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Design Optimization of Connecting Rod for a Single Cylinder Four Stroke Overhead Valve (OHV) Engine Using Topology Optimization

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Key words: Over Head Valve (OHV), connecting rod, reverse engineering, finite element analysis, topology optimization

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Abstract: The goal of the research work is to develop design optimization of a single-cylinder four-stroke Over Head Valve (OHV) spark ignition engine connecting rod. This study used reverse engineering techniques, to obtain an existing physical model. A three-dimensional connecting rod was created through SOLIDWORKS and it is imported to ANSYS environment for the coupled steady-state thermal structural analysis. The material used for the connecting rod is ADC12, A360 and ADC380. The objective of this paper focuses on the lightweight connecting rod design through coupled steady-state thermal structural analysis and to optimize the connecting rod design within the design domain using topology optimization. The results obtained from Finite Element (FE) analysis and Topology Optimization (TO) concluded the modified design is safe within the permissible stress, A360 indicates the von-Mises stresses 29.977 MPa, the higher factor of safety (n) is 5.61 and it is reduced the weight of the connecting rod was 129.05 g which are 8.88% less as compared to existing ADC12 without compromising the strength to weight ratio.

INTRODUCTION

The Internal Combustion (IC) engine with the connecting rod acts as a center link among the reciprocating piston and the rotating crankshaft. The most important critical components in an Internal Combustion Engine (ICE) is known as connecting rod and it is carried high cyclic loads which comprised of tensile like inertia and compressive loads due to combustion.

Gopinath *et al*.[1] discuss to discover reduces less weight opportunities for the manufacturing of aluminium, titanium and forged steel connecting rod. To get the aim of optimization, to decrease less mass of the connecting rod is 483 g and the optimized connecting rod model is 10.38% lower as compared to the present connecting rod of equal strength by using a topology optimization approach.

Aishwarya *et al*.[2] focuses on the design optimization for a 4-stroke petrol engine's connecting rod using FEM. It also concentrates the theoretical calculation based on the general standard formula as well as finite element analysis results such as Von-mises stress, strain, the factor of safety and fatigue life. Finally, they are comparing results theoretically and analytically it is very clear that the modified model shows the value of von-Mises stress and strain as less as compared to the existing model.

Vegi *et al*.[3] describe the design and analysis of forged steel connecting rod. Initially, the forged steel and carbon steel connecting rod were modeled using CATIA software then finite element analysis was carried out with the help of ANSYS Software. Based on the analysis results, comparing the study about forged steel and carbon steel connecting rod, significantly the weight is to be reduced, increased stiffness of forged steel connecting rod and also analyzed the fatigue life of the forged steel connecting rod.

Prakash *et al*.[4] discuss geometric dimensions of the present design of a tractor engine connecting rod. This analysis was performed based on the static loading, fatigue loading and optimization as per the given loading and boundary conditions. The serious areas have to be identified and improved by conducting both static and fatigue analysis.

Kuldeep *et al*.[5] this research paper describes the conventional material of the connecting rod is modeled using aluminium with silicon carbide and fly ash. After the finite element analysis results, the silicon carbide and fly ash of aluminium metal matrix composites decreasing the weight % of 43.48 with a 75% drop in displacement.

Canute *et al*.[6] discussed the hybrid metal matrix composites with aluminium A356 alloy and boron carbide powder (4%), fly ash (4%) as reinforcements by the stir casting method. High-temperature Tribological behavior of aluminium boron carbide fly ash composites using the pin on disc method with pin heating setup studied. Fly ash particles added as a secondary reinforcement material due to its notable mechanical, metallurgical and Tribological properties. Mechanical tests like a tensile test, microhardness test and microstructure studies were conducted. The significance of load, sliding velocity and temperature on the wear rate of the hybrid composites was evaluated. The test results showed considerable development in the mechanical properties and uniform particle distribution in the matrix.

Nakata *et al*.[7], discussed the microstructure modification of aluminium die casting alloy by using a friction heat and mechanical friction stirring action. The die-casting material ADC12 were used in this study has 4 mm plate thickness. Mechanical friction stirring action is done continuously in 14 times by four mm increments towards the targeted side. The test was done for the base and the specimen of the friction stirred one was found to be >1.7 times of the substrate. The results show the considerably increasing the hardness, metal and also the percentage of elongation is almost the same.

Most of the research papers discussed the lightweight connecting rod design optimization by using finite element analysis through the topology optimization approach. Internal Combustion Engine (ICE) performance and emission characteristics will play a major role based on the weight of the engine through an individual component such as engine piston, cylinder head, connecting rod, crankcase cover, crankcase and the crankshaft.

In recent years CAE packages could acquire the stress contours of an ideal component or product. By the advancement of computational power, to obtain optimized design with the help of topology optimization.

The objective of this paper focuses on the lightweight connecting rod design through reverse engineering techniques, finite element analysis and topology optimization to attain the lightweight connecting rod without compromising higher strength to weight ratio, ductility and reduces the overall production cost. This paper deals with the topology optimization of a single-cylinder 4-stroke spark ignition engine connecting rod. To obtain the result of incorporating additive manufacturing of any shape regardless of its complexity by reducing 8.88% mass from the initial design domain. An initial design considers thermal loads later it is verified for the performance under structural loading.

MATERIALS AND METHODS

Engine specification: This study attention is considered as topology optimized connecting rod with lightweight aluminium die casting materials; the geometry and the requirements of the connecting rod solely depend upon the engine. The specification of the OHV engine is used for Table 1.

Connecting rod: Material Compact weight and high structural rigidity are the key factors essential for all components of an IC engine. For this purpose, the industries widely used aluminium alloys. Davis[8], the density of Aluminium (ρ) of only 2.7 g cm^{-3}, about one-third of steel (7.83 g cm^{-3}). Aluminium Die Casting (ADC) alloys are lightweight, good castability, good mechanical properties, offer good corrosion resistance and dimensional stability. The application of aluminium matrix material is used for the application of the automotive industry, aircraft industry, in the construction of machines, like pressure vessels for cryogenic applications, etc.

Vaibhav *et al*.[9] have studied the comparative analysis between carbon steel connecting rod and aluminium metal matrix composite with silicon carbide and fly ash. This study is considered the specification of a 220cc air-cooled 4-stroke engine connecting rod; initially, the theoretical calculation was done using the

Table 1: Specification of the OHV engine

Types of engine	4 stroke, single cylinder, air-cooled engine
Bore x stroke	68×45 mm
Displacement	163 cm^3
Rated output	2.83 kW @ 3.600 rpm
Maximum Torque	10.3 Nm @ 2.500 rpm
Compression ratio	9.0: 1
Weight	15.1 kg

standard formula then analytically verified the value of von-Mises stress, strain, a factor of safety. The connecting rod was modeled by using Pro-Engineer and CAD model is exported into ANSYS Software. According to the comparative analysis, results show that the aluminium metal matrix composites with silicon carbide and fly ash gives better weight reduction and more stiffness.

Ghadimi *et al*.[10] studied the various percentage mass fraction of Al-5Ti-1B master alloy were produced by liquid-phase thermal annealing and plastic deformation for improving grain refinement of an aluminium cast metal. At first, Al-5Ti-1B master alloy was ball milled for various diameters with different hours to make a fine powder and, the ratio of ball to powder is obtained 15:1 and 400 revolutions per minute rotational speed was used. To improve its grain refining effect, followed by cold rolling, annealing and ball milling.

Schmidt *et al*.[11] discussed the temperature distribution among the sample and die, during the synthesis of TiB_2 using Spark Plasma Sintering. The behavior between titanium and boron is exothermic for the binary phases-titanium monoboride (TiB) and TiB_2. Due to this, the reactions can be easily detected by changing temperature distribution inside a sample.

Dhaneswara *et al*.[12] proposed on how the mechanical properties are enhanced like tensile strength, hardness and wear and microstructural modification of titanium and boron with ADC12 in various compositions of nano silicon carbide particles. The study of this work, aluminium metal matrix composites of ADC12 with 0.15% volume fraction of nano silicon carbide particles and grain refiners of titanium and boron as 0.0, 0.02, 0.04, 0.06 and 0.08 weight% were shaped by mechanical stirring. The improvement of tensile strength, hardness and wear mainly depend upon the Al_3Ti behaves as nucleants and the existence of the $MgAl_2O_4$ phase shows interphase among nano silicon carbide and aluminium die casting 12 composites. The microstructure examination displays the form intermetallic phase β-Fe, π-Fe and Mg_2Si due to more composition of magnesium and iron.

Aluminium gives the information about the adding of an aluminium titanium boron microstructure modifier enhances homogeneity and agrees for alloying elements gaining even distribution, decreases porosity, hot tearing in cast parts is removed, subsequent heat treatment process to improves and increases mechanical properties and machinability in the fabrication process.

Table 2: Chemical composition of selected materials percentage by weight

Elements	ADC12	A360	A380
Si	11.04	9.0	8.5
Fe	0.73	0.90	1.05
Cu	2.10	2.12	3.5
Mn	0.18	0.20	0.27
Mg	0.34	0.38	0.05
Zn	0.74	0.74	1.8
Ni	0.04	0.04	0.08
Ti	0.03	0.03	0.05
B	-	1.0	-
Pb	0.03	-	-
V	0.02	-	-
P	0.002	-	-
Sn	-	0.15	-
Al	Bal.	Bal.	Bal.

Table 3: Properties of materials

Designation	ADC12	A360	ADC380
Density (g cm^{-3})	2.82	2.68	2.76
Thermal conductivity (W mK^{-1})	92	113	109
Tensile strength (MPa)	320	324	340
Elongation (%)	2.5	3.6	4
Specific heat (J/g°C)	0.963	0.963	0.963
Hardness (HB)	79	83	85
Fatigue strength (5×10^8 cycle, MPa)	145	140	138
Elastic Modulus (GPa)	68.9	71	71
Yield strength (-0.2%, MPa)	167	169	176

The chemical composition test was conducted using a vacuum optical emission spectrometer to obtain the existing material (ADC12) and also the mechanical test was conducted. Obiekea *et al*.[13] stated that the microstructural examination and enhances the mechanical properties of die-cast aluminum A380 alloy casts produced under increasing pressure was studied practically. An ultimate tensile strength, tensile yield strength, elongation and the hardness values A380 cast samples that varied 76-85 HRN under increasing practically applied pressure. Based on the chemical composition test, a mechanical test of an existing connecting rod and A380 reference material, A360 is fabricated which is Al-Si based alloy as per the ASTM B179-09. The chemical composition of the used material for comparative analysis is tabulated in Table 2 and the properties of materials are summarized in Table 3. The geometrical values of existing co. rod as shown in Table 4.

Precious (2018), the two important sections used in connecting rods are I-Beam and H-Beam. The maximum standard connecting rods design of the I-Beam cross is used due to it provides a good combination of lightweight and high strength. An I-Beam connecting rod can face more compressive loads while also providing better tensile strength. In Fig. 1 shows the I-Beam cross-section of the connecting rod.

Table 4: Geometrical values of connecting rod

Name of the part	Dimensions (mm)
Length of connecting rod	83.70
Outer diameter of big end	37.00
Inner diameter of big end	27.90
Outer diameter of a small end	21.94

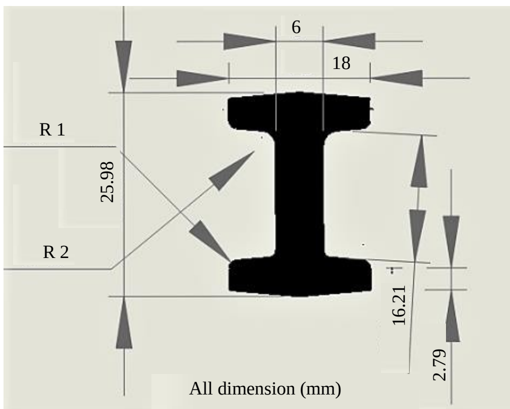

Fig. 1: I- Beam of a connecting rod

Reverse engineering: Kumar *et al*.[14] presents the process of reverse engineering is to obtain a geometric Computer-Aided Design (CAD) model by using a non-contact scanning technique of an existing physical model. Many research articles on CAD/CAM are about generating computer models and moving into physical products. Sometimes, however, industry concerns have a physical model of CAD models. The reasons are CAD models may not exist. Some industrialists requirement, models of production parts or subsystems to incorporate into a new product model. Present automobile engines and transmissions, for example are regularly reused in new models with only slight modifications. Bopaya *et al*.[15] discussed the 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, aircraft, marine, in medical life science and software industries, etc.

Initial modelling: This study utilized the highly accurate measurements of the steinbichler Comet L3D scanner with has a resolution of 2 Mpx and 1600×1200 pixels, measuring field of 400 mm, measuring the volume of 400×300×250 mm^3 and point to point distance of 259 µm to obtain of an existing physical model connecting rod. The scanned model and CAD model as shown in Fig. 2.

Finite element analysis: A 3-dimensional connecting rod 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.

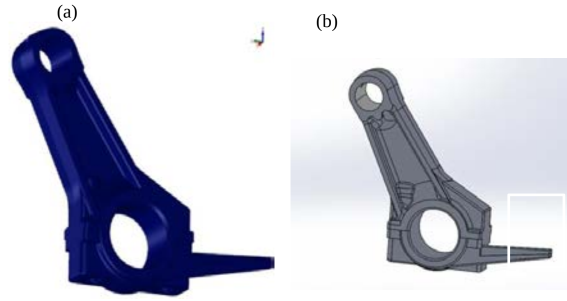

Fig. 2(a, b): Connecting rod (a) Scanned model and (b) CAD

Maximum pressure of 23 bar generated inside the cylinder due to the burning of the air-fuel mixture. This pressure will be transmitted into crankshaft via piston and connecting rod. Figure 3a shows the connecting rod model imported to ANSYS and Fig. 3b, fine-meshed connecting rod it consists of 72983 nodes and 47115 triangular elements.

Figure 4a shows the thermal loads at 160°C and the boundary conditions are applied through convective mode temperature 70°C and Fig. 4b, temperature distribution from the small end to the big end to attain a maximum temperature of 160°C. And the heat transferred per unit area in the connecting rod to reach the maximum is 0.8084 w mm^{-2} at a small end and the minimum is a big end of the connecting rod.

Figure 5a demonstrates, to ensure efficient design the applied compressive load as in the case of a uniformly distributed load is 1382.04 N and remote displacement along z-direction is -45 mm and rest of the directions are constrained zero degrees of freedom and Fig. 5b shows the maximum stress obtained as per the given loading of 36.73 MPa. Figure 6a displays the maximum deformation 45.021 mm at the big end cap and minimum deformation of 44.85 mm at the small end and Fig. 6b shows the minimum factor of safety for the connecting rod as 4.63.

Topology optimization: Bendsoe *et al*.[16] stated that topology optimization is to find an optimal structure using numerical methods to optimize the material layout within the design space. Kumar *et al*.[17] discussed formulate the general procedure for the design of compliant mechanisms from a given basic geometry.

Also to design a compliant amplifier from rectangular, taper and hexagonal basic design domains using topology optimization approach for the displacement amplification of the strain actuator and compliant mechanism design is to produce the marked output displacement. An optimization technique goal is to minimize connecting rod weight subjected to the effect of maximum loads such that the

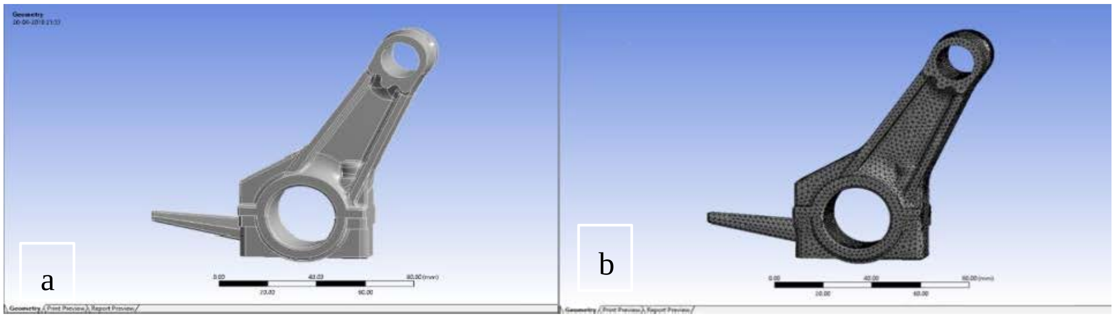

Fig. 3(a-b): Connecting rod model (a) imported to ANSYS and (b) meshed model

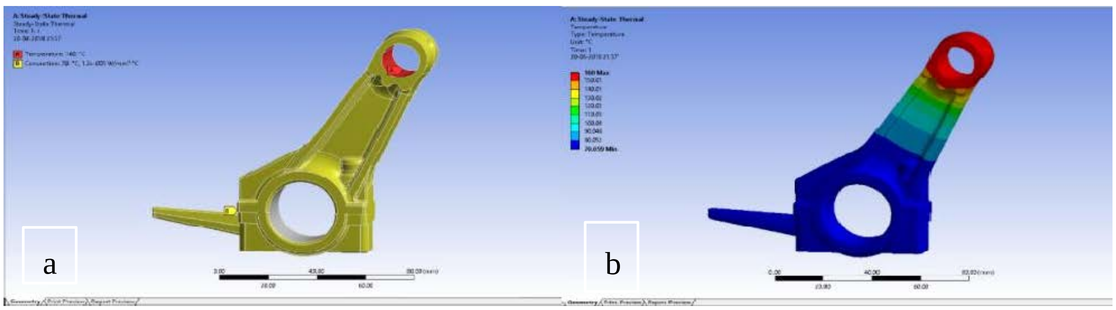

Fig. 4(a-b): Connecting rod (a) thermal boundary conditions and (b) temperature distribution

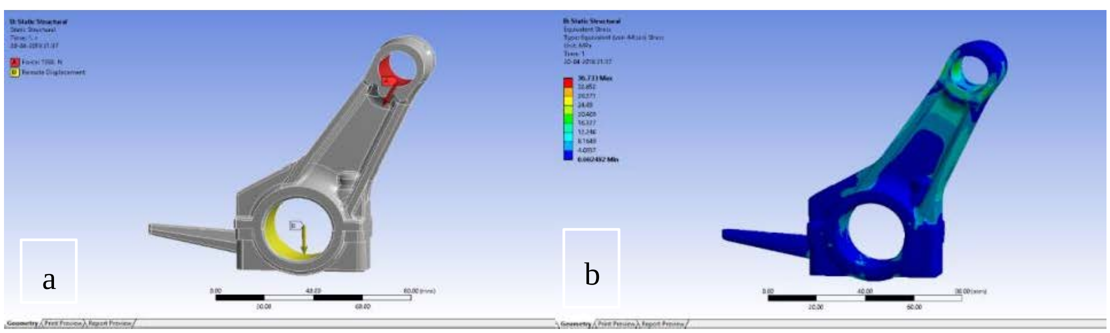

Fig. 5(a-b): Connecting rod (a) Structural boundary conditions and (b) von-Mises stress

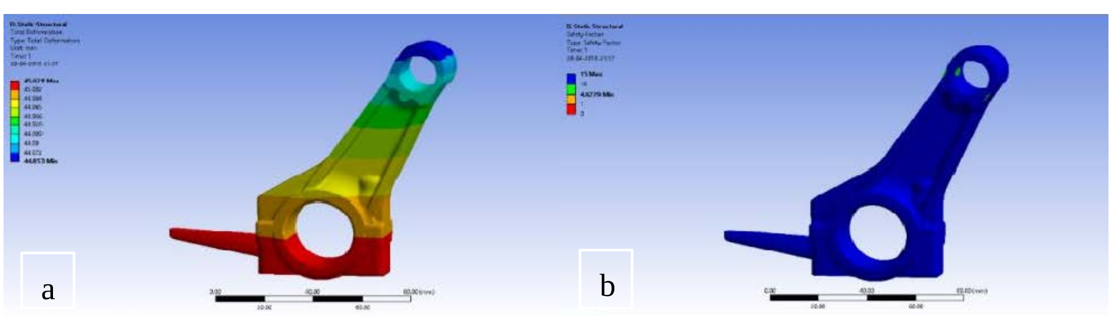

Fig. 6(a-b): Connecting rod (a) total deformation and (b) factor of safety

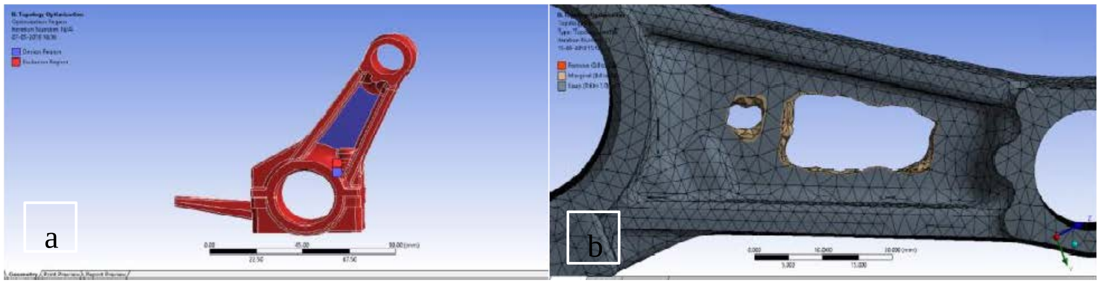

Fig. 7(a-b): (a) Load constraints given on connecting rod and (b) results for materials to keep

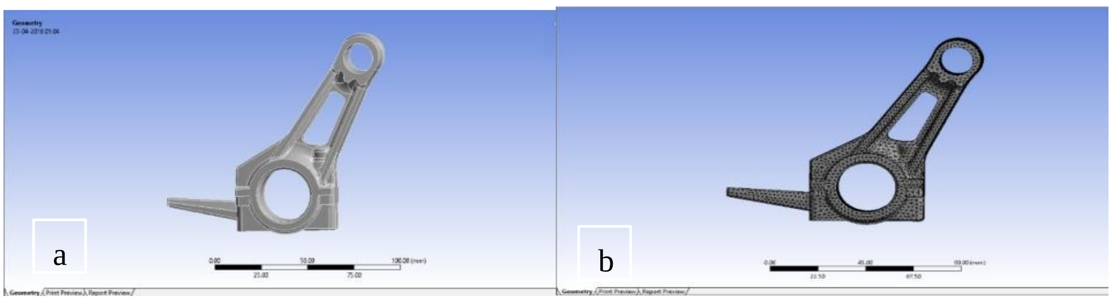

Fig. 8(a-b): (a) Optimized connecting rod model and (b) meshed model

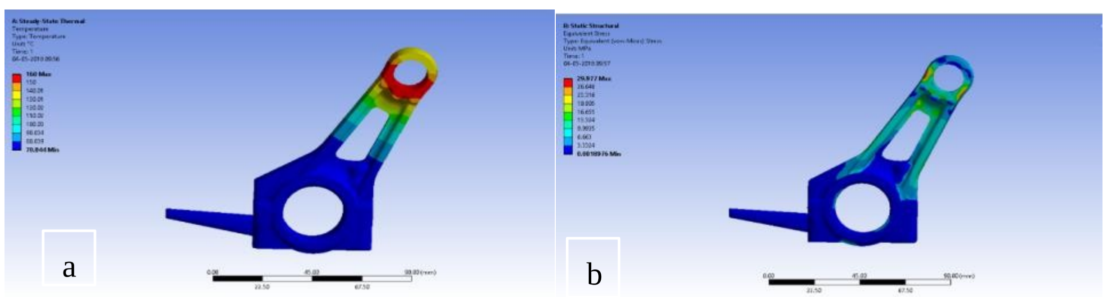

Fig. 9(a-b): Optimized connecting rod (a) temperature distribution and (b) von-Mises stress

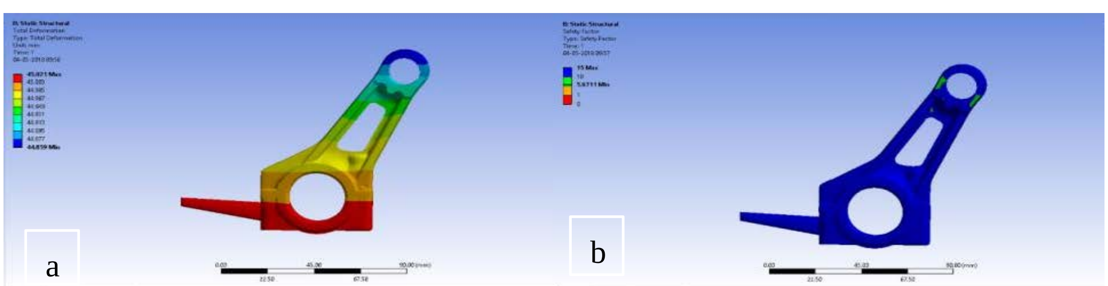

Fig. 10(a-b): Optimized connecting rod (a) total deformation and (b) factor of safety

permissible stress is within the design stress. The obtained buckling load due to the maximum gas pressure has to be a permissible limit.

Figure 7a displays the load constraints given on connecting rod and Fig. 7b shows the results for the materials to keep. Figure 8a shows the fully optimized model and Fig. 8b displays a meshed connecting rod model and it consists of 70956 nodes and 45692 triangular elements. Figure 9a maximum temperature distribution and Fig. 9b maximum stress 29.977 MPa occurs near the small end. Figure 10a shows total deformation and Fig. 10b factor of safety.

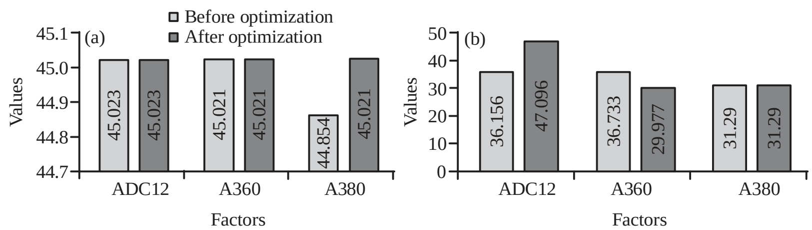

Fig. 11(a-b): Results for (a) total deformation (b) von-Mises stress, before and after optimization

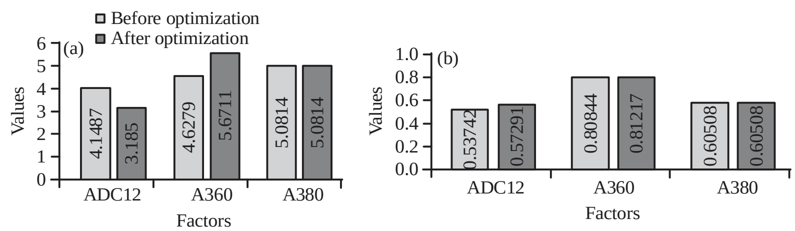

Fig. 12(a-b): Results for (a) factor of safety and (b) total heat flux, before and after optimization

RESULTS AND DISCUSSION

The von-Mises stresses, deformation and safety factors were obtained through ANSYS Software. The maximum von-Mises stresses have to be identified area in the transition part of connecting rod, between crank end and shank end. After optimized geometry, the high localized stresses are found at the connecting rod's small eye end. Mass of initial model is 141.63, 134.6 and 138.62 g and after the optimized model is reduced to 135.79, 129.05 and 132.9 g.

From the results obtained the graphs were plotted before and after optimization, Fig. 11a displays the total deformation of ADC12, A360 is almost equal and A380 is increased and Fig. 11b describes the von-Misses stresses of ADC12 is increased, A360 is decreased and A380 is equal to same. Figure 12a shows the factor of safety is ADC12 is decreased, A360 is increased and A380 is the same and Fig. 12b indicates the total heat flux of ADC12 is slightly increased, A360 is almost same and A380 is equal to 0.605 w mm^{-1}

CONCLUSION

Based on the coupled steady-state thermal structural analysis it is noted that the von-Misses 248 stresses, deformation, total heat flux and factor of safety for the given loading conditions of ADC12, A360 and A380 were studied and then the low-stress region in design domain it was decided to remove excess material. There are two problems to be discussed and solutions need to be advised.

At first, high localized stress at the small end of connecting rod, by increasing area by providing fillets this problem can be solved.

The second problem is during built-up; conventional manufacturing methods like casting, molding and Forming are not feasible with the design. Meanwhile, additive manufacturing will give a better result.

To reduce the weight of the connecting rod, topology optimization was conducted with the help of finite element analysis. The connecting rod shank region offers the utmost potential for weight reduction.

Before and after optimization, A360 shows better results than ADC12 and A380 is almost the same depending upon the graph values of von-Mises stresses, deformation, total heat flux and factor of safety.

Based on the analysis result, it is possible to decrease the connecting rod weight in two ways such as one is a selection of connecting rod materials A360 is obtained 7.03 g which are 4.96% less as compared to ADC12 and A380.

The topology optimized connecting rod reduced a net mass of 12.58 g and the topology layout is 8.88% less than the existing connecting rod material of ADC12 and A380 without compromising the strength to weight ratio.

The goal of the study is to obtain a 20% in a weight reduction of the initial design domain but the result was a promising 8.88% in weight reduction.

NOMENCLATURE

%	=	Percentage
µm	=	Micrometre
°C	=	Degree Celsius
g cm^{-3}	=	Gram per cubic centimetre
GPa	=	Gigapascal
HB	=	Hardness
J/g°C	=	Jules per gram-degree Celsius

mm	=	Millimetre
MPa	=	Mega Pascal
Mpx	=	Megapixels
mm^3	=	Cubic millimetre
N	=	Newton
n	=	Factor of safety
W mK^{-1}	=	Watts per meter-kelvin
W mm^{-2}	=	Watt per square millimetre

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