designing and analysis was done in Solidworks.
4. Material selection

Material and process selection of the following three parts (piston, connecting rod and crankshaft) has been performed by using the digital logic method which is one of the type of weighted property method [10]. This method is generally used where numerous material properties are given and the relative importance is not very much clear. Hence, determination of their weighting factors are intuitive in nature. When it comes to the selection of required materials the method is purely based on its performance index (C) where, \[ C = \text{Young’s modulus/Density} \]. The C values is different for different shapes and the type of load applied on it. For example, \( E/\rho = C \) for (stiff ties, centrifugal loading), \( E^{1/2}/\rho = C \) for (stiff beam and columns) and \( E^{1/3}/\rho = C \) for (stiff plates) etc. A logarithmic chart is designed to display these groups or “material indices” from which the material families which satisfy the performance index’s criteria can be selected. The chart used here for material selection of connecting rod is young’s modulus v/s density with equation \( E^{1/2}/\rho = C \) (minimum weight design of stiff beam). The chart does not give us the final material, but are valuable in guiding us quickly and efficiently to a subset of materials worth considering as shown in figure 2. It is also useful in making sure that we do not overlook a promising candidate material [5]. The materials selected from this chart using the Granta software are listed below. Similar procedures were followed for the other two components.

![Material selection procedure](image)

**Figure 1. Material selection procedure**

**Figure 2. Selection of materials using Ashby chart for Young’s modulus v/s**

The above figure shown is an example of material selection of light and stuff components

4.1 Piston

- Screening: {Function: To take gas force; Objective: To reduce the weight and increase the strength; Variable: Density; Constraints: Force, cross sectional area, length}
Table 2. Properties required for piston material selection

| Material                  | Properties                  | Frictional coefficient | Wear rate | Thermal capacity [J/K] | Thermal conductivity [W/m-K] | Specific gravity | Yield strength [MPa] | Tensile strength [MPa] |
|---------------------------|-----------------------------|------------------------|-----------|------------------------|-----------------------------|-----------------|----------------------|------------------------|
| Grey cast iron            |                             | 0.41                   | 2.36      | 0.46                   | 80                          | 7.2             | 460                  | 455                    |
| Ti-alloy                  |                             | 0.34                   | 246.3     | 0.58                   | 17.58                       | 4.42            | 700                  | 1014                   |
| Ni-alloy                  |                             | 0.39                   | 5.32      | 0.41                   | 12.6                        | 8.4             | 851                  | 1100                   |
| Al-alloy                  |                             | 0.36                   | 2.89      | 0.714                  | 190                         | 2.73            | 480                  | 510                    |
| Aluminium matrix composite|                            | 0.35                   | 3.25      | 0.98                   | 155                         | 2.7             | 276                  | 310                    |
| Aluminium matrix composite|                            | 0.44                   | 2.91      | 0.92                   | 180                         | 2.8             | 425                  | 485                    |
| Titanium composite        |                             | 0.31                   | 8.19      | 0.51                   | 17.85                       | 4.68            | 700                  | 1029                   |

Table 3. Performance index and final material for piston

| Material                  | Properties                  | Relative cost | Performance index | Final material |
|---------------------------|-----------------------------|---------------|-------------------|----------------|
| Grey cast iron            |                             | 1             | 51.04             | 51.04          |
| Ti-alloy                  |                             | 20            | 77.1552.30        | 1552.30        |
| Ni-alloy                  |                             | 17            | 69.211176.635     | 1176.635       |
| Al-alloy                  |                             | 10            | 48.0880.84        | 480.84         |
| Aluminium matrix composite|                            | 2.8           | 42.99120.39       | 120.39         |
| Aluminium matrix composite|                            | 2.6           | 52.46            | 136.40         |
| Titanium matrix composite |                            | 20.5          | 58.061190.23      | 1190.23        |

Relative cost = (Total cost of low carbon iron steel)/(total cost of a specific material). The more is the relative cost lesser will be the overall cost.

Final material = (Relative cost*Performance index). This value indicates the final rating of a specific material. Higher the value of final material results in greater chance of getting selected. But importance of the value of relative cost is more than that of final material.

Scaled value = (Minimum value in the list*100)/(Numerical value of property).

Performance index = \( \sum (\text{Scaled property}) \times (\text{weightage factor}) \), \( i \) = property number starting from top left corner. Weightage factor has been calculated by using the digital logic method [10].

4.2 Connecting rod

- Screening: - {Function: To carry the material; Objective: To reduce the weight and increase the fatigue cycle; Variable: Density; Constraints: Shape and force}

Table 4. Properties required for connecting rod material selection

| Material | Density [kg/m³] | Yield strength [MPa] | Ultimate tensile strength [MPa] | Brinell hardness | Fatigue strength [MPa] | Fracture Toughness [MPa-m½] | Working stress [MPa] | FOS |
|----------|-----------------|----------------------|---------------------------------|-----------------|------------------------|----------------------------|----------------------|-----|
| C-70     | 7850            | 420                  | 640                             | 190             | 270                    | 28.82                      | 106.667              | 6   |
| Al-360   | 2680            | 260                  | 310                             | 75              | 82                     | 17.3                       | 51.667               | 6   |
| T-2024   | 2780            | 324                  | 469                             | 120             | 138                    | 23.3                       | 78.167               | 6   |
| Al-7068  | 2850            | 683                  | 710                             | 190             | 220                    | 35                         | 118.333              | 6   |
Table 5. Performance index and final material for connecting rod

| Material | Properties | Relative cost | Performance index | Final material |
|----------|------------|---------------|-------------------|----------------|
| C-70     |            | 1.5           | 152.00            | 228.00         |
| Al-360   |            | 1.2           | 65.08             | 78.10          |
| T-2024   |            | 6.3           | 90.29             | 568.87         |
| Al-7068  |            | 7             | 140.16            | 981.15         |

4.3 Crankshaft

Table 6. Properties required for crankshaft material selection

| Material        | Properties                          | Density [kg/m³] | Youngs Modulus [MPa] | Yield Strength [MPa] | Thermal Expansion Co-efficient [K⁻¹] |
|-----------------|-------------------------------------|-----------------|----------------------|----------------------|--------------------------------------|
| Forged steel    |                                     | 7700            | 190                  | 241                  | 0.000015                             |
| 42CrMo4 Steel   |                                     | 7850            | 210                  | 750                  | 0.000012                             |
| Tungsten        |                                     | 19250           | 411                  | 1510                 | 0.0000046                            |

Table 7. Performance index and final material for crankshaft

| Material        | Relative Cost | Performance Index | Final Material |
|-----------------|---------------|-------------------|----------------|
| Forged steel    | 11.9          | 50.260            | 598.102         |
| 42CrMo4 Steel   | 6.5           | 54.317            | 353.060         |
| Tungsten        | 2.1           | 84                | 176.4           |

5. Calculations & design:

The design of connecting rod, piston and crankshaft is based on evaluation of safety against fatigue in highly stressed areas.

A. CONNECTING ROD

1. BIG END:
   - i. The max. inertial force = -0.031405 MN
   - ii. The bending stress for cap and shell= -164.83 MPa

2. SMALL END
   - Design of I-I section
   - i. Maximum stress in pulsating cycle= 30.4 N
   - ii. Mean Stress= 15.19 MPa;

3. CONNECTING ROD SHANK
   - i. Max stresses caused by compression forces = 79.447 MPa
   - ii. Min. stress caused by a tension force = 72.369 MPa

B. PISTON
   - Compression stress at section X-X:
     - i. Max compression force = 0.127769 MN;
     - ii. Compression stress = 37.81141 MPa;
   - Calculations for PISTON RINGS:
     - i. Bending stress of the ring in operation = 233.609 MPa
     - ii. Bending stress in slipping the ring over a piston = 298.2715 MPa
   - Calculations for PISTON PIN
     - i. Tangential shear stress= 109.4785 MPa
     - ii. Maximum Ovalization increase in the pin diameter = 4.18E-05 m

C. CRANKSHAFT
   - Calculations for CRANK WEB
Maximum twisting moments = 220185 N-mm

Maximum tangential stress = 8580544 Pa

Maximum normal stress = 50743628 Pa

Calculations for CRANK PIN

i. Moment resisting to twisting the crankpin = 98542.93 mm$^3$

Calculations for MAIN JOURNAL

i. Main journal moment resisting to torsion = 143138.8 mm$^3$

ii. Maximum tangential stress = 2.07E+01 MPa

Calculations for unit area pressure on CRANKPIN

i. Max pressure on crankpin = 41.03448 MPa

ii. Max pressure on main journal = 23.95062 MPa

**DESIGN CHANGE IN CONNECTING ROD:**

The different design iterations for the connecting rod are as shown below in the figure. The figure (a) is the original design that on which shape iterations were conducted by keeping the applied material same throughout it. The first iteration, as shown in figure (b) has square-shaped slots made in the shank. The second iteration (figure (c)), shows the connecting rod with a longitudinal slot in its shank.

![Figure 3](image-url)

**6. Analysis**

The materials selected for specific components after the material selection procedure needs to be verified by application of forces on them and analyzing whether they can withstand the operating conditions. Hence, the CAD models of the three components were generated. The static analysis of the components gave results for four parameters: Von Mises Stress, Strain, Displacement, and Factor of Safety. Material iterations and their analysis were carried out on the piston, the connecting rod and the crankshaft CAD parts to verify the results of the material selection process. Different shape iterations were conducted for the connecting rod shank, and then its static analysis was conducted.

**6.1 Piston**
Table 8. Result table for piston

| Sr. No. | Parameter   | Type/ Value                                      | Previous (Ni alloy) | Optimized (Ti-matrix composite) |
|---------|-------------|--------------------------------------------------|---------------------|----------------------------------|
| 1.      | Mesh type   | Solid Mesh (Standard mesh)                       | Min                 | Max                              |
| 2.      | Load applied| Normal force and pressure                        | 0.245 [MPa]         | 311.095 [MPa]                   |
| 3.      | Fixture type| Fixed geometry                                   | 0.184 [MPa]         | 310.869 [MPa]                   |
| 4.      | Stress (von Mises Stress) | 0.245 [MPa] | 311.095 [MPa] | 0.184 [MPa] | 310.869 [MPa] |
| 5.      | Displacement| 0 [mm]                                           | 0.073 [mm]          | 0.000 [mm]                       | 0.130 [mm] |
| 6.      | FOS         | 2.735                                            | 3.477.899           | 2.252                            | 3.808.660 |

6.2 Connecting rod

Figure 5. Analysis of original connecting rod and slotted shank connecting rod: (a) von Mises stress, (b) Displacement, (c) FOS
6.3 Crankshaft

![Image of crankshaft analysis]

Figure 6. Analysis of “forged steel” crankshaft: (a) von Mises stress, (b) Displacement, (c) Strain, (d) FOS

### Table 9. Analysis result table for connecting rod

| Sr. No. | Parameter          | Type/ Value                                           |
|---------|--------------------|-------------------------------------------------------|
| 1.      | Mesh type          | Solid Mesh (Blended curvature-based mesh)             |
| 2.      | Load applied       | Normal force and pressure                             |
| 3.      | Fixture type       | Fixed geometry                                        |
|         |                    | Without slotted shank, Al-7068                        |
|         |                    | With slotted shank, Al-7068                           |
| 4.      | Stress             | Min 0.103 [MPa] Max 1,219.8 [MPa]                     |
|         |                    | Min 0.379 [MPa] Max 1215.7 [MPa]                      |
| 5.      | Displacement       | Min 0.000 [mm] Max 0.031 [mm]                         |
|         |                    | Min 0.000 [mm] Max 0.031 [mm]                         |
| 6.      | Factor of Safety   | 0.560 Max 6,620.746 Max 0.562 Max 1803.243           |

7. Results

The yield strength of piston is reduced as more importance has been given to the relative cost of the material and also the weight has been reduced by 45.01% which satisfies our objective. The yield strength and the fatigue strength of the connecting rod is constant as the material has been kept the same but the weight has been reduced by 6.25% through the design optimizations. After selecting the material of crankshaft the modulus of rigidity has

### Table 10. Analysis result table for crankshaft

| Sr. No. | Parameter          | Type/ Value                                           |
|---------|--------------------|-------------------------------------------------------|
| 1.      | Mesh type          | Solid Mesh (Blended curvature-based mesh)             |
| 2.      | Load applied       | Normal force and pressure                             |
| 3.      | Fixture type       | Fixed geometry                                        |
|         |                    | Min                                                   |
|         | Stress (Von Mises) | 0.002 [MPa]                                           |
|         | Resultant displacement | 0.000mm                                           |
|         | Equivalent strain  | 9.684e-09                                            |
|         | Factor of Safety   | 5.855                                                 |
been increased and at the same time the crankshaft’s weight has been reduced by 1.8% since the forged steel is having large shear modulus and less density as compared to that of 42CrMo4 steel.

**Table 11. Result table**

| Component      | Parameter     | Previous design | Optimized design |
|----------------|---------------|-----------------|------------------|
|                | Values        | Material        | Values           | Material        |
| Piston         | Mass          | 3.31 [kg]       | 1.82 [kg]        | Ni composite    |
|                | Yield strength| 851 [MPa]       | 700 [MPa]        | Matrix          |
| Connecting rod | Mass          | 416 [g]         | 416 [g]          | Al-7068         |
|                | Yield strength| 100 [MPa]       | 100 [MPa]        | Al-7068         |
| Crankshaft     | Mass          | 50.18 [kg]      | 49.28 [kg]       | Forged steel    |
|                | Modulus of rigidity | 75 [GPa] | 79 [GPa] |

8. Conclusion

The pre-existing engine data was used to create a mathematical formulation in MS excel and empirical relationships were used to calculate different parameters for the three components i.e., piston, connecting rod and crankshaft. Literature related to the objectives of the project was studied and relevant information was collected. By using the weighted property method and Ashby chart, the materials for the three components were selected. An optimum design has been achieved through iterations in the design of the connecting rod resulting in its reduced weight. By using a material with greater shear modulus for the crankshaft, its torsional strength has been increased. The material change for piston from nickel alloy to Ti-composite matrix has resulted in a drastic reduction in its weight and cost as well since the relative cost of Ti-composite is maximum amongst all. These changes have reduced the weights of the target components, while at the same time keeping their respective strengths at optimal levels. Hence, these changes will work well when incorporated into the design of the whole engine and thus a whole comprehensive approach to combine these parts into the engine is required.

9. Acknowledgment

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