DESIGN AND OPTIMIZATION OF CRANKSHAFT FOR SINGLE CYLINDER 4–STROKE SPARK IGNITION ENGINE USING COUPLED STEADY-STATE THERMAL STRUCTURAL ANALYSIS

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ABSTRACT

The aim of the study is to design and optimization of crankshaft for a single cylinder four stroke over head valve (OHV) spark ignition engine. This paper used reverse engineering techniques, in order to obtain of an existing physical model. A three-dimensional crankshaft has been created with the help of SOLIDWORKS and, it is imported to ANSYS environment for the coupled steady-state thermal structural analysis. The material used for crankshaft is AISI 1040, AISI 1045, AISI 4140 and AISI 4615. The objective of this paper focuses the light weight crankshaft design through coupled steady-state thermal structural analysis, and to optimize the crankshaft design within the design domain using parametric optimization. The results obtained from finite element analysis and parametric optimization concluded, the modified design is safe along the selected materials for AISI 1045 and shows the maximum von-mises stresses 184.21 MPa, factor of safety (n) is 2.4428 and it is reduced weight of the crankshaft was 63 grams which is 4.04 % less as compared to existing crankshaft model without compromising the strength to weight ratio.

Keywords: OHV, crankshaft, reverse engineering, finite element analysis, parametric optimization.
1. INTRODUCTION

Farzin H. Montazersadgh et al., (2007). Crankshaft is a complex geometry in the internal combustion engine, which converts the reciprocating motion of the piston to a rotary motion with a four bar linkage mechanism. The crankshaft undergoes a large number of load cycles during its fatigue performance, durability and service life of this component has to be taken in the design process. Design and development of the crankshaft is an important issue in the manufacturing industry, in order to produce a less expensive component with the light weight, good fatigue strength with better fuel efficiency and higher power output.

Meng et al., (2011) carried out the static structural analysis and model analysis on four cylinder engine crankshafts and show the maximum stress, maximum deformation and unsafe areas were determined.

V. C. Shahane et al., (2016) discussed, a static structural and dynamic analysis was conducted on a single cylinder four stroke diesel engine crankshaft. A three dimensional cad model of the crankshaft was created using Pro/Engineer, according to the two dimensional drawing of the existing crankshaft. Finite element analysis was performed using ANSYS software under the static and dynamic condition to obtain the variation of stresses at different critical locations of the crankshaft. Boundary conditions were applied on finite element model as per the specification of the engine and engine mounting conditions. Optimization of the crankshaft was studied in the area of geometry and shape on the existing crankshaft and the optimized crankshaft design should be replaced with existing crankshaft, without changes in the engine block and cylinder head. The optimized crankshaft helps to increase the performance of the engine and causes reduction in weight. The optimization results shows to reduce 4.37% of the weight in the original crankshaft.

V. Sowjanya et al., (2016) studied that the relationship between the frequency and the vibration modal by the modal and harmonic analysis of crankshaft using FEA software ANSYS. A three - dimension model of diesel engine crankshaft is created using Pro-E software and FEA was performed to find the variation of stress magnitude at critical locations of crankshaft. Simulation inputs are taken from the engine specification chart.

G. Thirunavukkarasu et al., (2016) this author discussed there are many ways to reduce crankshaft weight, web design optimisation and reducing the bearing diameters etc. In his paper he demonstrates the crankshaft optimization through the hollow crank pins and journals which yields a weight reduction of 22% and also doubles the safety factor of the existing solid crankshaft design.

Paolo Citti et al., (2018). The author discussed about mechanical parts in an Internal Combustion Engine (ICE), the crankshaft needs additional attention concern selection of materials, heat treatments, manufacturing processes and costs. The aim of this work is to study the actual and future scope regarding the material choice for the crankshaft of high-performance engines. In particular, the actual development and improved quality attained by base materials and production technologies for this critical component of the engine. In this context, 38MnVS6 and 48MnVS3 materials are analyzed with surface hardening techniques, thermal treatments and their technical and cost saving potentials.
B. Vijaya Ramnath et al., (2018). In this paper, an attempt has been made to derive all the parameters such as designing, manufacturing, maintaining of products, service and structures. The crankshaft is reverse engineered using CMM device for unknown geometrical data’s. Computer aided modelling using CATIA and optimization analysis of crankshaft is used to study and compare the fatigue performance of three different materials of automotive crankshaft, namely forged steel, ductile cast iron and aluminium alloy. The dynamic analysis was done and verified by simulations in ANSYS. The maximum stress region and dangerous areas are found by the deformation analysis of crankshaft. Based on the finite element analysis results, possible weight reduction is determined to the feasible material forged steel after weight reduction.

K. Satyanarayana et al., (2017). To investigate the stresses induced AISI E 4340 forged steel in crankshaft. This study contains of two major segments, first segment is kinematic and dynamic analysis and second segment is FE stress analysis. Initially computerized variable compression ratio at compression ratio diesel engine testing machine of 16.5 for obtaining pressure vs crank angle variation was experimentally investigated. The kinematic and dynamic analysis was done analytically by evolving the equations of equilibrium from free body diagram of slider crank mechanism. The equations which are attained through this analysis are used as input for determining the stresses. These forces were applied along with boundary conditions; the stress analysis was performed at critical crank angles of rotation. The results in the form of von- mises stresses and deformation were used to evaluate the factory of safety of crank shaft.

In many research papers have discussed, these three Traditional methods by which a crankshaft is been manufactured: forging, casting and machining. There are some disadvantages of these methods like waste of material and time spent in post processing. This ultimately increases the manufacturing cost.

The main objective of this paper focuses on weight reduction in crankshaft design through reverse engineering practices, selection of material and parametric optimization in order to increase the engine performance and control the emission parameters, higher the strength to weight ratio and reduces the total cost of production.

2. MATERIAL AND METHODS

2.1. Engine specification

This paper attention is on crankshaft; the geometry and the requirements of the crankshaft solely depend upon the engine. The specification of the engine and material chemical composition is used for the following table 1.

<table>
<thead>
<tr>
<th>Engine type</th>
<th>4 stroke, Single cylinder, Air cooled engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore x Stroke</td>
<td>68 X 45 mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>163 cm³</td>
</tr>
<tr>
<td>Rated Output</td>
<td>2.83 KW @ 3,600 rpm</td>
</tr>
<tr>
<td>Maximum Torque</td>
<td>10.3 Nm @ 2,500 rpm</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>9.0: 1</td>
</tr>
<tr>
<td>Weight</td>
<td>15.1 Kg</td>
</tr>
</tbody>
</table>

2.2. Crankshaft: Material

Compact weight and high structural rigidity is the key factors essential for all components of an IC engine.
AISI 1040 carbon steel has high carbon content and can be hardened by heat treatment followed by quenching and tempering to achieve 150 to 250 ksi tensile strength.

AISI 1045 steel is medium tensile steel supplied in the black hot rolled or normalized condition. It has a tensile strength of 570-700 MPa and Brinell hardness ranging between 170 and 210. AISI 1045 steel is characterized by good weldability, good machinability, and high strength and impact properties in either the normalized or hot rolled condition. AISI 1045 steel has a low through hardening capability with only sections of size around 60 mm being recommended as suitable for tempering and through hardening. However, it can be efficiently flame or induction hardened in the normalized or hot rolled condition to obtain surface hardness in the range of Rc 54 - Rc 60 based on factors such as section size, type of set up, quenching medium used etc. AISI 1045 steel lacks suitable alloying elements and hence does not respond to the nitriding process.

AISI 4140 is a chromium molybdenum alloy steel. The chromium content provides good hardness penetration, and the molybdenum content ensures uniform hardness and high strength. AISI 4140 chrome molybdenum steel can be oil hardened to a relatively high level of hardness. The desirable properties of the AISI 4140 include superior toughness, good ductility and good wear resistance in the quenched and tempered condition. The AISI 4140 cold finished annealed chromium molybdenum alloy steel can be heated using various methods to yield a wide range of properties, hence it is often used as stock for forging as it has self-scaling properties. AISI 4140 is capable of resisting creep in temperatures up to 538°C (1000°F) and maintaining its properties even after long exposure at comparatively high working temperatures. The AISI 4140 cold rolled rounds are available in the 41L40 variant that contains 0.15 - 0.35 lead. The lead content improves machinability, but has significant effect on other desirable properties.

AISI 4615 Alloy steel is often subdivided into low alloy steel and high alloy steels. Low alloy steels exhibit mechanical properties superior to plain carbon steels due to the addition of alloying elements such as molybdenum, nickel and chromium. High alloy steels, on the other hand exhibit high strength at elevated temperatures, and hence they are used in applications involving aggressive environments to which the steel must be resistant. AISI 4615 is a nickel molybdenum steel.

The chemical composition test was conducted using a vacuum optical emission spectrometer in order to obtain the material AISI 1040. Based on the chemical composition test, it has been finalized as per the alloy steel standard: American Iron and Steel Institute (AISI). The chemical composition of the crankshaft materials are used in this study as shown in table 2 and the physical and mechanical properties of used materials are shown in table 3.

### Table 2 Chemical composition of selection materials % by weight

<table>
<thead>
<tr>
<th>Designation</th>
<th>MATERIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AISI 1040</td>
</tr>
<tr>
<td>Elements</td>
<td>Content (%)</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>98.6-99</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>0.60-0.90</td>
</tr>
<tr>
<td>Carbon (C)</td>
<td>0.370-0.440</td>
</tr>
<tr>
<td>Sulfur (S)</td>
<td>≤ 0.050</td>
</tr>
<tr>
<td>Phosphorous (P)</td>
<td>≤ 0.040</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>-</td>
</tr>
<tr>
<td>Molybdenum (Mo)</td>
<td>-</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>-</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 3: Physical and mechanical properties

<table>
<thead>
<tr>
<th>Designation</th>
<th>MATERIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Kg/M$^3$)</td>
<td>AISI 1040</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion (μm/M)(ºc)</td>
<td>11.3</td>
</tr>
<tr>
<td>Young’s Modulus (GPa)</td>
<td>210</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.26</td>
</tr>
<tr>
<td>Bulk Modulus (GPa)</td>
<td>140</td>
</tr>
<tr>
<td>Shear Modulus (GPa)</td>
<td>80</td>
</tr>
<tr>
<td>Isotropic Thermal Conductivity @ 0ºc (W/Mk)</td>
<td>51.9</td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>415</td>
</tr>
<tr>
<td>Ultimate Strength (MPa)</td>
<td>620</td>
</tr>
</tbody>
</table>

2.3. Reverse Engineering

Kumar, A et al, (2013) Reverse Engineering (RE) is the process of obtaining a geometric CAD model from measurements obtained by using non-contact scanning technique of an existing physical model. Bopaya, B.I. et al, (1994) it consists of following steps: Data acquisition, pre-processing, triangulation, feature extraction, segmentation and, surface fitting and the application of CAD/CAM/CAE tools. They are commonly used in automotive, air craft, marine, in medical life science and software industries etc.

This paper used reverse engineering techniques, accurate measurements of the steinbichler comet L3D scanner has resolution of 2Mpx and 1600 x 1200 pixels, in order to obtain of an existing physical model.

2.3.1. Initial Modeling

This paper utilized the highly accurate measurements of the steinbichler comet L3D scanner has resolution of 2Mpx and 1600 x 1200 pixels, measuring field of 400mm, measuring volume of 400x300x250 mm$^3$ and point to point distance of 259µm in order to obtain of an existing physical model crankshaft. The scanned model and CAD model as shown in Fig. 1 and side view of crankshaft before optimization as shown in Fig. 2.

Figure 1 Crankshaft (a) Scanned model and (b) CAD model

Figure 1 Side view of crankshaft before optimization
2.3.2. Finite element analysis

A 3-dimensional crankshaft has been created with the help of SOLIDWORKS 2016 and, it is imported to ANSYS 16.2 environment for coupled steady-state thermal structural analysis. Maximum pressure of 23 bar generated inside the cylinder due to burning of air fuel mixture. This pressure will be transmitted into crank shaft via piston and connecting rod. In Fig. 3. (a) Shows the crankshaft model imported to ANSYS and (b), fine meshed crankshaft it consists of 285208 nodes and 172986 triangular elements. Fig. 4. (a) Shows the thermal loads at $60^\circ$C and the boundary conditions are applied through convective mode temperature $22^\circ$C, and (b), temperature distribution from crankpin to main journal to attain a maximum temperature of $60^\circ$C. Fig. 5. (a), shows the heat transferred per unit area in the crankshaft to reach maximum is $1.0071 \text{ W/mm}^2$ at web fillet and (b) demonstrates, to ensure efficient design the compressive load was applied as a 2.34 MPa, fixed support at the bearing region and moment of 10300 N-m was applied at the output shaft key. Fig. 6. (a) Displays the maximum deformation 0.01814 mm at the crankpin region (b) shows the maximum stress obtained as per the given loading is 192.28 MPa. Fig. 7. (a) Displays the maximum shear stress of 105.85 MPa near the bottom fillet region of crankpin (b), Shows the minimum factor of safety for the crankshaft as 2.4303.

2.3.2.1. Analysis Results before Optimization

![Figure 2](image1.png)

Figure 2 Crankshaft model (a) Imported to ANSYS and (b) Mesh model

![Figure 3](image2.png)

Figure 3 Crankshaft (a) Thermal boundary conditions and (b) Temperature distribution
3. PARAMETRIC OPTIMIZATION

Amarjeet Singh et al., (2014) The crankshaft is among the large volume production components in an internal combustion engine industry, weight and cost reduction of this component are very effective in fuel efficiency and reducing the total cost of the engine. The main focus on the design of crankshaft which is as light as possible and at the same time the maximum stress value should also be within permissible limit. So during parametric optimization is to replace the present crankshaft with an optimum design by making negligible or no changes to the engine block and connecting rod. In many research articles have shown that the further optimization of the crankshaft is possible in terms of stress and weight reduction by using various parametric modifications in the crankshaft.

During investigation of the stress contour it is clear that some locations of the crankshaft like counterweight, crank web and connecting rod journal are experiencing less stress. The crank shaft has to be dynamically balanced in which the counter weight is subjected to negligible stress, so these section cannot modified. The most significant way during parametric changes is to remove or add material symmetric to the central axis. So based on the parametric changes were analyzed for optimization.

- On the crankpin region of the crankshaft there is a 14 mm diameter hole and its depth is through all and the depth of this hole does not affect the functioning of the crankshaft in order to achieve appreciable weight reduction as shown in Fig. 8.

**Figure 7** Optimized Crankshaft 2D Drawing

- To reduce the stress level at the fillet areas, fillet radius has to be increase. Due to increase in the fillet radius at the knuckle region of crank arm and connecting rod journal does not affect the connecting rod geometry meanwhile the connecting rod clearance is more sufficient

Fig. 9. (a) Shows the fully optimized model and (b) displays meshed crankshaft model and it consists of 284797 nodes and 169725 triangular elements. Fig. 10. (a) Shows the thermal boundary conditions (b) Shows temperature distribution along the crankshaft. Fig. 11. (a) Shows the total heat flux and (b) displays the structural loading conditions like pressure, fixed support and moment. Fig. 12, (a) Shows temperature distribution along the crankshaft surface and (b) the maximum equivalent (von-mises) stress is acting near the crankpin bottom surface close to web fillet is shown as 184.21 MPa. Fig. 13, (a) Displays the Shear stress developed in the crankshaft and (b) Shows the minimum factor of safety as 2.4428

3.1. Analysis results after parametric optimization

**Figure 8** Crankshaft model (a) Imported to ANSYS and (b) Meshed model

**Figure 9** Crankshaft (a) Thermal boundary conditions and (b) Temperature distribution
4. RESULTS AND DISCUSSIONS

Maximum von-mises stresses, deformation and factor of safety was found out in finite element analysis. Maximum stress occurred in the web fillet near the crankpin for compressive loading at crank journal. After optimizing the geometry, the high localized stress occurs near the bottom fillet region of crankpin from the results obtained the graphs were plotted before and after optimization, Fig. 14. (a) Displays the total heat flux of AISI 1040 and AISI 1045 is almost equal before and after optimization, AISI 4140 is less than AISI 1040, AISI 1045 and AISI 4615 is the lowest among all the others before optimization and AISI 4140 is the lowest among all the others after optimization, and (b) describes the total deformation in which AISI 4140 is having the maximum deformation and AISI 1045 deformation which is close to AISI 1040, AISI 4615 shows the lowest deformation among all the others. Fig. 15. (a) Shows that maximum von mises stress is developed in AISI 4140 and AISI 4615 is the lowest, AISI 1040 and AISI 4615 is almost equal and AISI 1045 is less than AISI 4140, (b) AISI 4140 is having the highest shear stress and AISI 4615 is having the lowest shear stress among these four materials. Fig. 16. (a) AISI 1045 is having the highest factor of safety among the others and AISI 4615 is the lowest among all the other materials, AISI 1040 is having little less factor of safety than AISI 1045, And AISI 4140 is having greater factor of safety than AISI 4615. The mass of the initial model for AISI 1040, AISI 1045, AISI 4140 and AISI 4615 is 1.554, 1.559, 1.555 and 1.555 Kilograms and after optimized model is reduced to 1.492, 1.496, 1.492 and 1.492 kilograms.
4.1. Comparison of results before and after optimization

![Figure 13](image1.png) Results for (a) total heat flux (b) total deformation, before and after optimization

![Figure 14](image2.png) Results for (a) von-mises stress (b) shear stress, before and after optimization

![Figure 15](image3.png) Results for (a) factor of safety before and after optimization

5. CONCLUSION

It is observed that by conducting the coupled steady-state thermal structural analysis shows total heat flux, total deformation, von mises stresses, shear stress and factor of safety as per the given loading conditions. After carrying out the coupled field analysis the stresses in loading conditions were studied and then areas where excess material can be removed were decided.

There are two problems to be analyzed and solutions need to be advised.

- At first, the high localized stress occurs near the bottom fillet region of crankpin, by increasing area by providing fillets in this region, problem can be solved.
- The second problem is during built-up; conventional manufacturing methods like casting, moulding, and forming are not feasible with the design. Meanwhile Additive manufacturing will give a better result.
Parametric optimization was performed to reduce weight of the crankshaft subjected to compressive load and tensile load. The crankpin region of the crankshaft offered the greatest potential for weight reduction.

- After parametric optimization, AISI 1045 is reduced the weight of the crankshaft by 63 grams from the 1559 grams or internal of 4.04%.
- AISI 1045 is the best material for crankshaft which can sustain or withstand engine load cycles, based on the yield strength, von mises stress and factor of safety for the optimized crankshaft design.
- Factor of safety for AISI 1045 is more as compared to other three material, means that design is much stronger

REFERENCES


