Topology Optimization And Structural Weight Analysis of a Parallel-Twin Engine Crankshaft.

Dillip Kumar Sahoo[1], Mohammed Musthakeem Basha[2], Sathwik Kotha[3]

[1]Associate Professor, School of Mechanical Engineering, Sathyabama Institute of Science and Technology, Chennai, TN, India,600119.

[2,3] UG students, School of Mechanical Engineering, Sathyabama Institute of Science and Technology, Chennai, TN, India,600119.

Email- dillipkumarsahoo@gmail.com[1], bashamusthakeem@gmail.com [2], sathwikkotha24@gmail.com [3]

Abstract

The crankshaft is one of the crucial parts for the internal combustion engine's efficient and accurate operation. Here, crankshaft analysis and topology optimization using computer-aided engineering is done for parallel twin-cylinder four-stroke engines. Using the Fusion 360 program, a twin-cylinder engine crankshaft model in three dimensions is produced. Multibody dynamics and product optimization software are used to determine the fluctuation in stress magnitude and deformation at the crucial point of the crankshaft finite element analysis (FEA). Using the topology optimization approach, the crankshaft's weight may be reduced without sacrificing the component's rigidity and durability. Investigations are conducted into the stress fluctuation during the engine cycle and the impact of torsion and bending loads on the analysis. We achieved a mass reduction of about 11.55% compared to the original component, while the crankshaft's rigidity was raised by 28%. Finally, we produced a lightweight crankshaft that maximized using raw materials.

Keywords: *Crankshaft, Topology Optimization, FEA,*

1 Introduction

The crankshaft is an important component in the internal combustion engine, which is responsible for engine power transitions. The big end of the connecting rod is connected to the crankshaft's bearing journal, which involves reciprocating the motion of the piston vertically or horizontally to rotational force. The crankshafts are used in various fields like automobile, marine, aeronautical, etc. [1-3]. The finite element approach was used to conduct a modal study of a 4-cylinder crankshaft under 3D modeling. To simulate the crankshaft dynamic behavior of an engine with V-shaped cylinders, gauge stress amplitude measurements at the crankpins were made experimentally [4].

On the crankshaft of a 380-diesel engine, Meng Jian et al. (5) described a 3-D finite element study. PRO/Engineer software and ANSYS were used for 3-D model and analysis for this investigation. Calculations were made to determine the crankshaft's maximum stress and strain. The dynamic simulation, kinetic analysis on a crankshaft, and various loading circumstances of a diesel engine were detailed by Xiaorong Zhou et al. (6). With the aid of 3D finite element analysis and the use of the ANSYS software, a full original model for the analysis of the fatigue and frequency behavior for crankshaft is used in this investigation. Under dynamic load conditions, crankshaft fatigue strength was examined, and modal analysis was performed. This method provides a solid framework for the changes in crankshaft design.

F. Erdogan et al. [7] used evaluation techniques on several used materials to investigate the efficacy of employing them in engine shafts. The development of the materials, their concepts, their characteristics, and their fundamental assembly methods have all been outlined. Although many studies have focused on examining this material, this potential suggests that the inventor is not generally constrained to a range of currently available homogeneous materials. Engineers and other experts are also concerned with the planning cycle with various used materials. By all accounts, using those various resources is probably the ideal strategy for acknowledging the company's sustainable growth [8]. In this work, three distinct crankshaft materials were structurally analyzed by Deep Singh et al. They also discovered potential strategies to lighten the component's weight [9].

In this work, the crankshaft of a two-cylinder four stroke engine, the analysis of crankshaft is done in object to reduce the weight of the material and lower the production cost. The reason for taking this project is to explore the opportunities of combining generative designs with additive manufacturing techniques to develop improvised designs to reduce material wastage during production through machines like computer numerical control manufacturing, casting in Mold, forging of material, etc.

2. Design Parameters and Material Selection

2.1 Design parameters

The design parameters are essential for 3d modelling of the crankshaft. By using the specific designs the load acts on the connecting rod and the diameter of the main journal, the number of cylinders to be placed and how the two connecting rod journals are being fared away from each other are analysed (Table 1)

Table 1. Design Parameter of Crankshaft

Type	The 4-stock internal combustion engine
No. Of Cylinders	2
Bore/Stroke	78mm/67.8mm
Compression ratio	9.5:1
Max power	47Bhp@7150rpm
Max torque	52Nm@5250rpm
Capacity	648cc

2.2. Material Selection

The material selection for the crankshaft was based on the literature survey. Three different materials, like Inconel 625, cast iron and titanium, were chosen based on their mechanical properties like stiffness, strength, hardness, availability, and cost of the material. The properties of Inconel 625, Cast Iron and Titanium are shown in Table 2, Table 3 and Table 4, respectively.

Table 2.Inconel 625 material properties

Density	Young's Modulus	Poisson's Ratio	Yield Strength	Ultimate Tensile Strength	Thermal Conductivity	Thermal Expansion Coefficient	specific heat
8.44E-06 kg / mm^3	150000 MPa	0.28	641 MPa	1000 MPa	0.0098 W / (mm C)	1.28E-05 C^-1	410 J / (kg C)

Table 3. Cast Iron Material Properties

Density	Young's Modulus	Poisson's Ratio	Yield Strength	Ultimate Tensile Strength	Thermal Conductivity	Thermal Expansion Coefficient	specific heat
7.40E-06 kg / mm^3	81496 MPa	0.235	151.7 MPa	179.3 MPa	0.04804 W / (mm C)	1.30E-05 C^-1	407 J / (kg C)

Table 4. Titanium Material Properties

Density	Young's Modulus	Poisson's Ratio	Yield Strength	Ultimate Tensile Strength	Thermal Conductivity	Thermal Expansion Coefficient	specific heat
4.43E-06 kg / mm^3	113763 MPa	0.35	882.5 MPa	1034 MPa	0.0067 W / (mm C)	8.60E-06 C^-1	409 J / (kg C)

3. CAD Modelling and Meshing

3.1. Crankshaft Modelling

The forces acting on the crankshaft have been calculated by reverse engineering on a four-cylinder Otto cycle engine. The thickness of the crankshaft and web thickness had been referred to. This present work is mainly based on crankshaft web modification. A slider-crank mechanism analyzed the forces acting on the crankshaft. A total force of about 4600 N is produced during the engine's power stroke. It has been calculated by comparing the compression ratio inside the cylinder.

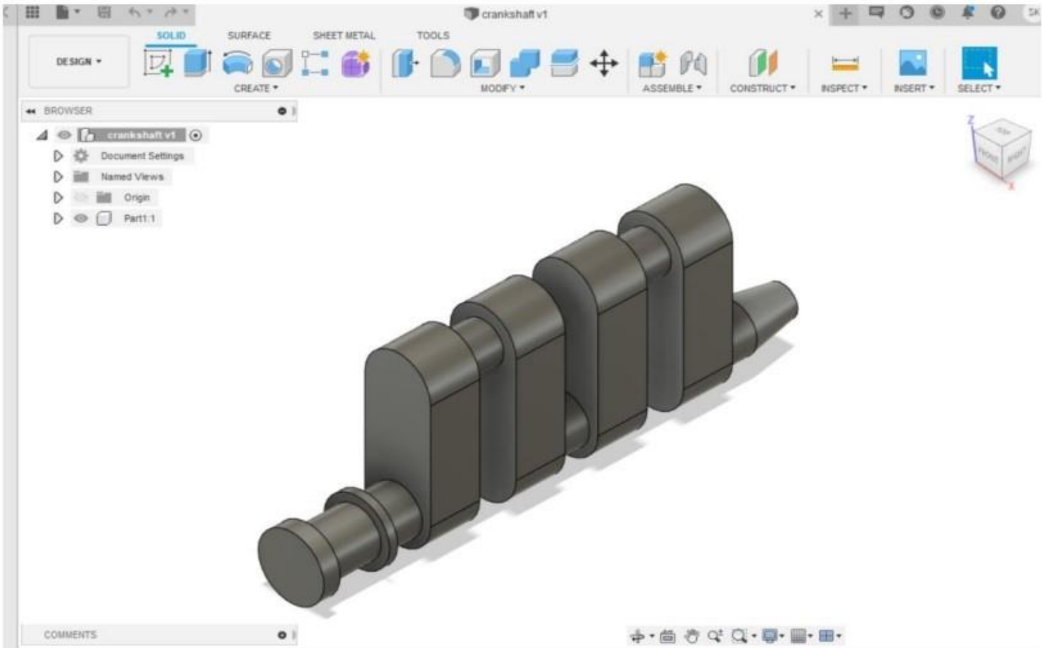

Figure 1. Modeling of the crankshaft

3.2. Meshing

It is an important process to obtain results accurately in finite element analysis. The smaller the mesh size, the more resolution of the design solutions as samples across the physical domains for higher accuracy the mesh size to be very fine results in an increase in time taken for processing. A finite element mesh includes nodes and elements: Nodes are points in 3d space, and Elements are the area or volume defined by nodes.

3.3. Selection of mesh elements

The geometry provided by the element poses the template for meshing. Based on the area defined in a domain, the element types are wildly classified into the following Shell elements, Solid elements and Line elements

The shell elements are usually used in modal structures in which one dimension, the thickness, is significantly smaller than the other dimensions. Conventional shell elements use the condition to discretize the body of a 3d model by defining the geometry at a reference surface of the model. Conventional shell elements have both displacement and rotational degrees of freedom, but in the continuum, the shell element only discretizes an entire three-dimensional body. The thickness is decided from the element nodal geometry. While the Continuum shell elements have transposition degrees of freedom only in the thickness property of the material. From a modeling point of view, continuum shell elements appear as if 3d continuous solids, but their kinetic and constitutive behavior is analogous to standard shell elements.

The cad model geometry describes the entire geometry in Solid elements. The tetrahedrons are the element type for three-dimensional, solid meshes. In linear tetrahedral element is defined by four corner nodes connected by straight edges. A parabolic tetrahedral element is described by four corner nodes, six mid-side nodes, four corner nodes, and six edges. For the same mesh density for several elements, parabolic tetrahedral elements possess improved results than linear elements because they denote curved boundaries more accurately and make better mathematical approximations. Parabolic tetrahedral elements require more computational resources than linear elements.

Table 5.Mesh Settings of the crankshaft

Use Adaptive Sizing	Yes
Resolution	Default (2)
Mesh Defeaturing	Yes
Defeature Size	Default
Transition	Fast
Span Angle Center	Coarse
Initial Size Seed	Assembly
Bounding Box Diagonal	0.40133 m
Average Surface Area	3.3839e-004 m²
Minimum Edge Length	1.05e-005 m
Nodes	63768
Elements	42298

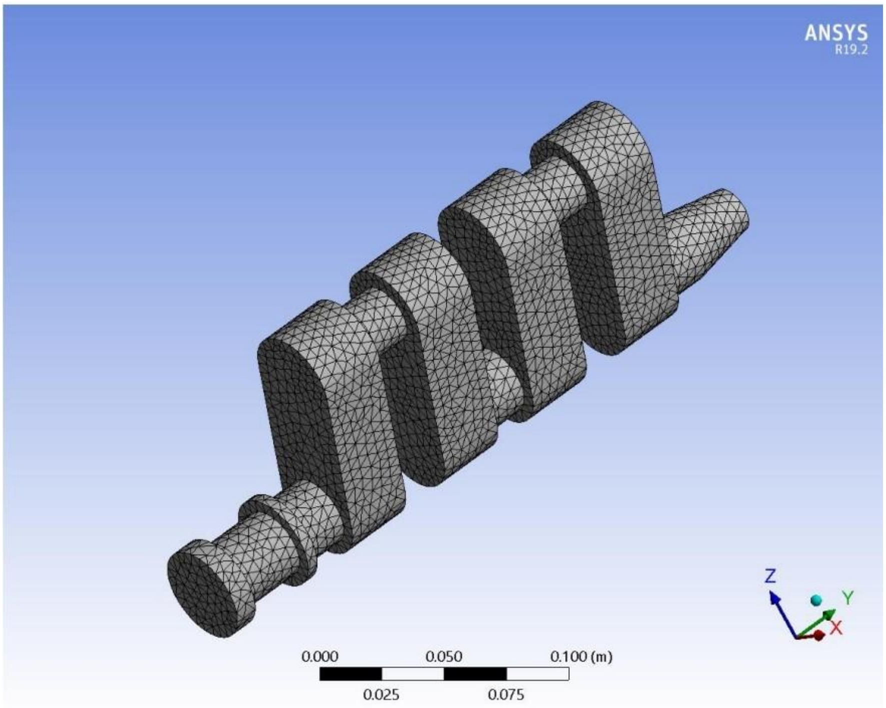

Figure 2. Meshed structures of the crankshafts

4. Result and Discussions

4.1. Analysis of crankshaft based on different materials.

4.1.1 Cast iron

An analysis of cast iron material shows maximum deformation is represented in green color in the figure, and minimal deformation is shown in red. The blue color represents the average value. The maximum deformation value is 1.29E04mm in the region between 4-4.25-time intervals. The maximum deformation is due to the application of unbalanced force during the power stroke of the otto engine cycle. The maximum stress induced in this model is 8.8418e+007 Pa. the stress value is too high and can result in structural failure. Hence, the cast iron material is unsuitable for topology optimization.

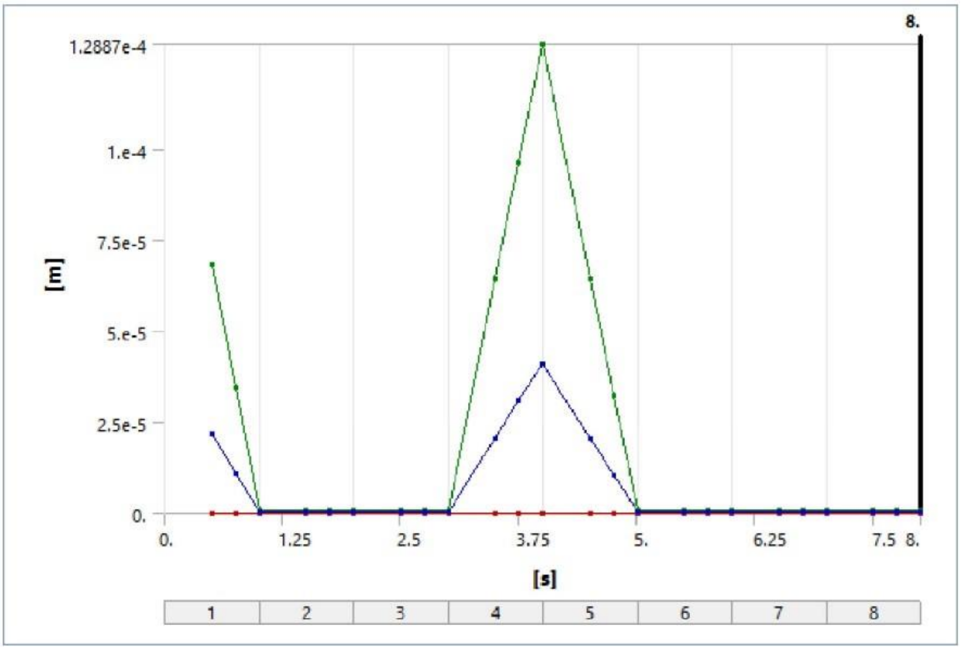

Figure 3. time vs. deformation of the crankshaft on cast iron material

4.1.2. titanium

An analysis of titanium material shows maximum deformation is represented in green color in the figure, and minimal deformation is shown in red. The blue color represents the average value. The maximum deformation value is 2.7E-04mm in the region between 4-4.25-time intervals. The maximum deformation is due to the application of unbalanced force during the power stroke of the otto engine cycle. The maximum stress induced in this model is 5.7804e+007Pa. The stress value is manageable so that the topology optimization technique can optimize the material. Still, in terms of economic value, the cost of titanium is very high compared to the other two materials, so the material titanium is removed from the topology optimization criterion.

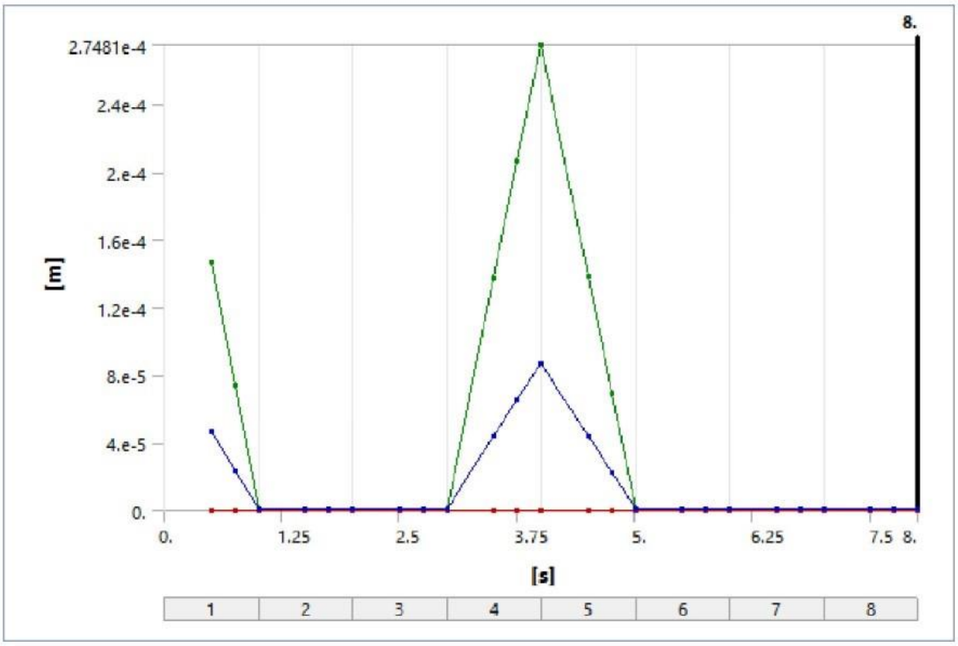

Figure 4. Time vs. Deformation of the crankshaft on titanium material

4.1.3. Inconel 625

An analysis of Inconel 625 material shows maximum deformation is represented in green color in the figure, and minimal deformation is shown in red. The blue color represents the average value. The maximum deformation value is 1.28E04mm in the region between 4-4.25-time intervals. The maximum deformation is due to the application of unbalanced force during the power stroke of the otto engine cycle. The maximum stress induced in this model is 8.8418e+007Pa. The stress value is manageable, so the material can be optimized through the topology optimization technique by comparing the other two materials Inconel manufacturing feasibility is high. It can be manufactured through SLM, molding, machining, and welding, and it is economical. The Inconel crankshaft's production cost is too manageable, and the material wastage is very low in the SLM manufacturing method.

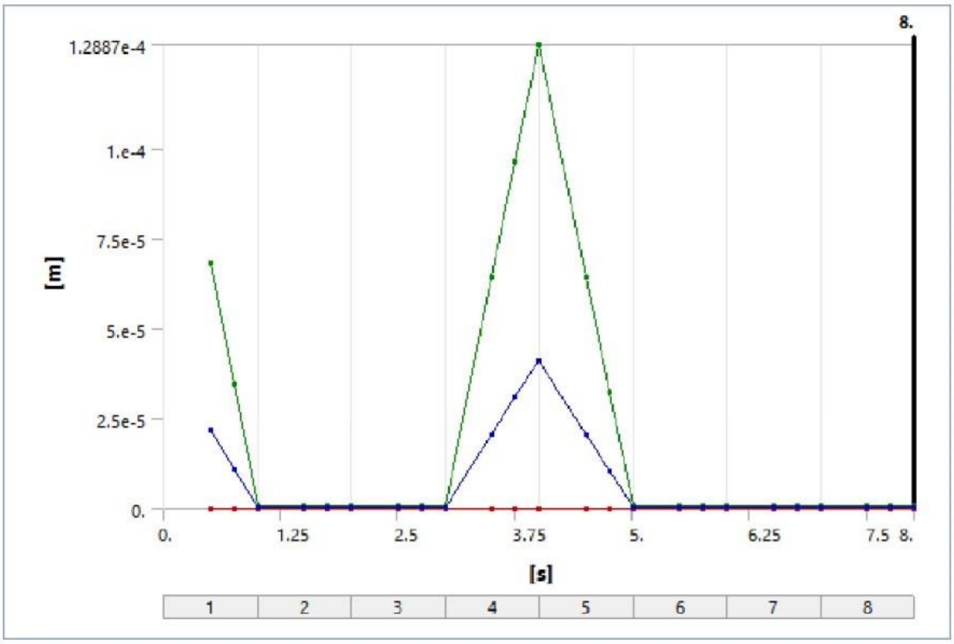

Figure 5. time vs. deformation of the crankshaft on Inconel 625 material

4.2. Topology optimization

The results are calculated from mesh in the ANSYS WORKBENCH form optimization module by supplying loads, boundary conditions, and weight reduction percentage. There are no deflection, tension, or frequency limitations, so the results are immediately obtained. These findings indicate the content that should be discarded and the material that should be kept.

The optimization concentrated on the non-essential pieces that needed to be cut. It is recommended that the excessive form and arrangement of the geometry be excluded from the form optimization. Topology optimization lets you decide where supports and loads can be placed on a content volume, and the programmer can figure out the right form for you. Structures can now be lightly weighted rapidly, CAD forms extracted, and the streamlined configuration quickly checked. For more precise restimulation, you can also simulate spatially based materials like composite parts, 3D printed structures, and bones and tissues.

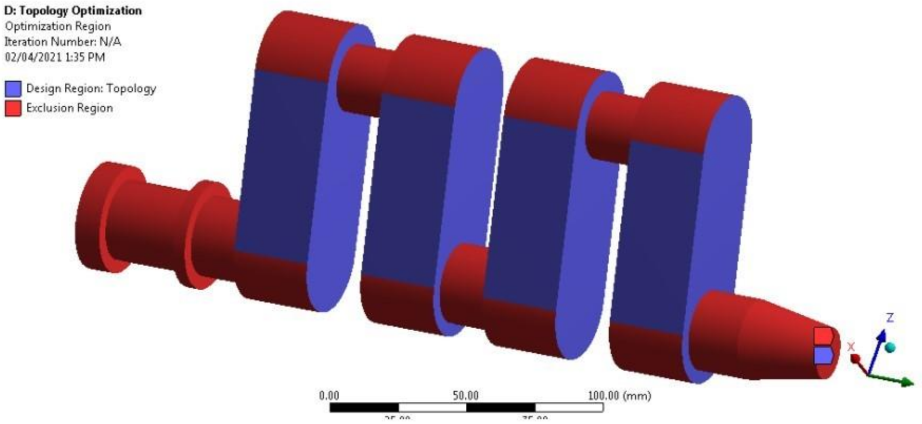

Figure 6.Selection of exclusion region in topology optimization

The selected exclusion region surfaces are selected because of upcoming joints or touching parts nearby the exclusion region where the optimization will take it as an obstacle or preserve areas.

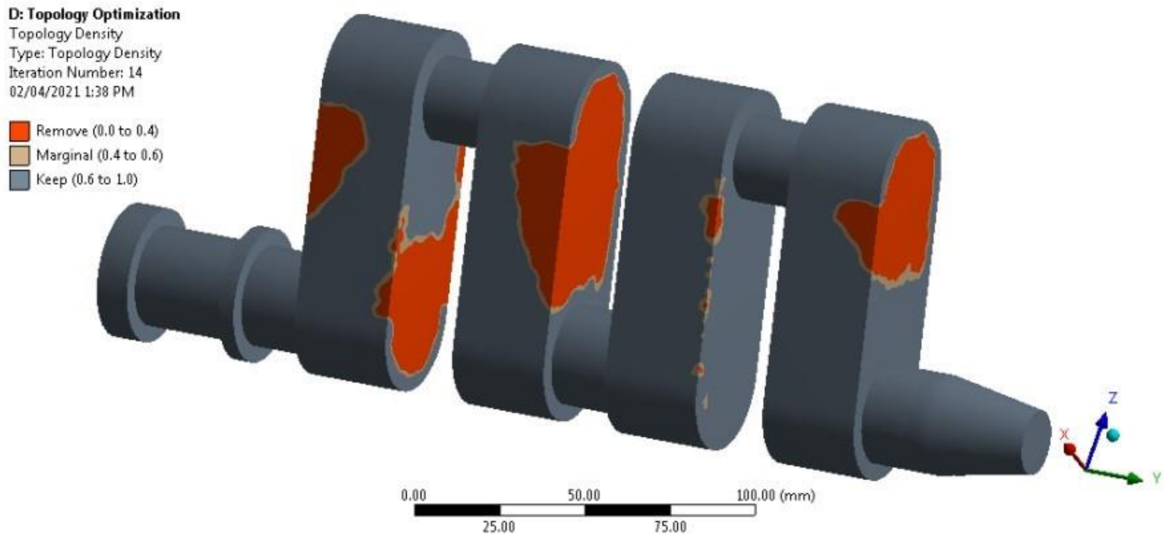

Figure 7. The outcome of topology optimization where material can be the removal

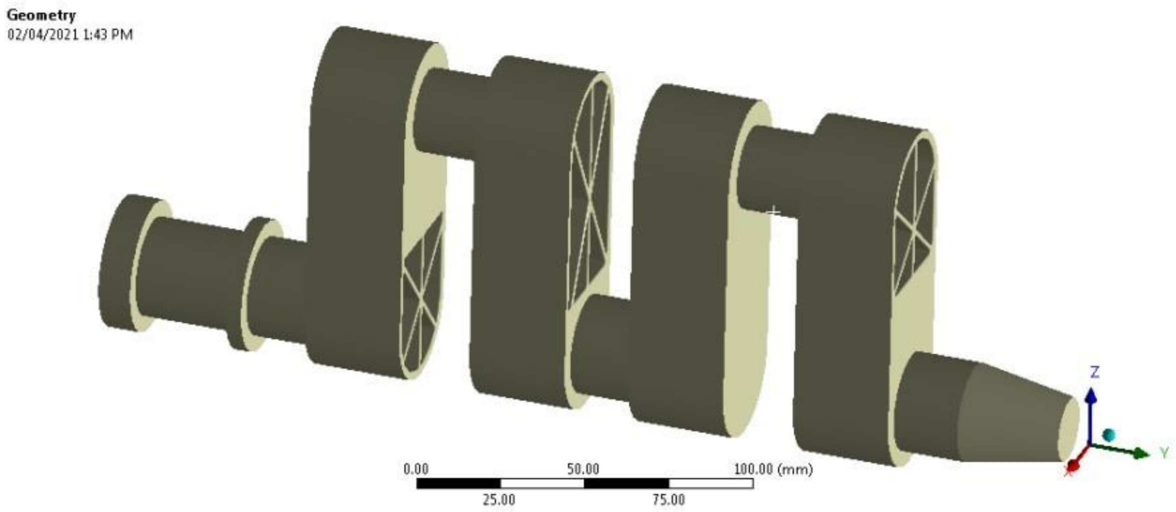

Figure 8. Modified designs from topology design

The modified design was changed by taking the topology design as input, and the excess material was removed without affecting the stiffness. To support the preserved obstacles, the rib-like structure was employed to provide support. The optimized design is further undergoing design finite element analysis for validation of optimized design.

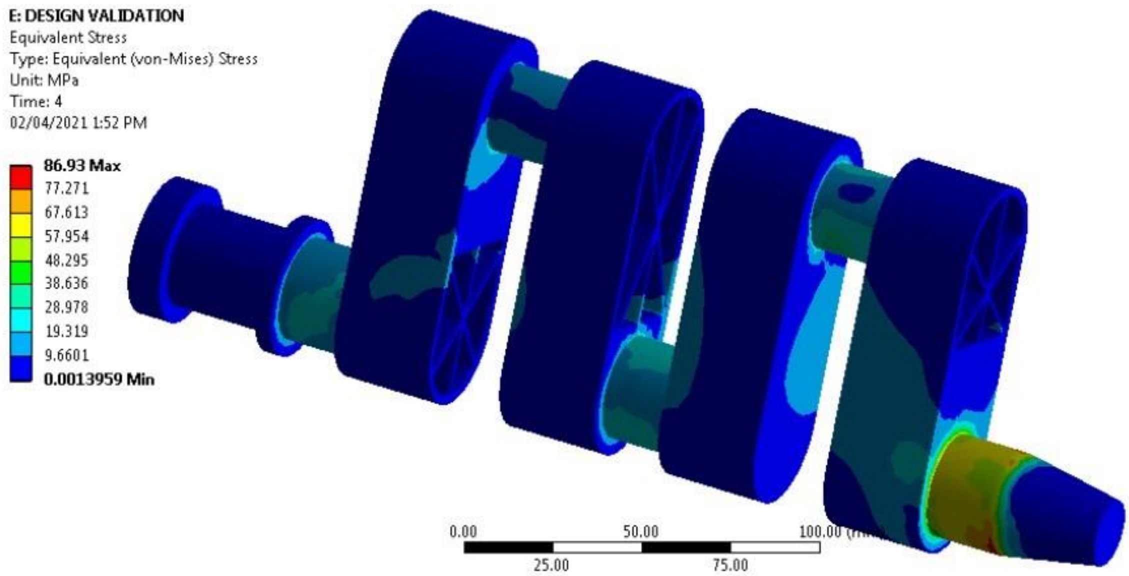

Figure 9. Equivalent stress occurs on the optimized crankshaft

4.3. Shape optimization

The crankshaft was optimized with the aid of a shape optimization technique shown in figure 10 and figure 11. The optimization concentrated on the non-essential elements that needed to be cut. The needless form and configuration of the crankshaft are suggested by shape optimization. The primary goal is to reduce the crankshaft's weight and the overall manufacturing expense. The optimized model, as can be shown, reduces the weight from the original configuration until the value converges. These optimizations are being implemented to determine the best design and shape of the crankshaft to boost efficiency and power, especially at the critical position. Based on the maximum principles stress and mass of the crankshaft, it compares the original and optimized designs. Because of the lowest stress and mass, the optimized crankshaft was chosen as the best-optimized concept. The stress-induced on model is thoroughly studied under topology optimization from ANSYS software. Materials were reduced from the existing model to provide a lightweight model without affecting the design stiffness. In analysis, the obtained von misses stress is lower than yield strength, so the design is safe for weight optimization.

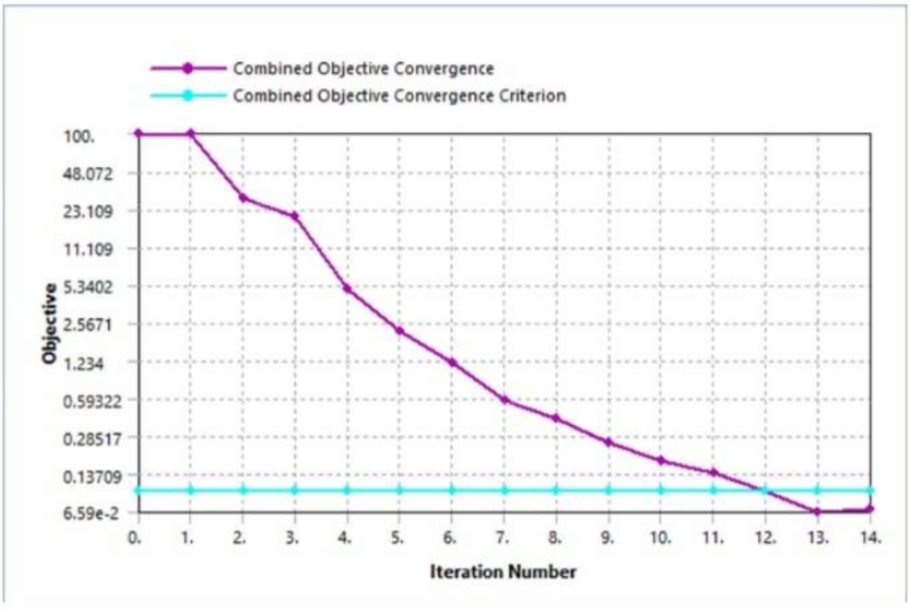

Figure 10. The compassion of original and iterations

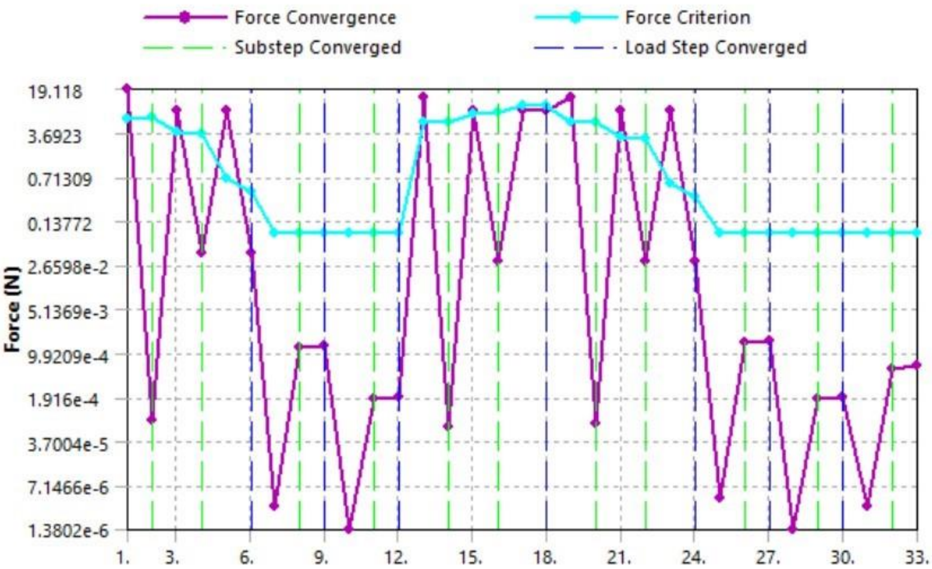

Figure 11. Shape Optimization-Design validation

4.4. Comparisons

Some materials were reduced from the model to provide a lightweight model without affecting the design stiffness. In this analysis, the obtained von misses stress is lower than yield strength, so the design is safe for weight optimization. The conventional design goes to topology optimization of the crankshaft (refer figure 12) where the material parameters, manufacturing methodology, and required mass content are given as input and maximum stiffness as a constraint. Initially, the design of the crankshaft weighed about 5.02kg. After the optimized model, the crankshaft weighs about 4.44kg.

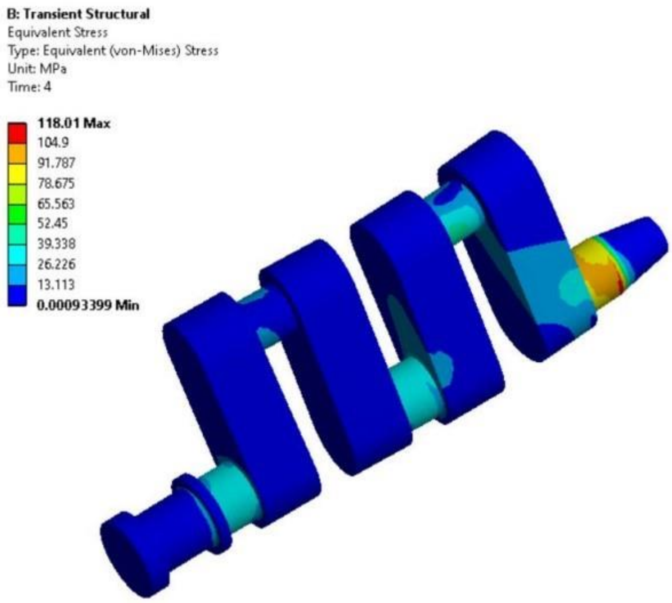

Figure 12.Equivalent stresses at peak load before optimization

About 11.55% of the weight has been removed from the crankshaft model. From figure 13 the stress induced on the crankshaft has been reduced by about 28% in the optimized model. In real-time production, about half a ton of material can be saved in the manufacturing of 1000 pieces of the crankshaft.

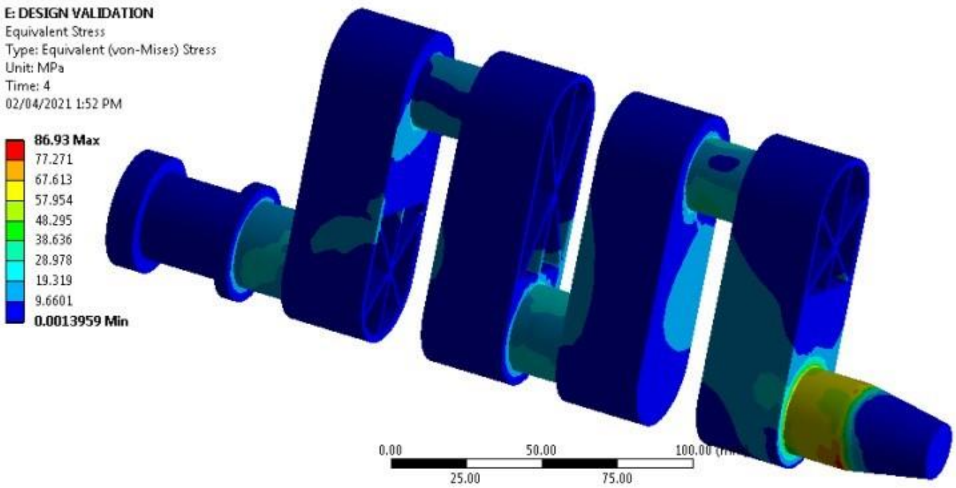

Figure 13. Equivalent stress at peak load after optimization

As the optimized design provides a better stiffer model. Inconel possesses higher yield strength, resulting in lesser brittle fracture than cast iron. The material elongates when subjected to higher loads. The stiffness of the model is increased by 14% in light weight-optimized model

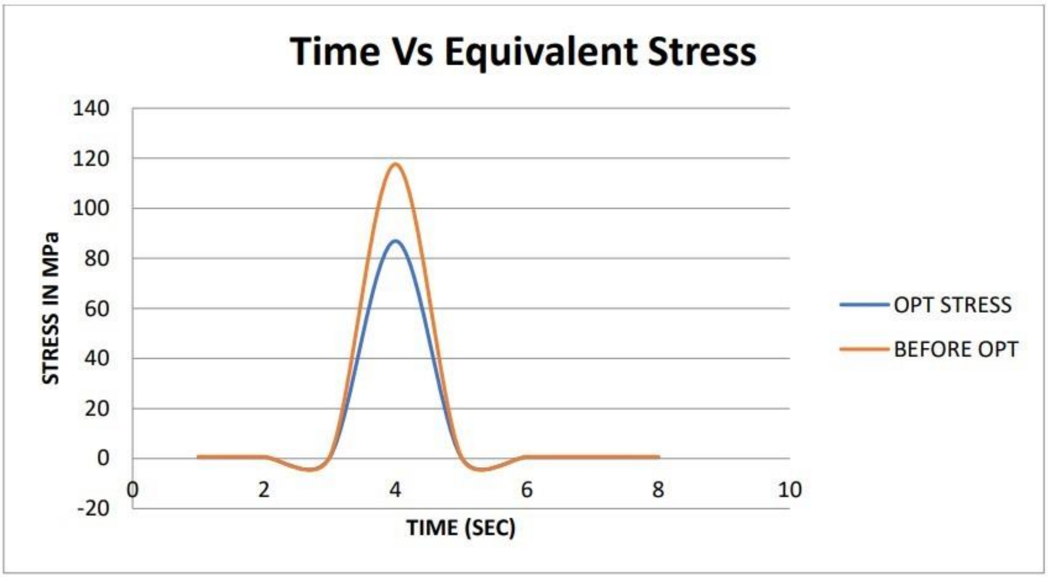

Figure 14.Time vs. equivalent stress with before and after optimized model

The development of equivalent stress with respect to time before and after optimization of the model is shown in figure 14. It has been observed that the higher stress is induced in the model before optimization. The deflection of crank shaft model before and after optimization is shown in figure which reflect that the deflection is less in the proposed model after optimization.

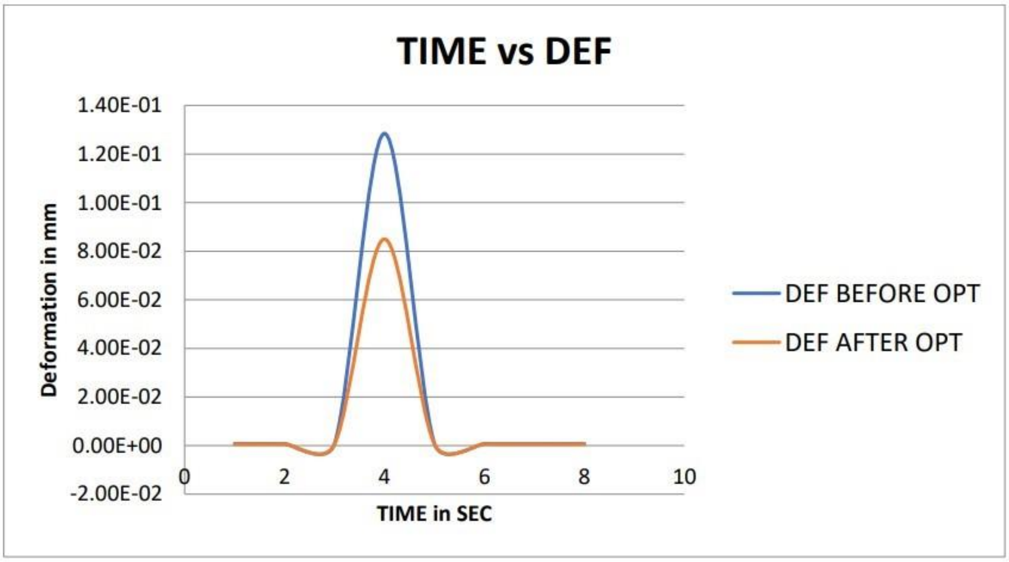

Figure 15.Time vs. deformation of before and optimized model

· 6. Conclusion

From the finite element analysis or FEA analysis, we learned that optimized design shows us good performance results for the crankshaft of a twin-cylinder engine. The given stress and deformation results for the optimized parts of the crankshaft of the twin-cylinder engine within the limit of an acceptable factor of safety limit, which confirms the design and analysis of the crankshaft in means of rigid body dynamics, transient structural analysis have been achieved. And use the topology optimization technique to possibly reduce the weight of the crankshaft.

References

[1] Zissimos P. Mourelatos, "A crankshaft system model for dynamic structural analysis of internal combustion engines," Vehicle Analysis and Dynamics Lab, Elsevier Science Ltd., June 2001.

[2] Crankshaft from an inline four-cylinder engine with pistons, connecting rods and flywheel. Illustration copyright Eaglemoss publications/Car Care Magazine.

[3] Priya. D. Shah, Prof. Kiran. K. Bhabhor, "Parametric Optimization of Four Cylinder Engine Crankshafts." International Journal of Engineering Science Invention, Vol. 3 Issue 6, June 2014, PP.38-43.

[4] Karthick Loganathan, Naresh Mallireddy, Yogaraja Jeyaraj and A. Sasikumar. Modeling and analysis of an EN8 crankshaft material in comparison with Forged steel crankshaft, May 2021

[5] M. Jian, Y. Liu and R. Liu (2011). Finite Element Analysis of 4-Cylinder Diesel Crankshaft. International Journal of Image Graphics and Signal Processing, Vol.3, pp.22-29.

[6] Xiaorong Zhou, G. Cai and Z. Cheng. The Whole Crankshaft Model for Dynamic Simulation Analysis of the Diesel, Published 22 May 2010

[7]. F. Erdogan, “Fracture mechanics of functionally graded materials,” *Composites Engineering*, vol. 5, no. 7, pp. 1–5, 1995.

[8]. M. B. Alazzam, F. Hajjej, A. S. AlGhamdi, S. Ayouni, and M. A. Rahman, "Mechanics of materials natural fibers technology on thermal properties of the polymer," *Advances in Materials Science and Engineering*, vol. 2022, Article ID 7774180, 2022.

[9] Guru deep Singh, Ashwin Misra, Design and optimization of crankshaft for four-cylinder 4-stroke spark ignition engine using transient structural analysis, International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) ISSN(P): 2249-6890; ISSN(E): 2249-8001