An optimized design of a connecting rod based on buckling and fatigue analysis

Submitted By

Sabbir Rahman; 180011108

Md. Mustakim Haque; 180011135

Md. Abu Ishrak Utsho; 180011127

Supervised By

Dr. Md. Zahid Hossain

A Thesis submitted in fulfillment of the requirement for the degree of Bachelor of Science in Mechanical Engineering

Department of Mechanical and Production Engineering (MPE)

Islamic University of Technology (IUT)

May, 2023

Candidate's Declaration

This is to certify that the work presented in this thesis, titled, "An optimized design of a connecting rod based on buckling and fatigue analysis", is the outcome of the investigation and research carried out under the supervision of Dr. Md. Zahid Hossain, Professor, Islamic University of Technology (IUT-OIC) .

It is also declared that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

Sabbir Rahman

Student No: 180011108

Md. Abu Ishrak Utsho

Student No: 180011127

Md. Mustakim Haque

Student No: 180011135

RECOMMENDATION OF THE BOARD OF SUPERVISORS

The thesis titled "**An optimized design of a connecting rod based on buckling and fatigue analysis**" submitted by **Sabbir Rahman,** Student No: 180011108, **Md. Abu Ishrak Utsho,** Student No: 180011127, and **Md Mustakim Haque**, Student No: 180011135 has been accepted as satisfactory in fulfilment of the requirements for the degree of B Sc. in Mechanical Engineering **on 19th May, 2023.**

Prof. Dr. Md. Zahid Hossain

MPE Dept., IUT, Board Bazar, Gazipur-1704, Bangladesh.

Abstract

Connecting rod, a vital component of an automotive engine, undergoes stress and deformation producing useful rotary motion. The following work was done aiming to fulfil a research gap in the premises of connecting rod. Even though quite a few numbers of works have been done to analyse Ti6Al4V as connecting rod material, none of them displayed a separate design based on its buckling load. However, calculating the design parameters and designing accordingly for different materials offers a chance of improvement. In this study, we designed a separate model for Ti6Al4V while maintaining same factor of safety against buckling which resulted in 60% weight reduction than the 42CrMO4 model. The design was verified using static and fatigue analysis in Ansys. The mass was even reduced further by response surface optimization technique weighing 0.196 kg only instead of original weight of 0.839 kg. This lightweight model made the design more compact and the reduced materials decreased engine load which improved the efficiency of the engine. Finally, how the neck radius affects the stress developed on the connecting rod was analysed and total deformation revealed a significant pattern with the increasing fillet radius and consequently the stress reduced drastically until a optimal point was reached. Finding this optimal fillet radius will help the future researchers to design more compact connecting rod with minimal stress and deformation.

Contents

List of Figures

1. Introduction

1.1 Literature Review

The purpose of a vehicle requires rotating motions, therefore the connecting rod, a component in between the piston and the cylinder is used to convert the piston's reciprocating movement into usable rotary motion [1]. To serve this purpose connecting rod undergoes a complex motion itself which includes both the reciprocating and rotary motion. Connecting rod is an important component of automobile engines and numerous works have been done towards their improvement. Sriharsha and Rao focused on establishing design aspects for connecting rods and recommended that the structure must have superior compressive and strength properties [2].

The combustion of the fuel inside the chamber creates high pressure on the piston end of the connecting rod [1]. Haider et al. investigated the application of the finite element method to calculate the deformation and strength properties of a connecting rod [3]. Desai et al. examined connecting rods under changed loading scenarios and concluded that maximum stress developed on the piston end, putting it at risk of failure [4]. Satbhai and Talmale developed a methodology for the design process with the help of existing literature and outlined a modified design for Pulsar-220 with improvements to the original design [5].

Gautam and Ajit utilized static structural simulation to identify the highest stress location and concluded that the stress concentration was maximum adjacent to the root of the smaller end making it vulnerable to both static and fatigue failure due to cyclic stresses produced by the piston assembly [6]. Vegi and Vegi explored the design of connecting rods of a two-wheeler and found that forged steel guards more against fatigue failure and offers a better yield factor of safety than carbon steel [7], [8].

The risk of fatigue failure in a connecting rod is high as it undergoes repetitive tensile and compressive stresses. Additionally, because it acts as a column, the connecting rod also experiences buckling stress. Thus, it is crucial to take fatigue properties into account and search for alternative materials. Patil et. al. performed a comprehensive review of the works done on the design and stress analysis of connecting rods subjected to various loading conditions and opined that utilizing a lightweight, yet strong alternative might yield better results than the commonly used forged steel connecting rod [8].

With the advent of the field of metallurgy, a wide variety of materials with desirable properties become available to use for specific purposes. Seralathan et. Al. performed stress analysis on A356, A356-5%SiC-10% fly ash stir casting, A356-5%SiC-10% fly ash stir casting, and Al2024-T3 for a diesel engine connecting rod, and concluded that A356-5%SiC-10% fly ash stir casting provided the best performance in terms of total deformation, maximum stress, and strain developed [9]. Verma and Jain analyzed connecting rods of a two-wheeler using four aluminum alloys and found that A356-5 percent Sic-10 percent fly is the best candidate among them to manufacture connecting rods [10]. Satish et al. also carried out stress analysis on AA2014, AA6061, and AA7075 for the design of the connecting rod of a bike. Based on the analytical calculations and FEA analysis, they found that the AA2014 had the lowest weight and the highest stiffness among the three materials evaluated [11]. Rao et. al. conducted both experimental and simulation studies to estimate the fatigue life of a connecting rod in a Sundry I.C engine. The authors carried out a kinematic and dynamic analysis at different compression ratios and also at four separate critical crank angles using forged steel, titanium alloy, and aluminum alloy. Subsequent analysis on Ansys indicated that of all the materials used, titanium Alloy offers a fatigue life ten times more than aluminum alloy and a hundred times more than that of forged steel. Based on the result, the authors opined titanium alloy is ideal for connecting rods when engines operate on heavy loads and aluminum alloys can be used for engines with a light load to reduce costs [12].

Buddi and Rana used reinforced aluminum matrix composites Al7068 and Si3N4 manufactured in different variants and used a different process to use in connecting rods to explore weight reduction opportunities while preserving or lowering the maximum stress, maximum strain, and the maximum deformation formed as a result of loading. By using an experimental setup, it was found that increasing the weight of Si3N4 up to 5% in the Al-Si3N4 composites results in better hardness and elasticity and diminishes flexibility. The authors suggested further fatigue and dynamic studies for these materials and testing new materials for weight reduction prospects [13]. Kumar et. al. modifies and simulated dynamic analysis using different chromium-molybdenum alloys for the connecting rod of the Bajaj pulsar 150cc motorbike and determined that 42CrMo steel alloy had smaller dimensions and used less material than the 20CrMo and 30CrMo connecting rod materials to withstand the requisite pressure operated within the chamber [14].

Wable and Gale analyzed stresses induced in connecting rods of two-wheeler engines. In internal combustion engines, the thrust force due to combustion and the mass of inertia of connecting rod subject it to huge compressive and high tensile stresses respectively, which are repetitive in nature. The work was aimed to replace the forged steel connecting rod with an aluminum MMC-made connecting rod which was found to offer better strength with a lower weight [15].

Gupta and Nawajish compared Al360, Beryllium (alloy 25), and Mg alloy and assessed that Beryllium alloy has lower maximum equivalent stress, maximum equivalent strain, displacement, and shaky behavior in connecting rods in comparison to the rest of the two materials [16]. Kumar Verma et. al. designed and analyzed connecting rod of a Yamaha bike using chrome steel and titanium instead of traditional materials and found that these materials gave superior results [10].

Patil-Dhande et. al. approached weight reduction optimization by changing the materials used in connecting rods. They found out that the glass fibers and glass fibers offered significant weight reduction and are subjected to less stress than cast iron but deforms in greater amounts [17]. Wankhade and Ingale reviewed the use of different materials in connecting rods and from their analysis concluded that high-strength carbon fiber obtains better results than Al 7075 and Al 6061 [18]. Lade et. al. compared std. Unidirectional Carbon Fibre connecting with a connecting rod formed with aluminum alloy and stainless steel. The study concluded that carbon fiber obtains better results in terms of maximum pressure, less deformation, and lightweight but the cost of it makes it harder to use carbon fiber for general purposes [19]. Lade et. al. carried out another study focused on the dynamic analysis of connecting rods using carbon fiber and found that carbon fiber has similar advantages over steel [20]. Shenoy and Fatemi performed an optimization intending to cut manufacturing costs and reduce the weight by minimizing the machining steps without substituting forged steel as a material and found out that considering the connecting rod separately rather than part of the assembly significantly alters the results. They concluded that the region in between the ends has the highest potential for weight reduction and the main consideration during optimization should be fatigue safety. They also recommended that such a section modulus should be used that can withstand the whipping stress [21].

Several primary Multi Attribute Decision-Making method techniques were tested by Teraiya et al. for the selection of acceptable material for the connecting rod, and it was determined that the VIKOR method is most suited for this application, however, the TOPSYS method can also be used. The author compared 42CrMO4, Al alloys (2021,6061, 7075), C70, EN-8D, AISI 1141, FS, and TP 2024 to find out that 42CrMo4, En-8D, C70 were the best candidates among them while Forged steel and AISI can be identified as succeeding options but Al 2014 and 6061 are not a good choice for connecting rod [22]. Gopinath and Sushma conducted a static load stress investigation and identified that from the shank region of a forging steel connecting rod a significant reduction of mass is attainable [23].

Le et. al. presented a novel analysis technique to handle the first and second modes of buckling for the connecting rod utilizing finite element analysis and found that the suggested procedure estimated the buckling stress better than the classical formula when compared to values measured in rig experiments Then they examined the variation of stress when the area of the shank is reduced which revealed that stress sensitivity to buckling is either significantly higher or similar to those of yield and fatigue. Finally, the author recommended that Buckling, along with other variables such as yield and fatigue, should be addressed by the authors while attempting to reduce the weight of the connecting rod shank [25].

Shanmugasundar et al. investigated the modelling, analysis, and topology optimization of the connecting rod of a four-stroke spark ignition engine, as well as developed a fine-tuned design for manufacturability. The authors highlighted that the updated model is more efficient than the initial one with lesser stress developed and 3.5% reduced mass for the same material [26]. Ajayi et al. performed shape optimization by reducing clearance at the bigger end to avail the advantages of titanium alloys, including higher strength, and significantly reduced deformation, and obtained an 11.7% reduction in weight. But the authors suggested designing the connecting rod considering manufacturability and opined same technique can be applied to calculate other design parameters [27].

From the literature discussed above, it is established that usual materials for connecting rod design are forged steel or cast iron. A number of works has been done to analyze the effect of using other alloys (Titanium, Magnesium, Beryllium) and Titanium has been identified as a very promising material for designing connecting rod. However, these studies developed a design considering buckling phenomenon for steel and used the same model while analysing for titanium alloys. But as titanium has superior properties, a separate design for titanium alloy to withstand buckling can offer more room for weight reduction. Also, it is evident from the literature that the neck between small end and shank connecting rod is one of the regions which is subjected to maximum stress. It is yet to explore how the change in neck radius effects the connecting rod in terms of maximum stress developed and fatigue safety.

1.2 Objectives

This research work aims to fulfil the following objectives:

(i) To design separate models for $42CrMO_4$ and Ti6Al4V maintaining the same factor of safety against buckling. This modification in design has provided a significant change in the result.

(ii) To perform response surface optimization and review the values obtained from analysis before and after the optimization. The improved design will be preferable since the required fatigue factor of safety will be preserved, and the model will weigh less than the original.

(iii) To investigate the effect of neck radius on the stress concentration developed in the connecting rod. This correlation will provide us with a useful pattern while designing the connecting rod.

1.3 Methodology

Connecting rods are crucial components in reciprocating engines, connecting the piston to the crankshaft and converting the reciprocating motion of the piston into rotational motion. The material and cross-section of the connecting rod significantly impact its performance, durability, and weight. Steel, forged steel, aluminium alloy, and titanium alloys are commonly used as materials for connecting rods, with I-sections and H-sections as the preferred cross-sections. The I-section is favoured as it provides more support with less weight, while some high-power engines employ the H-sections to sustain more stress without bending.

The next step involved preparing a model in SolidWorks and importing it as IGES into ANSYS Workbench for meshing. Meshing is the process of splitting a model into a finite number of tiny components to use the finite element technique. The accuracy of the simulation output for any given boundary conditions depends on the fineness of the grid. ANSYS Workbench was also employed to evaluate the stress and deformation and estimate the fatigue life and fatigue factor of safety of the connecting rods designed using both materials.

Furthermore, the existing design was optimized using Response Surface Optimization in ANSYS Workbench to reduce weight while maintaining the fatigue factor of safety. Response Surface Optimization is a technique used to optimize the design parameters of a system subject to constraints. This method involves fitting a mathematical model to the simulation data and finding the optimal values of the design parameters that satisfy the constraints. Then, the validity of the candidate points was verified using the design verification feature in ANSYS. Finally, the values obtained through response surface optimization were compared with the results for the unoptimized model, and the change in mass was factored in.

In conclusion, the study employed Ti6Al4V and 42CrMO4 steel as materials of choice for modelling connecting rods and I-sections. The simulation results obtained using ANSYS Workbench provided insights into the stress, deformation, and fatigue life of the connecting rods designed using both materials. The optimization using Response Surface Optimization technique resulted in a reduction in weight while maintaining the fatigue factor of safety. The findings of this study can aid in the design and optimization of connecting rods for reciprocating engines, leading to improved performance, durability, and weight reduction.

2. Validation and Design Calculations

2.1 Validation

In the paper taken as reference, Basavaraj et. al. employed four different materials to model the connecting rod of a 100cc IC engine of a motorbike from AISI 4140 Cr-Mo high tensile steel, forged steel, Al7075 T6, 42CrMO4 and analysed them with finite element analysis [1]. Using the parameters published in the literature, a geometrical model was generated and the equivalent stress, total deformation, fatigue life and fatigue factor of safety obtained were very close to the values obtained in the reference paper and the results are plotted in figure 1 to figure 4, respectively.

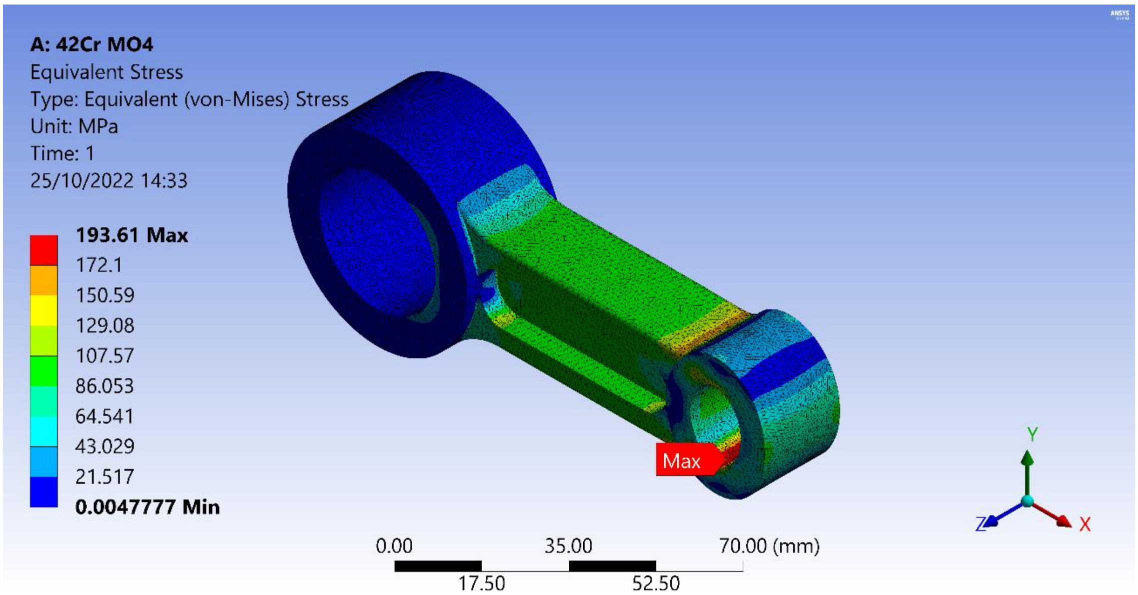

Figure 1: Equivalent Von Mises stress of the connecting rod using reference paper data

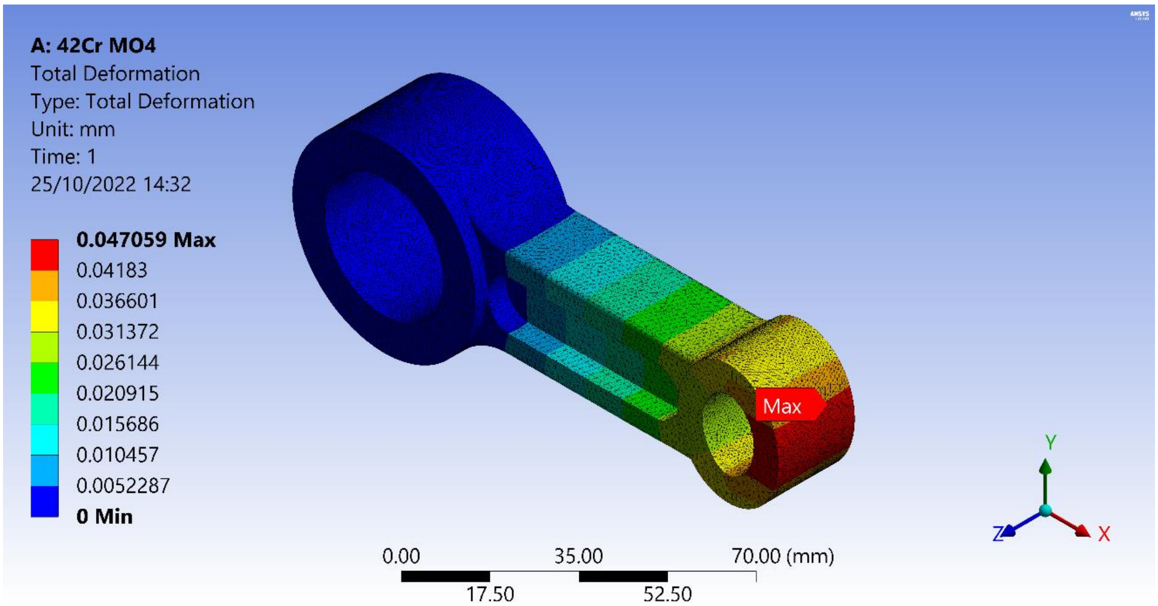

Figure 2:Total deformation of the connecting rod using reference paper data

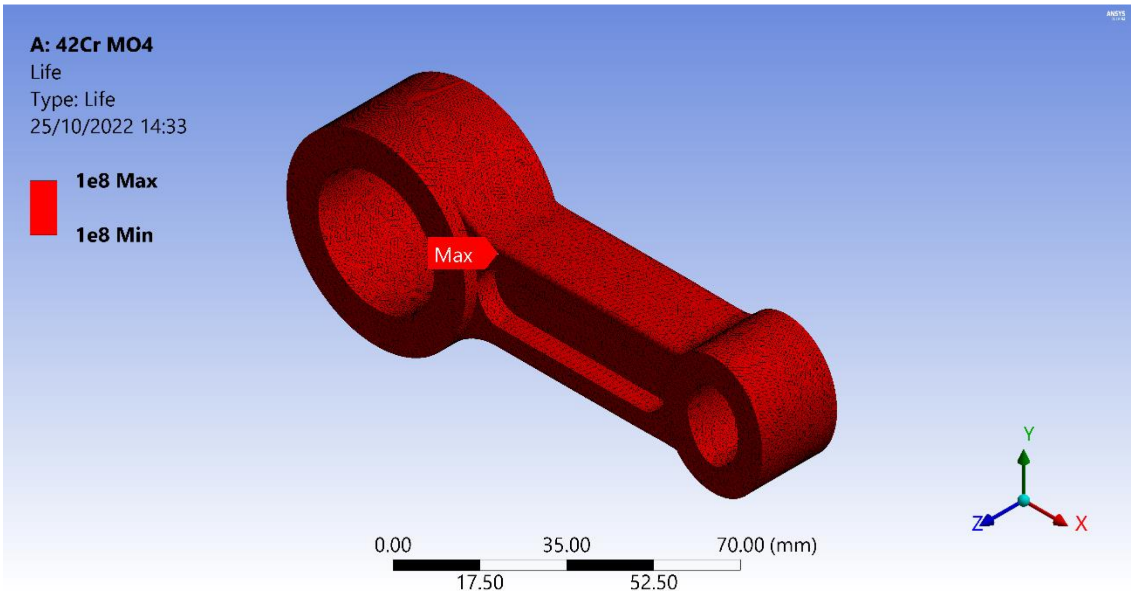

Figure 3: Predicted fatigue life of the connecting rod using reference paper data

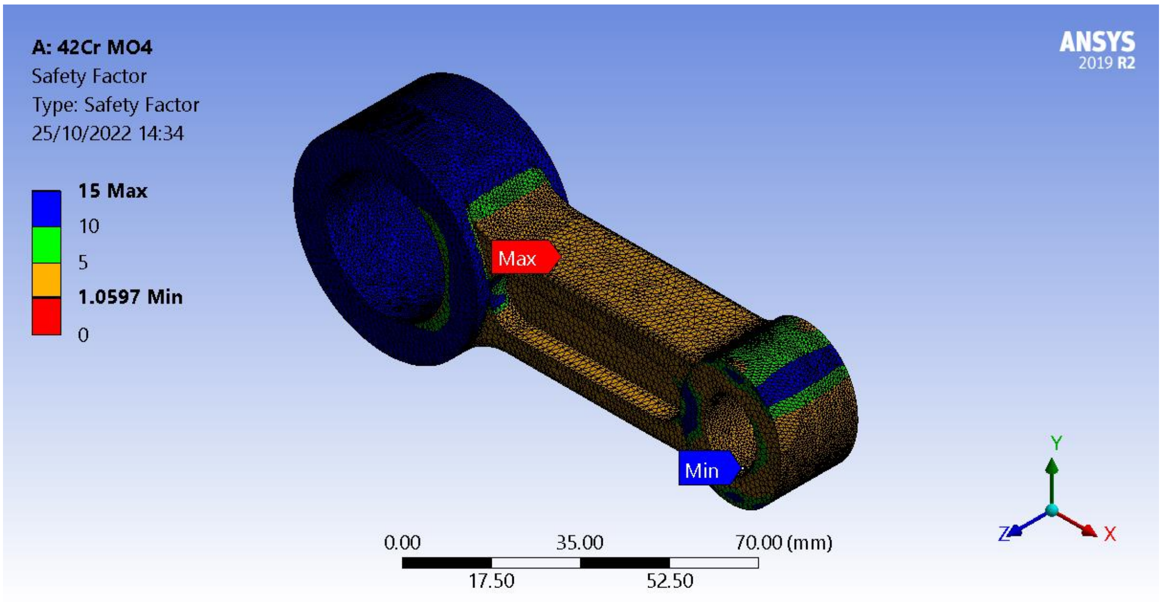

Figure 4: Fatigue safety factor of the connecting rod using reference paper data

The obtained values from the simulation and the values from reference paper are compared in table 1.

Table 1
Comparison of results simulation and reference paper data

S. No.	Parameters	Reference paper Data	Simulation
1	Equivalent stress (MPa)	190.86	193.6
3	Fatigue life (cycles)	1e8	1e8
4	Minimum Fatigue factor of safety	1.075	1.058
4	Maximum total deformation (m)	5.52e-8	4.71e-8

2.2 Design Calculations

In this study, the materials of choice for modelling the connecting rod and I-section are Ti6Al4V and 42CrMO4 steel. These materials were chosen based on their properties, including strength, toughness, and fatigue resistance. Table 2 lists the necessary properties of 42CrMO4 and Ti6Al4V.

Table 2
Material Properties [29]

	42CrMO4	Ti6Al4V (Annealed Bar)
Density, kg/m3	7700	4430
Young Modulus, GPa	200	114
Ultimate Strength, MPa	650	900
Yield Strength, MPa	350	860
Poisson Ratio	0.33	0.33

In this study, a Hero Splendour Plus I.C. Engine connecting rod has been considered and the engine specifications are outlined in table 3.

Table 3
Specifications of Hero Splendor Plus I. C. Engine [1]

1	Type of engine	Air-cooled
2	No. of cylinders and Strokes	Single cylinder, 4 stroke
3	Combustion system	Spark ignition
4	Displacement (cm3)	97.2
5	Bore(D) × stroke (L)	50.0 × 49.5
6	compression ratio	9.9: 1
7	Maximum power output (kW/rpm)	5.9/8000
8	Maximum torque (Nm/rpm)	8.05/6000

The design parameters of the connecting rod were calculated using both materials, following the engine specifications listed above. Figure 5 shows 3D model of the connecting rod with calculated dimensions using $42CrMO_4$ as material.

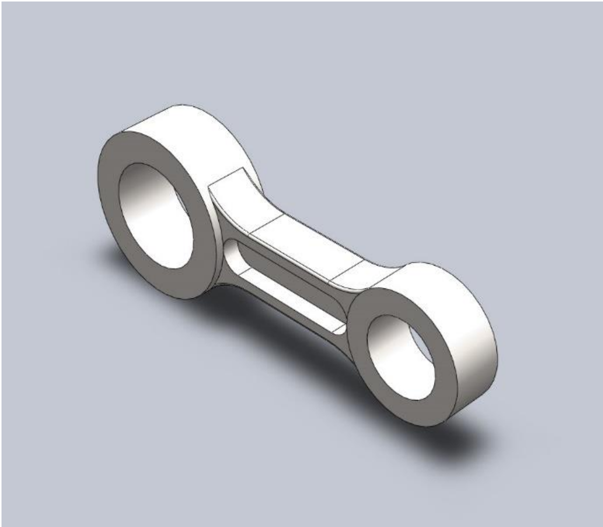

Figure 5: 3D model of connecting rod using SolidWorks

Self-Ignition Temperature of Petrol $[T] = 288.85\ K$, density $[\rho] = 737.22\ kgm^{-3}$,

Mass $[M] = 737 * 97.2 * 10^{-6} = 0\ .071636\ kg$,

The molecular weight of petrol $[M_w] = 114.228\ g.mol^{-1}$

Gas constant [R] $= \frac{8.313}{0.114228} = 72.775$

The pressure of the piston at the piston end is,

$$P = \frac{mRT}{V} = \ 15.485\ MPa \qquad (1)$$

Due to this pressure force exerted on connecting rod is,

$$F_{gas} = \left(\pi * \frac{D^2}{4}\right) * P = 30404.73\ N \qquad (2)$$

Using a factor of safety $[n] = 2.5$ the buckling load is,

$$F_b = F_{gas} * FOS = 75100\ N \qquad (3)$$

Radius of the crank is calculated as $[r] = \frac{stroke\ length}{2} = 24.75\ mm$.

The length of the connecting rod is $l = 2.5 * 49.5 = 124\ mm$

Where, the accepted length of the connecting rod is 1.25 to 2.5 times of stroke of the engine [7] .

The ratio of the length of the connecting rod to the radius of the crank $[n] = \frac{l}{r} = 5$,

maximum angular speed at maximum torque is $[\omega_{max}] = \frac{2\pi N_{max}}{60} = 837.8\ rad/s$

Using $r = \frac{bore}{2} = 25mm$ Maximum inertia force of the reciprocating parts is calculated as

$$F_{in} = M\omega_{max}{}^2 r\left(1 + \frac{1}{n}\right) = 1492.44\ N \qquad (4)$$

2.2.1 Small end Diameters

To find the inner diameter of the piston end $(\boldsymbol{d_p})$, by taking $l_p = 2d_p$ and $p = 15\ Mpa$ (design bearing pressure can be taken for small end P_{b1}=12.5 to 15.4 MPa [7]) we use gas force

$$F_g = d_p * l_p * p => 30404.73 = d_p * 2d_p * 15 \qquad (5)$$

Piston ends inner diameter, $d_p = 31.84\ mm = 32mm$

The outer diameter of the piston end, $d_o = d_p + 2t_b + 2t_m = 51.84\ mm$

Where, thickness of the bush (t_b) varies between 2 to 5 mm and the value of the marginal thickness (t_m) can be varied in the range of 5 to 15 mm.[7]

2.2.2 Big end Diameters

To find the inner diameter of the crank end $[\boldsymbol{d_p}]$, by taking $l_c = 1.5d_p$ and $P = 10.8\ Mpa$ (Design bearing pressure for the big end can be taken as $P_{b2} = 10.8\ to\ 12.6\ MPa$ [7] we use gas force,

$F_g = D_c * l_c * p$

$=> \; 30404.73 = D_c * 1.5D_c * 10.8$ (6)

Big end Inner diameter (Crank end) $D_c = \; 43.32\, mm = 43mm$

And the nominal diameter of the bolt is calculated as $[d_b]$ = 1.2 * 4.47 = 5.36 mm.

Big end outer diameter= $D_c + 2t_b + 2t_m + 2d_b = 67.84mm = 68mm$

2.2.3 I-section calculations

For a I –section with a flange and web thickness of t, let the height is $5t$ and the width is $4t$. The height at the smaller end is 0.75 to 0.9 times the mean height and the accepted value of the height at the bigger end is 1.1 to 1.2 times of mean height.

So, the area is, $A = 2 * (t * 4t) + (3t * t) = 11t^2$

For a connecting rod, it is considered like both ends hinged for buckling about x-axis and both ends fixed for buckling about y-axis. A connecting rod should be equally strong in buckling about either axis $I_{xx} = 4\, I_{yy}$ [7]

If $I_{xx} > 4I_{yy}$ then buckling will occur about y-axis and if $I_{xx} < 4I_{yy}$,then buckling will occur about x-axis.

Now moment of inertia along the x-axis,

$I_{xx} = \left(\frac{419}{12}\right) t^4$ (7)

Moment of inertia along the y-axis,

$I_{yy} = \left(\frac{131}{12}\right) t^4$ (8)

Dividing equation (7) with equation (8) gives $\frac{I_{xx}}{I_{yy}} = 3.2$

The Connecting rod is designed for buckling about x-axis. Radius of gyration along the x-axis,

$K_{xx} = \frac{I_{xx}}{A} = 1.78t$

Rankine formula for a given thickness of I-section is Buckling Load, $F_b = \frac{\sigma_c A}{1+a\left(\frac{l}{k_{xx}}\right)^2}$ (9)

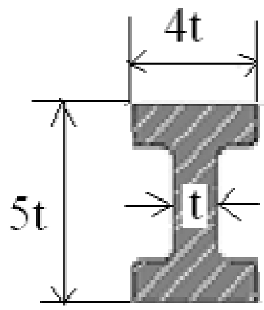

Figure 6: Standard dimension of I-Section [7]

For 42CrMO4 steel, using the Rankine formula with $a = \frac{1}{7500}$ *[1] gives,*

=> $75100 = 250 * \frac{11t^2}{1+\left(\frac{1}{7500}\right)\left(\frac{124}{1.78t}\right)^2}$ => $t = 5.286\ mm$

Width, $B = 4t = 21.14\ mm$

Height, $H = 5t = 26.43\ mm$

Height at the big end, $H_1 = (1.1\ to\ 1.25)H = 29.07\ mm$

Height at the small end, $H_2 = (0.75\ to\ 0.9)H = 23.79\ mm$

For Ti6Al4V, using the Rankine formula,

$75100 = 860 * \frac{11t^2}{1+\left(\frac{1}{1308.3}\right)\left(\frac{124}{1.78t}\right)^2}$ Here,$a = \frac{\sigma_c}{\pi^2 E} = \frac{1}{1308.3}$

=> $t = 3.138\ mm$

Width, $B = 4t = 12.55\ mm$

Height, $H = 5t = \ 15.06\ mm$

Height at the big end, $H_1 = (1.1\ to\ 1.25)H = 16.57\ mm$

Height at the small end, $H_2 = (0.75\ to\ 0.9)H = 13.56\ mm$.

3 Analysis

3.1 Design in SolidWorks

The calculated design parameters of the connecting rod using 42CrMO$_4$ and Ti6Al4V are listed together in table 4. SolidWorks was used to build the 3D model of the connecting rod using these parameters.

Table 4
Connecting rod specifications

Parameters	Values (mm)	
	42CrMO4	Ti6Al4V
1. Thickness, t	5.286	3.138
2. Width, W	21.14	12.24
3. Height. $H = 4t$	26.43	15.06
4. Height at the crank end, $H1$	29.07	16.57
5. Height at the piston end, $H2$	23.79	13.56
6. Inner diameter at the piston end, d_p	32	32
7. Outer diameter at the piston end, d_o	52	52
8. Inside diameter at the crank end, D_p	43	43
9. Outer diameter at the crank end, D_o	68	68

The 2D drawing of a connecting rod with appropriate nomenclature is shown figure 7.

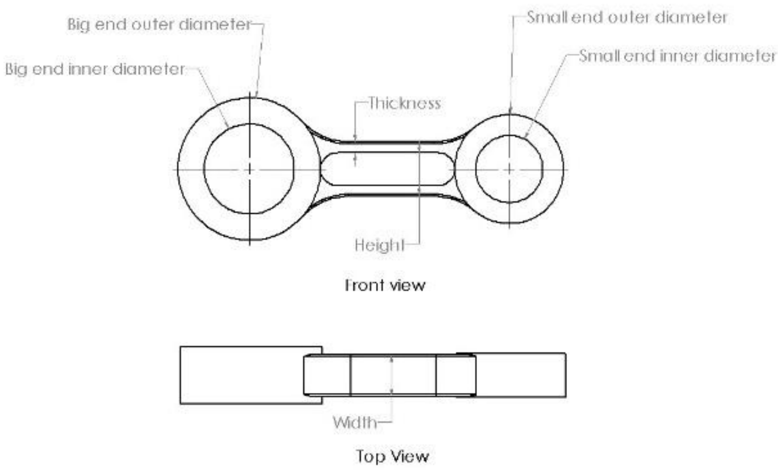

Figure 7: 2D drawing with appropriate nomenclatures

3.2 Analysis in ANSYS

For static analysis, the 3D model of the connecting rod is then loaded into ANSYS workbench. There are two methods for conducting a static stress analysis: one is linear static analysis, which has been considered in this analysis and the second method is the non-linear analysis used for more complex geometries. The tetrahedral mess with having a fine size with 185597 nodes and 108816 elements for 42CrMO4 and 173651 nodes and 99967 elements for Ti6Al4V. A force of 30404 N, which is calculated previously, applied from the piston end along the body of connecting rod to analyze the equivalent von mises stress, total deformation, fatigue life, and fatigue factor of safety. Figure 8 shows meshing of the connecting rod for analysis in ANSYS. In the connecting rod made of 42CrMO4 the maximum stress developed is 181.63 MPa with a maximum deformation of 0.072mm and in case of Ti6Al4V 358.6 MPa these values are 358.6 Mpa and 0.323mm, respectively. In both cases, the region of maximum stress is inner surface of the small end and a significant amount of stress develops in the neck region between small end and shank.

Figure 8: meshing of the connecting rod in ANSYS

The results for the equivalent stress, total deformation, fatigue life and fatigue factor of safety when the material is 42CrMO4 are plotted in figure 9,10,11,12, respectively.

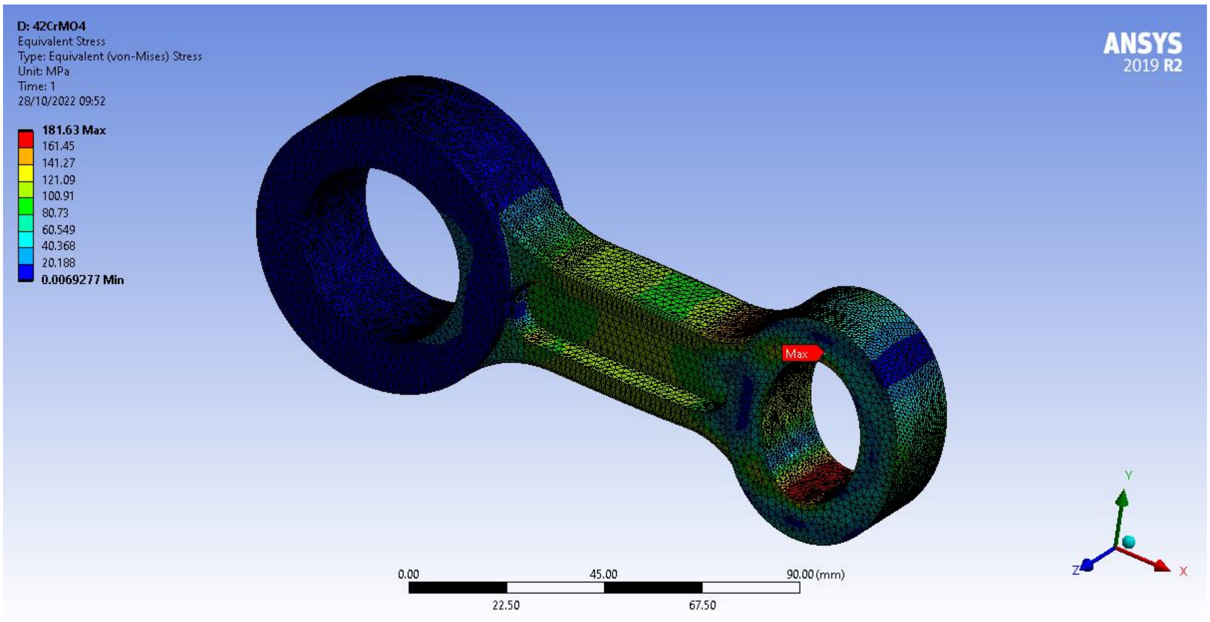

Figure 9: Equivalent stress of the connecting rod with 42CrMO4 as material

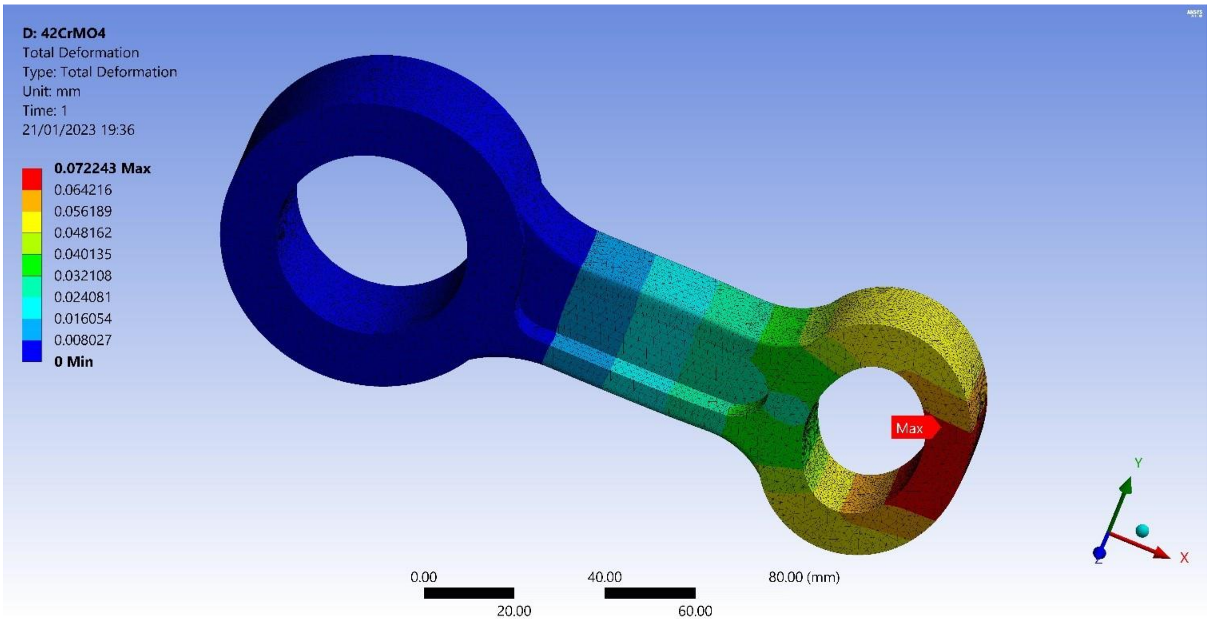

Figure 10: total deformation of the connecting rod with 42CrMO4 as material

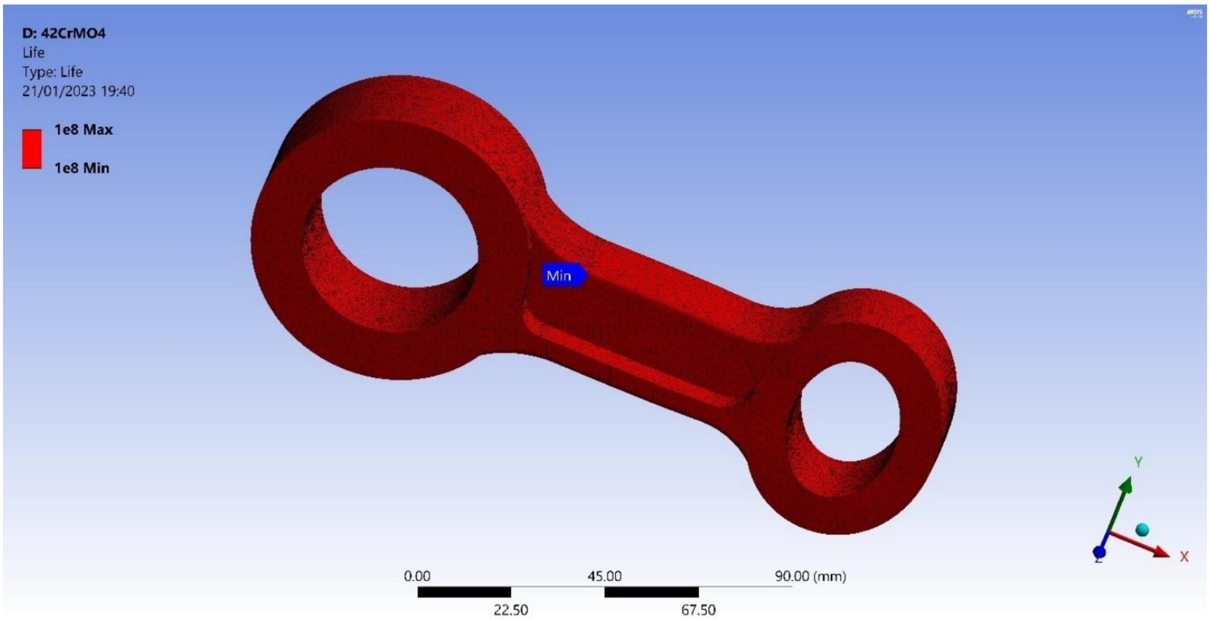

Figure 11: Predicted fatigue life of the connecting rod with 42CrMO4 as material

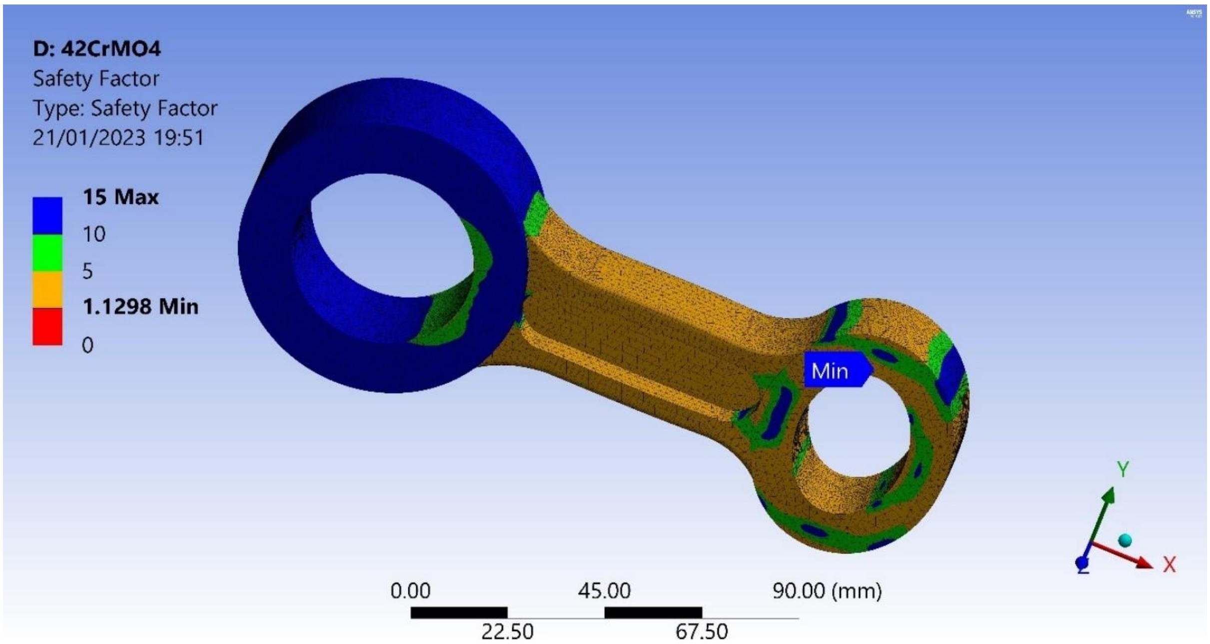

Figure 12: Fatigue factor of safety of the connecting rod with 42CrMO4 as material

The results for the equivalent stress, total deformation, fatigue life and fatigue factor of safety when the material is Ti6Al4V are plotted in figure 9,10,11,12, respectively.

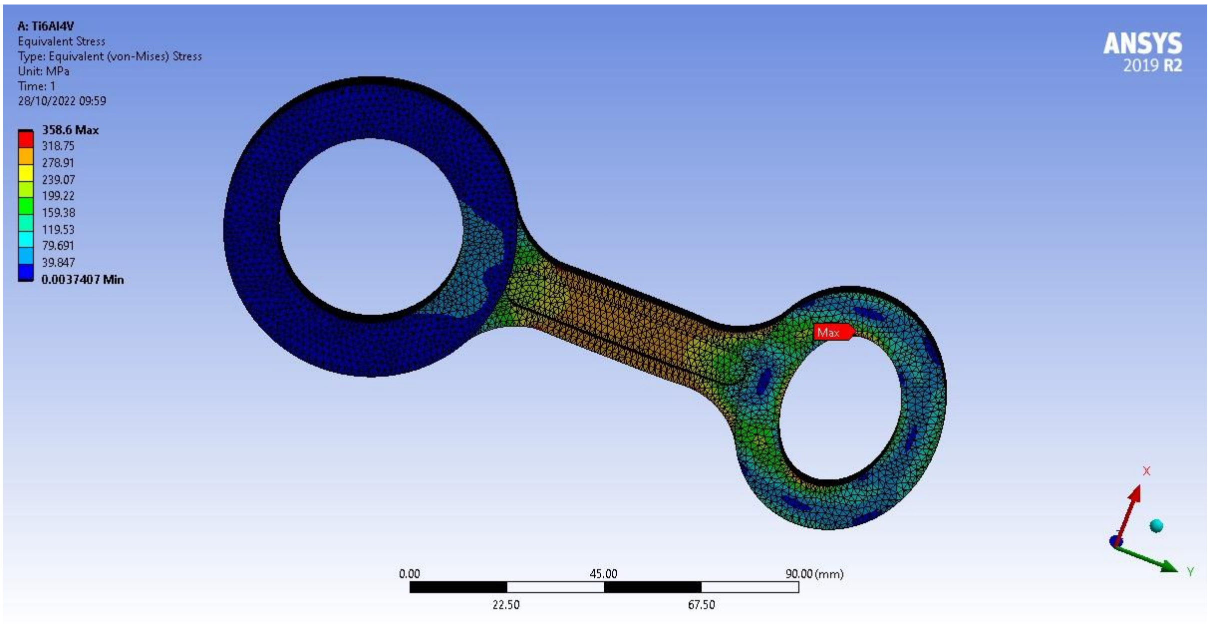

Figure 13: Equivalent stress of the connecting rod with Ti6Al4V as material

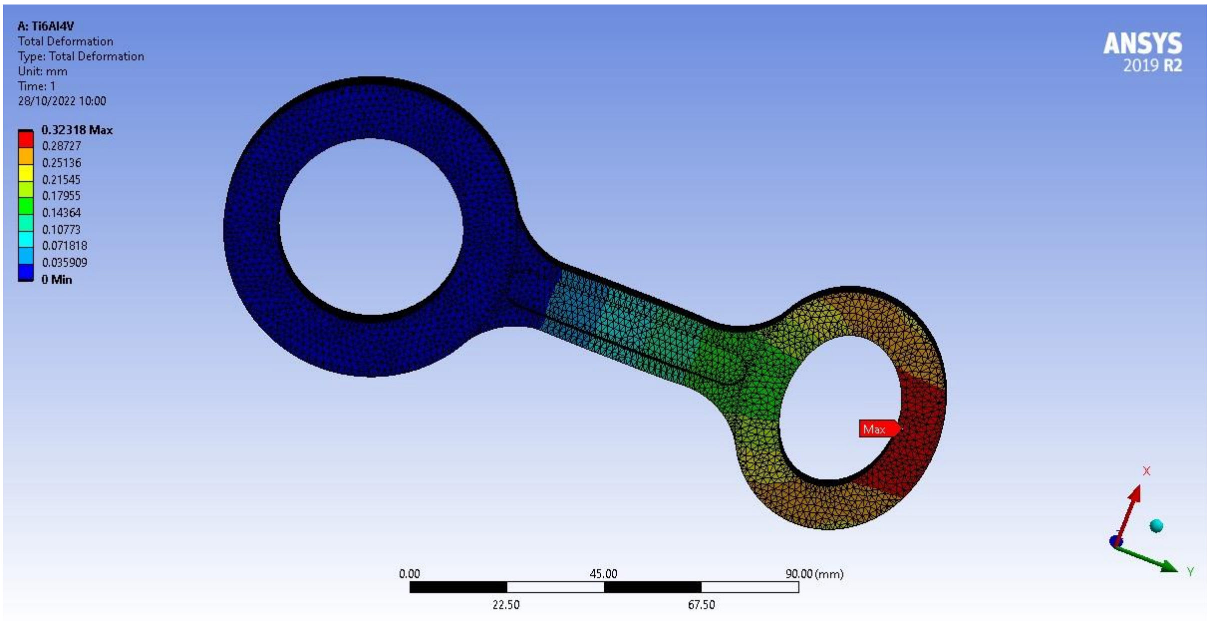

Figure 14: Total deformation of the connecting rod with Ti6Al4V as material

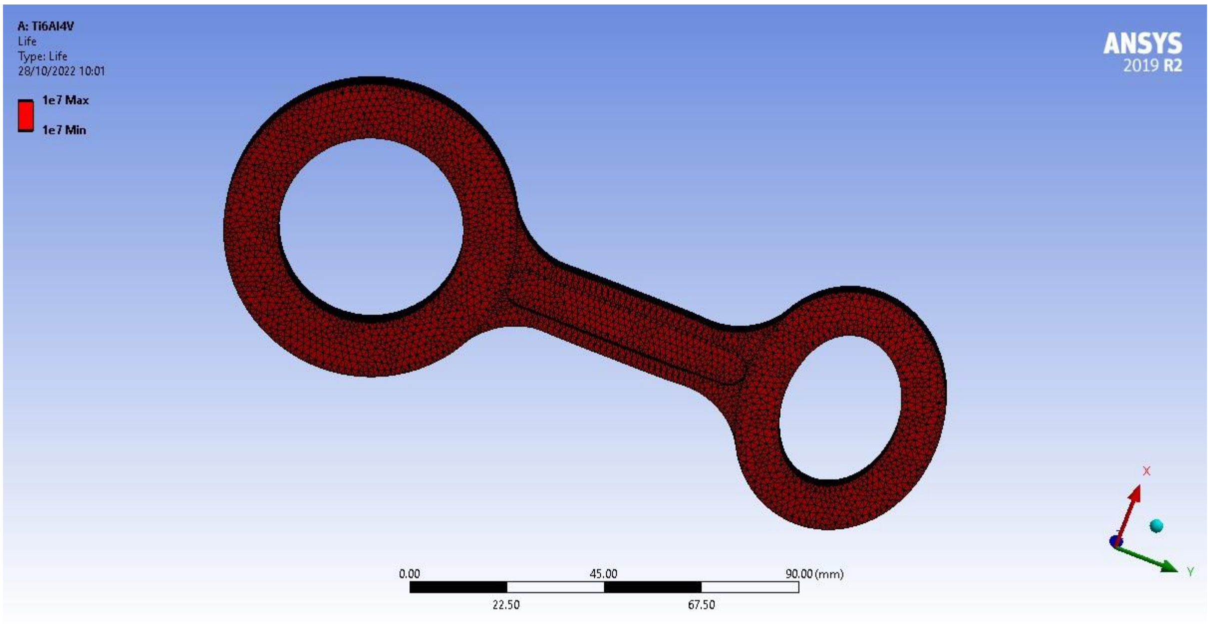

Figure 15: Predicted fatigue life of the connecting rod with Ti6Al4V as material

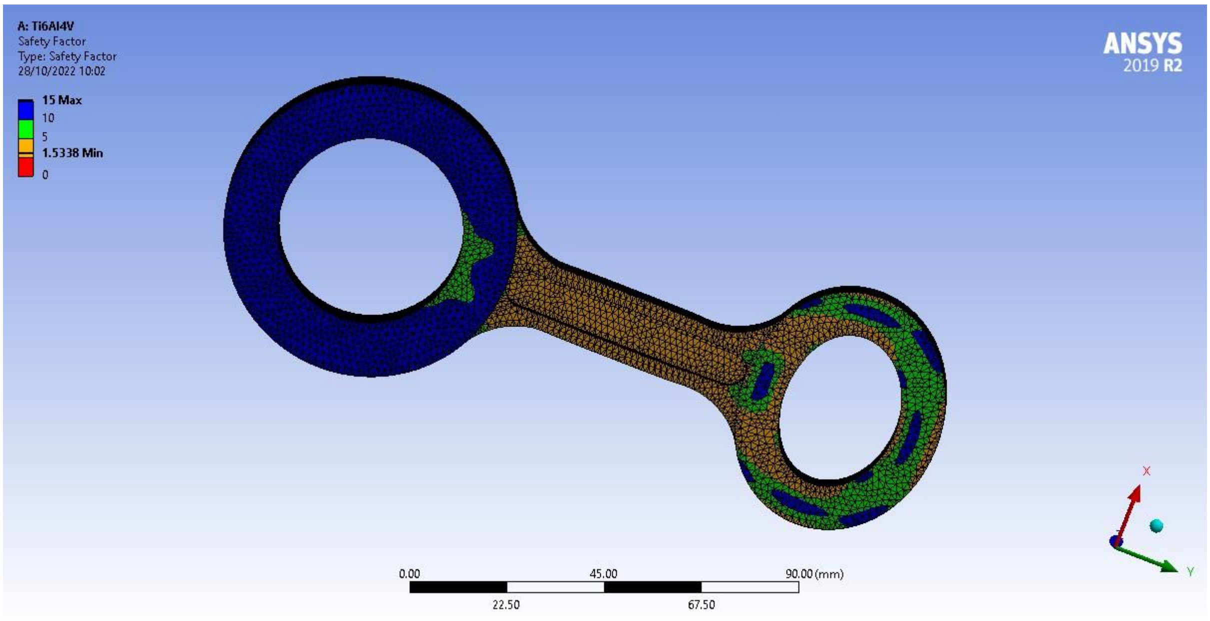

Figure 16: Fatigue factor of safety for connecting rod with Ti6Al4V as material

The analysed values for both materials are listed in Table 5.

Table 5

Comparison of Output parameters for 42CrMO4 and Ti6Al4V as material

S. No.	Parameters	42CrMO4	Ti6Al4V (Without optimization)	Comment
1	Equivalent stress (MPa)	181.63	358.6	Very high strength of Ti6Al4V compared to 42CrMO4 steel compensates for the rise in stress.
2	Total deformation (mm)	0.072	0.323	
3	Fatigue life (cycles)	1e8	1e7	
4	Fatigue factor of safety	1.1298	1.5338	
5	Mass (kg)	0.839	0.262	

3.3 Response Surface Optimization

A trial-and-error method is typically used to redesign an engineering structure that has failed until a benchmark is reached. This procedure is cumbersome, imprecise, and inefficient. With the latest analysis techniques and software, numerical optimization methods overcome these drawbacks. Parametric optimization is the modification of the design using some algorithm to achieve specific objectives by maintaining the design constraints provided [21].

In this study equivalent, von misses stress, total deformation, the mass of the object, and fatigue factor of safety are specified as output parameters. Then, as indicated in table 6 with specified lower and higher boundaries for the piston end system is added to the workspace. As part of optimization, design optimization fits data from the simulated design responses into

response surface equation models by design experiments [30].

Table 6
Parameter Range settings

Values	Crank end outer diameter	Piston end outer diameter
Original	68	52
Lower Bound	60	49
Upper Bound	70	55

Then five inputs for each of the input parameters within the specified range are then used to develop a DOE table. After sampling the design space using Centre Composite Design (CCD), a response surface is generated from the finite element simulation. Figure 17 shows the plot of the fatigue safety factor response versus two varying input diameters.

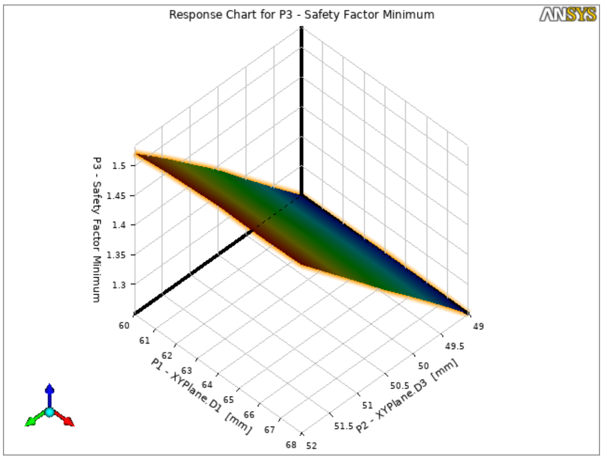

Figure 17: Response chart

In the optimizer window, the objectives and constraints for the study are configured. Using the fitted response models, the dimensions that satisfy each of the design requirements are obtained. Three candidates for the design were determined by evaluating the whole design space region for values that more closely align with the objectives defined earlier.

The three candidate points identified by Ansys as possible dimensions are shown in Table 6. Finally, the obtained values for the candidates are verified using the design by verification to compare the Finally, the obtained values for the candidates are verified using the design by verification to compare the values obtained for output parameters from optimization with actual simulation results and the best one is considered for the connecting rod.

Table 6
Candidate points for optimized design

	Candidate Point 1	Candidate Point 2	Candidate Point 3
Big end outer diameter (mm)	60.002	60.834	61.695
Small end outer diameter (mm)	49.001	49.13	49.086
Safety Factor Minimum	1.2505	1.2631	1.2597
Equivalent Stress maximum (MPa)	439.93	435.18	436.19
Geometry Mass (kg)	0.1962	0.2020	0.2074

3.4 Effect of Neck Radius

From the analysis of the connecting rod's existing model, it is evident that the crank and pin end's neck radius is where the stress is more concentrated. In this analysis, the radius of the fillet which connects the shank and the piston end of the connecting rod was used as a parameter to perform response surface optimization. The effect of fillet radius on output parameters (equivalent stress, total deformation, fatigue safety factor) is shown in table 7.

Table 7
Effect of neck radius on output parameters

Neck radius (mm)	Safety Factor Minimum	Equivalent Stress Maximum	Geometry Mass(Kg)
5	0.8757	628.09	0.2595
10	1.1097	495.64	0.2600
15	1.3009	422.78	0.2606
20	1.4569	377.5	0.2614
25	1.5331	358.75	0.2622
30	1.5464	355.67	0.2630
35	1.5473	355.46	0.2638

The maximum stress developed as well as the fatigue safety factor varies drastically with the fillet radius. At a fillet radius of 5mm, the maximum stress induced is 628 MPa which will result in failure of the body during operation. The stress gradually reduces with increasing fillet radius, dropping to 358.27 MPa at a 25mm radius. Further increment in the fillet radius to 30mm and 35 mm does not affect the stress significantly.

4 Results, Discussion and Conclusions

4.1 Results and Comparisons

The values obtained from analysis for the connecting rod made with 42CrMO4 and Ti6Al4V, before and after response surface optimization are tabulated in table 8.

Table 8
Comparison of results before and after optimization

S. No.	Parameters	42CrMO4	Ti6Al4V	
			Original	Optimized
1	Equivalent stress (MPa)	181.63	358.6	439.28
2	Total deformation (mm)	0.072	0.323	0.379
3	Fatigue life (cycles)	1e8	1e7	1e7
4	Fatigue factor of safety	1.1298	1.5338	1.252
5	Mass (kg)	0.839	0.262	0.196

As listed in table 8, the connecting rod manufactured with Ti6Al4V before optimization has an equivalent stress of 358.6 MPa compared to the 181.63 MPa equivalent stress which acts on the initial design. The stress rose further to 439.28 MPa after the optimization has done. Total deformation of connecting rod also then goes up similarly, going from 0.072 mm to 0.323 mm and 0.379 mm, respectively. The fatigue life for all the cases remained constant that is infinite life before failure. the factor of safety against fatigue failure has been predicted to be 1.1298 for the material 42CrMO4. But for connecting rod made with Ti6Al4V, it climbed to 1.5338 and became 1.252 after optimization. Also, the mass of the connecting rod drastically fell from 0.84kg in the case of 42CrMO4 to 0.262kg for Ti6Al4V which was reduced further to 0.196kg after optimization. Also, the equivalent von mises stress, total deformation, predicted fatigue life, and factor of safety guarding against fatigue is compared in the bar plot illustrated in figure 18.

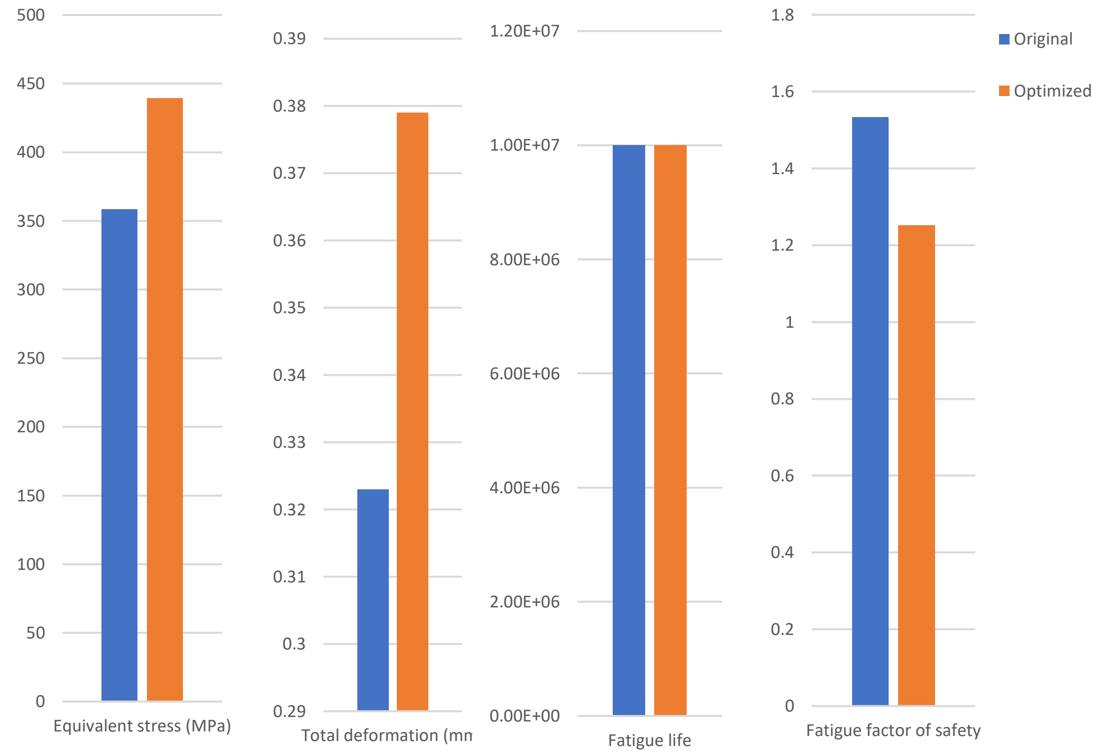

Figure 18: Comparison of numerical values for optimized and unoptimized model with Ti6Al4V material

4.2 Discussion

In this study, initially, the design parameters of the connecting rod for both the materials- 42CrmO4 and Ti6Al4V, were determined analytically from the engine specifications. SolidWorks has been used for developing the model, and ANSYS for the finite element analysis of the model. Utilizing response surface optimization from the ANSYS workbench module, the initial design is optimized for weight reduction and the obtained values are validated by verifying the design point feature from the module. According to the obtained results, the following conclusions are drawn:

i. The equivalent stress and total deformation have increased when the Titanium alloy is employed from the 42CrMO4. This is due to the change in design parameters which are calculated to safeguard against buckling during operation. However, Ti6Al4V provides more fatigue factor of safety even with the increased stress and deformation because of its superior metallurgical properties.

ii. The response surface optimization has been mainly performed on the crank end of the connecting rod where the effect of the stress developed due to the thrust of the piston and the inertia of mass is minimal.

iii. The mass has been reduced by 76.7% by modifying the design for Ti6Al4V, from 0.84 kg for 42CrMO4 to 0.262 kg and 0.196 kg before and after modification.

iv. In this study, we identified that the maximum stress developed varies drastically with the fillet radius. From the previous analysis we found that maximum stress developed reduces with increasing fillet radius up to 25mm. After that change in neck radius does not affect maximum stress developed significantly. Thus, it can be inferred that the stress induced by connecting rod can be minimized by increasing the neck radius to an optimal value.

4.3 Conclusions

The usage of Ti6Al4V instead of $42CrMO_4$ and optimizing the basic model with response surface method reduced the weight by 76.7% while maintaining equilvalent or more factor of safety against buckling and fatigue. Using Titanium results in 2.6 kg mass reduction in a 4-cylinder engine improv fuel efficiency as well as fewer raw materials. Thus, despite of its cost, for the fabrication of the connecting rod, this optimized design with Titanium can be employed. Also, the design can be made compact for any connecting rod by utilizing the pattern identified in paper and determining the optimal value for neck radius to induce minimum stress.

References

[1] Y. Basavaraj *et al.*, “FEA of NX-11 unigraphics modeled connecting rod using different materials,” in *Materials Today: Proceedings*, 2021, vol. 46, pp. 2807–2813. doi: 10.1016/j.matpr.2021.02.620.

[2] “Design Considerations for Connecting Rod,” *Int J Eng Adv Technol*, vol. 9, no. 3, pp. 2368–2373, Feb. 2020, doi: 10.35940/ijeat.c5759.029320.

[3] I. Journal, A. A. Haider, A. Kumar, A. Chowdhury, M. Khan, and P. Suresh, “Design and Structural Analysis of Connecting Rod,” *International Research Journal of Engineering and Technology*, 2018, [Online]. Available: www.irjet.net

[4] F. Desai, K. Jagtap, and A. Deshpande, “Numerical and Experimental Analysis of Connecting Rod,” *International Journal of Emerging Engineering Research and Technology*, vol. 2, no. 4, pp. 242–249, 2014, [Online]. Available: www.ijeert.org

[5] M. S. Satbhai and P. S. Talmale, “REVIEW ON DESIGN AND ANALYSIS OF TWO WHEELER CONNECTING ROD,” *International Research Journal of Engineering and Technology*, 2017, [Online]. Available: www.irjet.net

[6] K. Priya Ajit, “Static Stress Analysis of Connecting Rod Using Finite Element Approach.” [Online]. Available: www.iosrjournals.orgwww.iosrjournals.org

[7] L. K. Vegi and V. Gopal Vegi, “Design And Analysis of Connecting Rod Using Forged steel,” *Int J Sci Eng Res*, vol. 4, no. 6, 2013, [Online]. Available: http://www.ijser.org

[8] N. P. Patil, P. N. Patil, and R. Y. Patil, “DESIGN ANALYSIS OF CONNECTING ROD FOR WEIGHT REDUCTION IN CASE OF A CI ENGINE-A REVIEW,” *Int J Eng Sci Res Technol*, doi: 10.5281/zenodo.891686.

[9] S. Seralathan *et al.*, “Stress analysis of the connecting rod of compression ignition engine,” in *Materials Today: Proceedings*, 2020, vol. 33, pp. 3722–3728. doi: 10.1016/j.matpr.2020.06.137.

[10] R. Kumar Verma and A. Kumar Jain, “Modelling and analysis of two-wheeler connecting rod with different materials using FEA,” *Mater Today Proc*, vol. 62, no. P10, pp. 5867–5876, Jan. 2022, doi: 10.1016/j.matpr.2022.04.621.

[11] T. Sathish, S. Dinesh Kumar, and S. Karthick, “Modelling and analysis of different connecting rod material through finite element route,” in *Materials Today: Proceedings*, 2020, vol. 21, pp. 971–975. doi: 10.1016/j.matpr.2019.09.139.

[12] S. v Uma, M. Rao, T. V. H. Rao, K. Satyanarayana, and B. Nagaraju, “Fatigue Analysis Of Sundry I.C Engine Connecting Rods,” 2018. [Online]. Available: www.sciencedirect.comwww.materialstoday.com/proceedings

[13] T. Buddi and R. S. Rana, “Fabrication and finite element analysis of two wheeler connecting rod using reinforced aluminum matrix composites Al7068 and Si3N4,” in *Materials Today: Proceedings*, 2021, vol. 44, pp. 2471–2477. doi: 10.1016/j.matpr.2020.12.541.

[14] A. Kumar and D. Kumar, “Dynamic Analysis of Bajaj Pulsar 150cc Connecting Rod Using ANSYS 14.0.” [Online]. Available: www.trp.org.in

[15] S. Wable and D. S. Galhe, “ANALYSIS OF STRESSES INDUCED IN CONNECTING ROD OF TWO WHEELER ENGINE,” 2016. [Online]. Available: www.ijariie.com

[16] A. Gupta and M. Nawajish, “DESIGN AND ANALYSIS OF TWO WHEELER CONNECTING ROD USING DIFFERENT MATERIALS,” 2014. [Online]. Available: http://www.ijarse.com

[17] R. Y. Patil, M. Student, and A. Professor, “Issue 1 | IJEDR1801016,” *International Journal of Engineering Development and Research*, vol. 6, 2018, [Online]. Available: www.ijedr.org

[18] N. A. Wankhade, S. Ingale, and / Cam, “Review on Design and Analysis of Connecting Rod Using Different Material,” 2017. [Online]. Available: http://ijesc.org/

[19] M. K. Lade1, R. P. Harode2, and D. B. Lade3, “Static Load Analysis of Carbon Fiber Connecting Rod,” *International Journal of Research in Advent Technology*, vol. 3, no. 9, 2015, [Online]. Available: www.ijrat.org

[20] M. K. Lade, D. Bankar Lade, D. B. Meshram, and R. P. Harode, “Dynamic Load Analysis of Carbon Fiber Connecting Rod,” *International Journal of Research in Advent Technology*, vol. 3, no. 9, 2015, [Online]. Available: www.ijrat.org

[21] P. S. Shenoy and A. Fatemi, “Connecting Rod Optimization for Weight and Cost Reduction Reprinted From: Innovations in Steel Sheet and Bar Products and Processing (SP-1951) 2005 SAE World Congress Detroit, Michigan,” 2018.

[22] V. Teraiya, D. Jariwala, H. v Patel, and D. Babariya, “Material Selection of Connecting Rod using Primary Multi Attribute Decision Making Methods: A Comparative Study,” 2018. [Online]. Available: www.sciencedirect.comwww.materialstoday.com/proceedings2214-7853

[23] D. Gopinath and C. v. Sushma, “Design and Optimization of Four Wheeler Connecting Rod Using Finite Element Analysis,” in *Materials Today: Proceedings*, 2015, vol. 2, no. 4–5, pp. 2291–2299. doi: 10.1016/j.matpr.2015.07.267.

[25] M. K. Lee, H. Lee, T. S. Lee, and H. Jang, “Buckling sensitivity of a connecting rod to the shank sectional area reduction,” *Mater Des*, vol. 31, no. 6, pp. 2796–2803, Jun. 2010, doi: 10.1016/j.matdes.2010.01.010.

[26] G. Shanmugasundar, M. Dharanidharan, D. Vishwa, and A. P. Sanjeev Kumar, “Design, analysis and topology optimization of connecting rod,” in *Materials Today: Proceedings*, 2020, vol. 46, pp. 3430–3438. doi: 10.1016/j.matpr.2020.11.778.

[27] O. K. Ajayi, B. O. Malomo, S. D. Paul, A. A. Adeleye, and S. A. Babalola, “Failure modeling for titanium alloy used in special purpose connecting rods,” in *Materials Today: Proceedings*, 2021, vol. 45, pp. 4390–4397. doi: 10.1016/j.matpr.2020.11.852.

[28] P. Mishra and S. Sinha, “STRESS ANALYSIS AND TOPOLOGY OPTIMIZATION OF CONNECTING ROD OF TWO WHEELERS USING FEA,” *International Journal of Mechanical Engineering and Technology (IJMET)*, vol. 9, no. 9, pp. 559–568, Sep. 2018.

[29] R. Boyer, G. Welsch, and E. W. Collings, Eds., *Materials Properties Handbook: Titanium Alloys*, 1st ed. ASM International, 1994.

[30] Y. Liu and X. Chen, *Finite Element Modeling and Simulation with ANSYS Workbench*. London, New York: CRC Press, 2014.