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DESIGN ANALYSIS AND OPTIMIZATION OF PISTON 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, analysis and optimization of piston 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 piston 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 piston is Die Cast Aluminium (DCA) 1, 2, and 3. The objective of this paper focuses the light weight piston design through finite element analysis, and to optimize the piston design using parametric optimization. The results obtained from coupled field analysis and parametric optimization, concluded the modified design is within the permissible limit along the selected materials for DCA2 and shows the maximum von misses stresses 78.75MPa, factor of safety (n) is 5.67 and yield strength of 165MPa and it is reduced the piston weight was 12.14 grams which is 7.42% less as compared to existing DCA1 without comprising the strength to weight ratio.

Key words: OHV, piston, reverse engineering, finite element analysis, DCA, parametric optimization.

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1. INTRODUCTION

The drive of the Internal Combustion Engine (ICE) piston is to transfer from gas force in the cylinder to the crankshaft via connecting rod. A piston is a critical part of an ICE. Due to the piston endures the cyclic gas pressure, inertia force may cause the fatigue damage of piston, wear, head cracks etc. By the chemical reaction of burning the gas creates the high temperature which makes the piston expand which creates thermal stress and thermal deformation. The thermal deformation and mechanical deformation causes piston cracks, tortuosity etc. Hence it is very essential to analyze the temperature distribution, stress distribution, thermal load, mechanical load and heat transfer in order to minimize the stress, and different loads on working condition of the piston. Most of the internal combustion engine piston is made of Al alloy which have thermal coefficient is 80% higher than the cylinder bore material made of cast iron.

This author focuses to optimize the design by finding weight and stiffness for various materialistic mass and volume of the con rod. This paper will conclude whether the existing and modified design and it is clear that the stress and strain obtained by the modified design is less when compared to the existing design [1].

This paper studied the thermal and the stress distribution of the piston which is initialized with four materials (Pure Aluminium, A6061, Al – GHS 1300 and Al-Sic-Graphite) by using by finite element method. The specification used for the specification belongs to four stroke single cylinder Hero-Honda motor cycle. The results predicted the maximum stress and the dangerous region on the different aluminum alloys piston using FEA [2].

Analysis of the thermal and mechanical stress distribution in the many parts of the piston to know the stresses due to the gas pressure and thermal variations using with Ansys. The engine piston is designed by using CATIA V5R16 and analysis was done form graphics software ANSYS 11.0. The volume of the piston is reduced by 24%, the thickness of barrel is reduced by 31%, width of other ring lands of the piston is reduced by 25%, von-misses stress is increased by 16% and deflection is increased after optimization. But all the parameters are well with in design consideration [3].

In this study work there are two steps of study of the piston are Designing and Analysis. Firstly design the model of the piston based on the design specification using modeling software like INVENTOR. Import the model of the piston into the analysis software ANSYS in IGES format. Then the analysis has been carried out on the various parameters such as stress, deformation and temperature. In this work focused on the optimized piston through the mass and volume become reduced. The deformation also increased after the optimization which is responsible for the stress distribution on the piston head or piston crown [4].

This paper describes the stress distribution of the piston four stroke engines by using FEM. The main objective of the author is to investigate and analyze the thermal stress and maximum or minimum principal stresses. The stress concentration on the piston head, piston skirt and sleeve are reduced by optimization with using Pro-E/ CREO software the structural model of a piston will be developed. Finite Element Analysis technique (FEA) to forecast the higher stress and critical region on that component [5].

In this work the analysis of the piston consists of mainly design and analysis. Design the model of the piston like PRO-E. The constrains which are act on the working condition of the piston after the model of piston into the analysis software ANSYS in IGES format. The three different materials like Al alloy 4032, AISI 4340 Alloy Steel & Titanium Ti-6A1-4V were used for the finite element analysis. The performance analysis is carried out on various parameters such as stress, total deformation and temperature distribution. After the analysis of the three different materials, Al alloy is suitable for internal combustion engine [6].

There are lots of research works proposing, for engine pistons, new geometries, materials and manufacturing techniques, and this evolution has undergone with a continuous improvement over the last decades and required thorough examination of the smallest details. Anyhow all these studies, there are a huge number of damaged pistons. Damage mechanisms have different origins are mainly wear, high temperature distribution, and fatigue load.

Current years CAE packages could acquire the stress contours of any ideal component or product. By the advancement of computational power, to obtain optimized design with the help of topology optimization. This paper deals the selection materials based on the finite element analysis and parametric optimization of a piston for a single cylinder four stroke spark ignition engine. In order to obtain the result of incorporating additive manufacturing of any shape regardless of its complexity by reducing significant percentage mass of initial design domain. The initial design considers thermal loads later it is verified for the performance under structural loading. The objective of this paper focuses the light weight piston design through reverse engineering techniques, selection of materials and parametric optimization in order to improve the performance and emission characteristics, bear 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 piston; the geometry and the requirements of the piston solely depend upon the engine. The specification of the engine is used for the following Table 1.

Table 1. Specification of the engine

Engine type	4 stroke, Single cylinder, Air cooled engine
Bore x Stroke	68 X 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

2.2. Piston: Material

Compact weight and high structural rigidity is the key factors essential for all components of an IC engine. For this purpose, the industries widely use aluminum alloys. Aluminum has a density of only 2.7 g/cm3, approximately one-third as much as steel (7.83 g/cm3). Aluminum die casting alloys are light weight, has good cast ability, good mechanical properties, offer good corrosion resistance and dimensional stability [7]. The application of aluminum matrix material is used in the automotive industry, aircraft industry, in construction of machines, as pressure vessels for cryogenic applications etc.

The present paper is to study the possibility of enhanced grain refinement of an aluminium cast metal by making the use of fragmented Al3Ti and TiB2 particles in an Al_5Ti_B master alloy. Various sizes of particles were provided by heat treatments and plastic deformation on a commercially-available Al_5Ti_B wire [8].

In this study, the investigation of the temperature distribution between sample and die was done during the Spark Plasma Sintering synthesis of TiB2. The reaction among titanium and boron is exothermic for the binary phases—titanium monoboride (TiB) and TiB2. Because of this, the reactions can be easily observed by temperature changes inside a sample [9].

Addition of Ti-B grain refiner in Al-ADC12/nanoSiC composite results in enhancement of tensile strength, hardness, and wear resistance through grain refinement. In this research, composite of Al-ADC12/nanoSiC (0.15%vf) with variations of TiB respectively (0.0), (0.02), (0.04), (0.06), dan (0.08) wt% were produced by stir casting. The increase in mechanical properties of composites mainly because of Al3Ti acts as nucleants which initiates the grain refinement and the existence of MgAl2O4 phase indicates an interphase between nanoSiC and ADC12 matrix. However, the increase of Ti-B addition after optimum number gives no significant results. High composition of iron and magnesium addition will form intermetallic phase β-Fe, π-Fe, and Mg2Si [10].

The addition of a titanium boron aluminum grain refiner improves homogeneity and allows for a uniform distribution of alloying elements, reduces porosity, eliminates hot tearing in cast structures, improves responsiveness to subsequent heat treatment, and enhances mechanical properties and machinability in the fabrication process [11].

The chemical composition test was conducted using a vacuum optical emission spectrometer in order to obtain the material DCA1 and also mechanical test were conducted. This author stated that the microstructure and mechanical properties of die cast aluminum A380 alloy casts produced under varying pressure was investigated experimentally. The hardness of the die cast A380 samples that solidified under different applied pressures varied from 76 to 85 HRN and likewise tensile strength, yield strength and elongation of the samples displayed an increase with increased pressure. Based on the chemical composition test and mechanical test of existing piston and DCA3reference material, DCA2 is fabricated which is Al-Si based alloy as per the ASTM B179-09. The chemical composition of material is tabulated in Table 2 and the properties of materials are summarized in table 3. The geometrical values of existing piston as shown in Table 4.

Table 2: Chemical composition of selected materials % by weight

Element	DCA1	DCA2	DCA3
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: Physical and mechanical properties.

Designation	DCA1	DCA2	DCA3
Density (g/cm^3)	2.82	2.68	2.76
Thermal Conductivity (W/mK)	92	113	109
Tensile strength (MPa)	320	324	340
Elongation (%)	2.5	3.6	4
Specific heat (J/g^{0}C)	0.963	0.963	0.963
Hardness (HB)	79	83	85
Fatigue strength (5x10^8 cycle, MPa)	145	140	138
Elastic Modulus (GPa)	68.9	71	71
Yield strength (-0.2%, MPa)	167	169	176

Table 4: Geometrical values of piston

Name of the part	Dimensions
Length of piston	53.2 mm
Outer diameter of piston	67.75 mm
Inner diameter of gudgeon pin area	18 mm

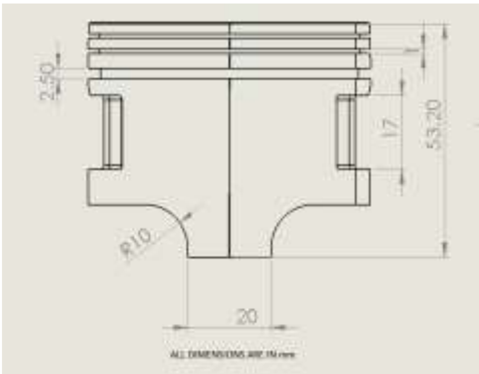

Figure. 1. 2D drawing of piston before optimization

2.3. Reverse Engineering

Reverse engineering is the process of obtaining a geometric CAD model from measurements obtained by using non-contact scanning technique of an existing physical model [13].

Many research articles on CAD/CAM are about generating computer models and moving into physical products. Sometimes, however, industries concerns have physical model to CAD models. The reasons are CAD model 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. This paper describes, it consists of following steps: Data acquisition, preprocessing, triangulation, feature extraction, segmentation and, surface fitting and the application of CAD/CAM/CAE tools [14].

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 piston. The scanned model and CAD model as shown in figure 2.

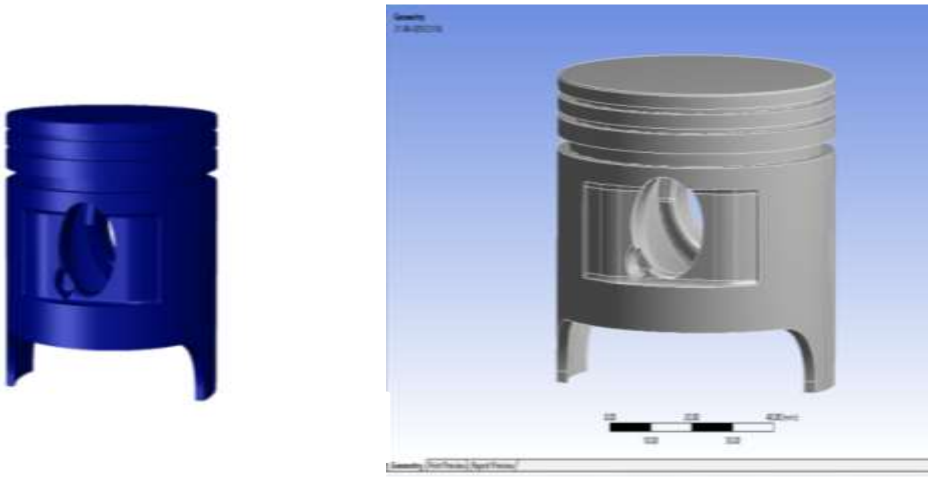

Figure. 2. Piston (a) Scanned model and (b) CAD model

2.3.2. Finite element analysis

A 3-dimensional piston 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 con rod and piston. In figure 3. (a) Shows the piston model imported to ANSYS and (b) fine meshed piston consists of 100903 nodes and 62756 triangular elements. Figure 4. (a) shows the thermal loads at 3000C and the boundary conditions are applied through convective mode temperature 700C, and (b) temperature distribution from top surface of the piston to the bottom of piston to attain a maximum temperature of 3000C and, the heat transferred per unit area in the piston to reach maximum is 2.0006 W/mm2 near the piston ring and minimum is at bottom of piston. Figure 5. (a) demonstrates, to ensure efficient design the compressive load was applied as a 23.4 bar, and remote displacement along z-direction is -45mm and rest of the directions are constrained zero degrees of freedom and (b) shows the maximum stress obtained as per the given loading of 65.068MPa. Figure 6. (a) Displays the maximum deformation 45.106mm at the bottom of the piston skirt and minimum deformation of 44.885mm at the top of piston and (b) Shows the minimum factor of safety for the piston as 2.6127.

2.3.2.1. Analysis Results before Optimization

Figure. 3. Piston model (a) Imported to ANSYS and (b) Mesh model

Figure. 4. Piston (a) Thermal boundary conditions and (b) Temperature distribution

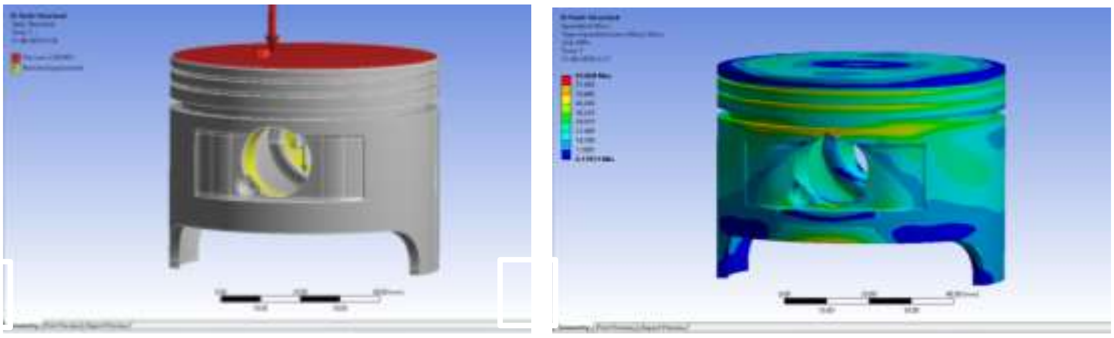

Figure. 5. Piston (a) Structural loading conditions and (b) Equivalent (von-mises) stress

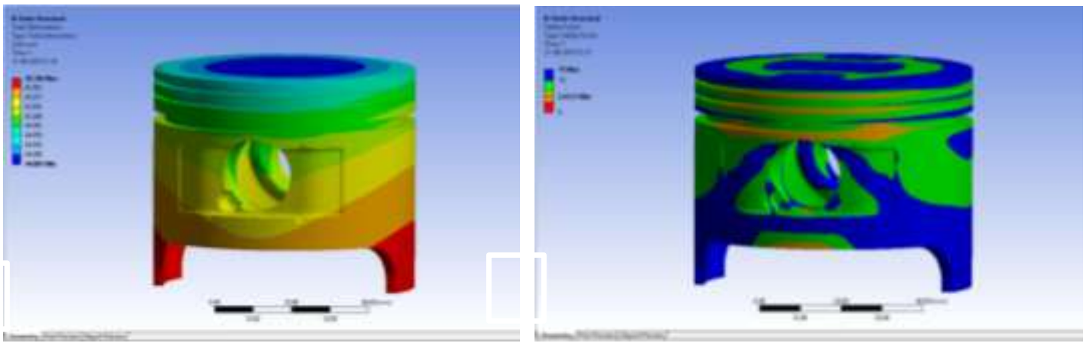

Figure. 6. Piston (a) total deformation and (b) factor of safety

3. PARAMETRIC OPTIMIZATION

Modern engines with variable valve train or different direct injection concepts require pistons with complex crown shapes which would often lead to a higher piston weight. Therefore in every new piston development, the piston geometry is optimized in particular in the ring belt/piston skirt area. Intensive application of numerical simulation methods enables significant weight reductions while increasing at the same time the load-bearing capacity. Newly developed alloys with better cast ability, but also higher fatigue resistance in the critical temperature and stress region, allow the realization of thinner wall structures. Improved casting methods enable large recesses for the ring belt and hence a considerable reduction in the piston weight. But also the use of steel pistons in i. c engines is discussed again and again. The advantages of steel pistons such as reduced installation clearances, low fuel consumption figures and long service life would have to be evaluated against customer demands such as low emission levels, lightweight, efficient cooling and a competitive price. But up to now, there are no definite indications that steel pistons would be a viable concept for mass production. The piston model was modified using the results obtained from parametric optimization. In figure 8. (a) Shows the piston model imported to ANSYS and (b), fine meshed piston consists of 100903 nodes and 62756 triangular elements. Figure 9. (a) shows the temperature distribution from top surface of the piston to the bottom of piston to attain a maximum temperature of 3000C and, the heat transferred per unit area in the piston to reach maximum is 2.0006 W/mm2 near the piston ring and minimum is at bottom of piston and (b) shows the maximum von-mises stress of 78.757Mpa. Figure 10. (a) Describes the total deformation of maximum 45.091mm and (b) shows the safety factor 2.1585.

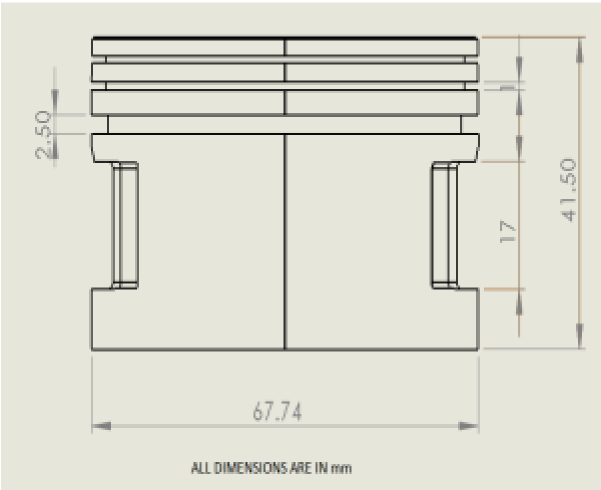

Figure. 7. 2 D optimized drawing

3.1. Analysis results after parametric optimization

Figure. 8. Piston model (a) Imported to ANSYS and (b) Meshed model

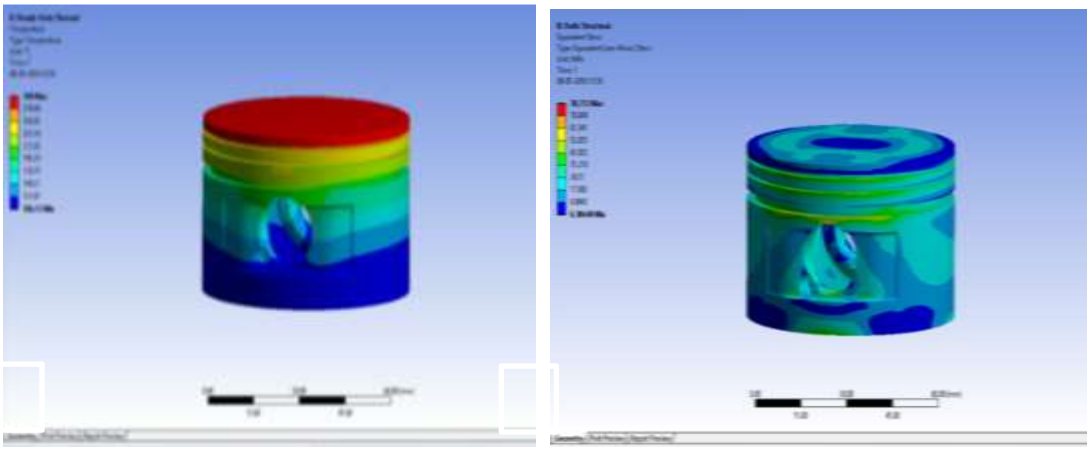

Figure. 9. Piston (a) Temperature distribution and (b) Equivalent (von-mises) stress

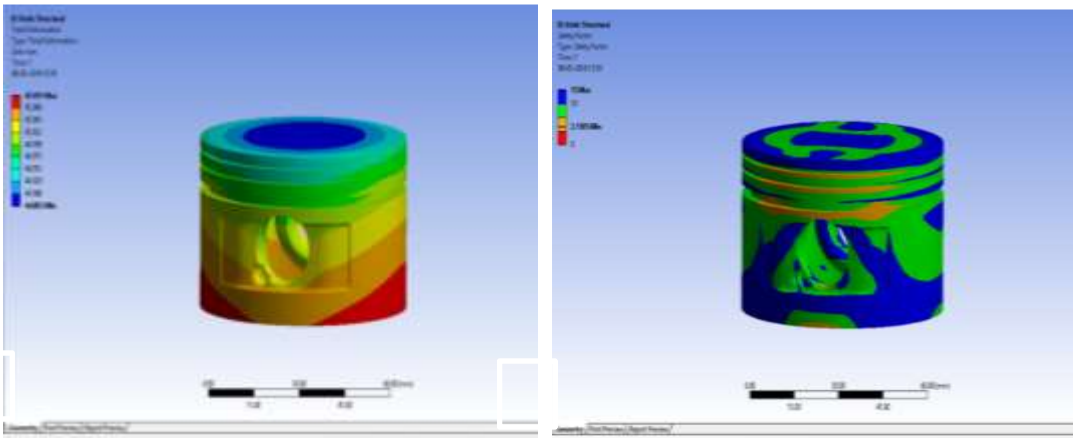

Figure. 10. Piston (a) total deformation and (b) factor of safety

4. RESULTS AND DISCUSSIONS

Maximum von-misses stresses, deformation and factor of safety was found out in finite element analysis. Maximum stress occurred in the pin boss fillet area, the mass of the initial model is 163.53 grams and after optimized model is reduced to 159.29 grams. Fig. 11 Results for (a) total deformation (b) von-mises stress, before and after optimization Figure 12. (a) Shows the factor of safety is ADC12 is low, A360 is maximum and A380 is close to A380, and (b) indicates the total heat flux of ADC12 is slightly increased, A360 is almost same and A380 is equal to 0.605 w /mm2.

4.1. Comparison of results before and after optimization

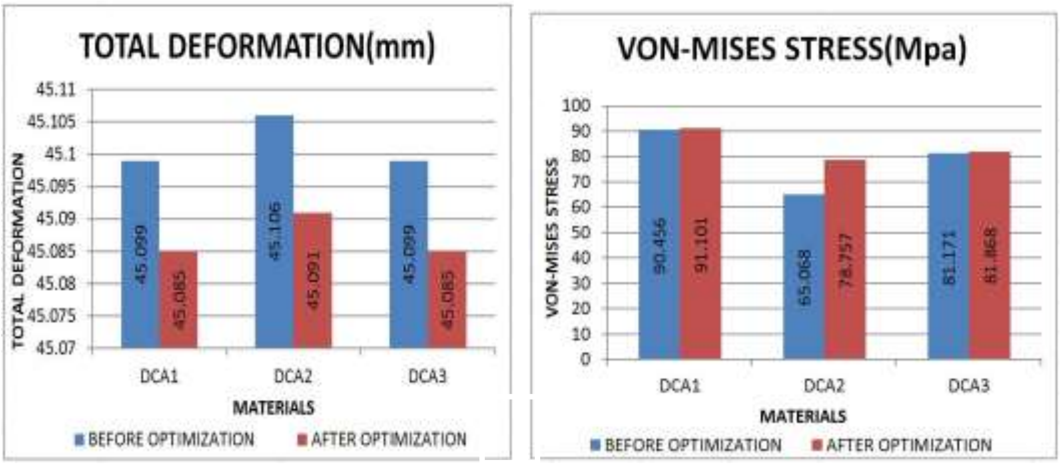

Figure. 11. Results for (a) total deformation (b) von-mises stress, before and after optimization

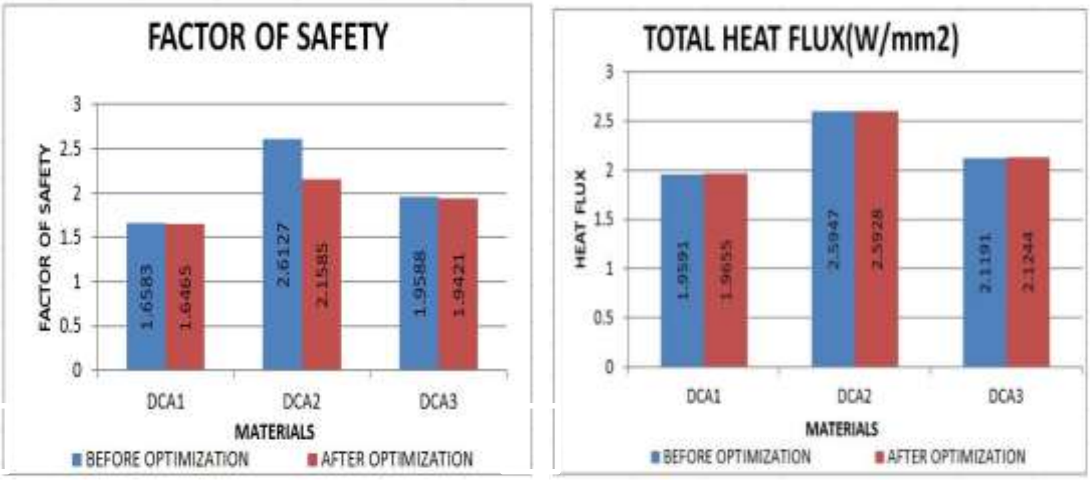

Figure. 12. Results for (a) factor of safety and (b) total heat flux before and after optimization

5. CONCLUSION

It is observed that by conducting the coupled steady-state thermal structural analysis shows von misses stresses, deformation and factor of safety for the given loading conditions. After carrying out the coupled steady-state thermal structural analysis the stresses in loading conditions were studied and then area where excess material can be removed were decided. Parametric optimization was performed to reduce weight of the piston subjected to compressive load and tensile load. The Bottom piston skirt region of the piston offered the greatest potential for weight reduction. Based on the analysis result, it is possible to reduce the weight of the piston material in two ways such as one is selection of piston materials A360 is obtained 155.41 grams which is 8.12 % less compared to ADC12 and the other is mass of the optimized piston is 151.39 grams and the optimized geometry is 7.42 % lighter than the existing piston without compromising the strength and stiffness.

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