Thermal Structural Optimization of IC Engine Piston

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***Abstract*—The primary purpose of this work is to investigate the effect of the piston crown and piston boss thicknesses on the stresses generated on the piston. A 150-cc piston, made from A4032 Aluminum, of type "Bajaj," was considered in the present investigation. The piston head was subjected to a double-action of gas pressure and heat from the combustion process. Piston pin bore was considered to act as cylindrical support. ANSYS 15 was used to run the simulation process using the thermal structural couple technique. Different thicknesses of the piston crown and piston boss were selected and studied. The comparison and optimization processes depended on the Von-Mises stress, mass, and temperature distribution in the piston. Based on the stress values obtained for different piston sizes, the results clearly showed that the optimal piston design was 3 mm piston crown and 2 mm piston boss thicknesses. The optimal piston design reduced the total stress and mass, but it increased the temperature generated in the piston.**

***Index Terms*—ANSYS, Bajaj 150 cc, IC engine, Piston boss, Piston crown, Thermal, and structural analysis**

I. INTRODUCTION

During the last decades, numerous research works in the field of automotive engineering were devoted to the enhancement of engine performance. Moreover, the apparent connection between carbon dioxide emissions from engines and global warming, affecting the world severely, has urged scientists and engineers to develop a new class of lightweight engines that are less pollutant and more efficient. This target could be achieved through different techniques, among which optimization is considered as the best one. Such a method gives a total preview of the problem and helps to choose the best between possible alternatives.

The enhancement of the engine performance is conducted by several optimization processes applied to the engine parts individually. One of the crucial elements that contribute directly to engine efficiency is the piston. However, optimization is usually an expensive process that needs numerous experimental studies and requires a large amount of material. Fortunately, non-destructive techniques were developed to meet the requirements of studies like these.

II. LITERATURE REVIEW

A thorough investigation of the literature shows many studies focusing on Piston simulations and the Internal Combustion engine (IC engine). In 2006, P. Carvalheira1 and P. Gonçalves [1] provided a finite element analysis (FEA) for two engine pistons, made of Aluminum cast alloy A390 and Ductile Iron 65-45-12. This work was a part of a low fuel consumption IC engine project applied to the new vehicle XC20i. Its main aim was to suggest two different materials for the piston and to choose the better one. After the material selection, an exhaustive analysis of the original design parameters was conducted to make the design more reliable and to improve its safety [1].

M. SreeDivya and K. Raja Gopal [2] worked on design and material optimization of the piston by using PROE and ANSYS. Their main objective was to attain less volume and better efficiency. They concluded that "the optimized design of a silumin piston can be used to reduce the material cost and to optimize the engine efficiency by minimizing its weight. The previous conclusion led to the selection of Silumin (AL-Si alloy) as the best material for the piston due to its excellent physical properties [2]. Along with the previous study, Ajay Raj Singh and Pushpendra Sharma conducted a thermal stress analysis studying three types of Aluminum alloys of a piston used inside a four-stroke single-cylinder engine of Bajaj Kawasaki motorcycle [3]. The Bajaj Kawasaki piston analysis identified a new approach to

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enhancing the performance of the engine by reducing the piston mass, which minimizes its inertia forces. The dimensions of the piston shape were also investigated by taking into consideration the thickness of the piston head, the piston barrel, and the skirt length.

A. R. Bhagat, Y. M. Jibhakate, and Kedar Chimote conducted another study of thermal stress analysis distribution on the piston during the combustion process [4]. They delivered a descriptive optimization for the piston head and the piston skirt sleeve to minimize the stress concentration in the upper piston. The results showed that, due to its lower stiffness, a stress concentration in the piston crown generates a deformation in the piston skirt and hence creates a crack on the upper end of the piston crown.

In this paper, we propose a modified piston design for Bajaj 150 cc engine, made from A4032 aluminum alloy. This design provided an acceptable elongation to failure, hardness, and yield strength properties [5]. Therefore, the purpose of this study is to examine the design using thermal structure analysis and come up with the best dimensions for both piston crown thickness and piston boss, which can give better resistance to temperature and forces.

III. Geometry and Modeling

A. Engine Specifications

The Bajaj 150 cc pulsar DTS-I engine specifications are displayed in Table I.

TABLE I. Bajaj 150 cc Pulsar Specifications [6]

Engine Type	Four stroke, single-cylinder, air-cooled
Bore x stroke	56 x 58.8 mm
Displacement	149.01 cc
Maximum power	14.09 hp at 8500 rpm
Maximum speed	108 km/h
Maximum torque	12.76 Nm at 6500 rpm
Fuel consumption	48.4 km/L
Compression ratio	9.5: 1

B. Geometry

The original drawing of the piston [2] was complicated and required intensive meshing studies. Therefore, for the sake of simplicity in analysis and meshing, the normal shape of the piston was sketched by SolidWorks (Figs.1 and 2), then the drawing was used for the Thermal-Structural analysis.

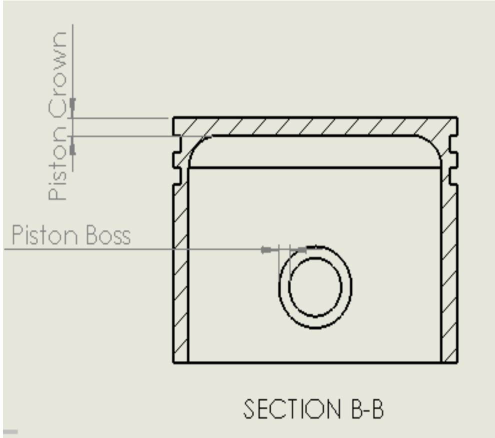

Figure 1. Piston Boss and piston crown Bajaj 150cc pulsar piston

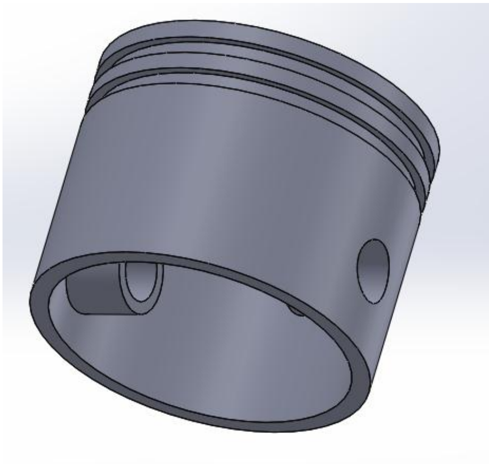

Figure 2. 3D model of Bajaj 150 cc used in the study

C. Material

Due to their essential thermal and mechanical properties, most pistons are made of cast iron, cast aluminum, and forged aluminum. As illustrated in Table II, the fundamental features that are usually considered in the selection of an IC engine piston material are the coefficient of thermal expansion, the thermal conductivity, the mechanical strength, the density, and the wear resistance. Aluminum A4032 was used in this study, as it is widely used in pistons manufacturing.

TABLE II. Properties of Aluminum A4032 Alloy (At Room Temperature) [5]

Parameters	Aluminum alloy A4032
Elastic modulus (GPa)	79
Ultimate tensile strength (MPa)	380
0.2% yield strength (MPa)	315
Poisson’s ratio	0.33
Thermal conductivity (W/m K)	154
Coefficient of thermal expansion (1/K)	79.0 x 10^{-6}
Density (kg/m^3)	2684

D. Boundary Conditions

The gas pressure in the engine cylinder and the heat directed to the piston head are the significant loads that affect the piston design.

The gas pressure on Bajaj 150cc pulsar piston head is about 2 MPa [2]. For safety considerations, 2.8 MPa was taken as the gas pressure inside engines.

The heat directed to the piston was calculated by the following equation [7]:

$$H = C \times HCV \times m \times BP \qquad (1)$$

$$H = CxHCVxmxB.P.H = CxHCVxmxB.P.$$

Where:

H = Heat flow through piston head [in kW].

C = Constant representing that portion of the heat supplied to the engine, which is absorbed by the piston.

HCV = Higher calorific value of fuel [in kJ/kg].

D = Density of Benzene fuel [in kg/m^3].

m = Mass of the fuel used [in kg/B.P.s].

BP = Brake power of the engine per cylinder power.

C and HCV are constant values obtained from Ref [7]. The BP was obtained using the information in Table I. The ‘’m’’ value was obtained by knowing the maximum speed, and fuel consumption from Table I, then the ‘’m’’ value was found to be 50.4×10^6 kg/kW.s.

E. Modeling

The piston pinhole was set to be the fixed support in the study, while the piston head faced both, the gas pressure and the heat flux of the combustion process. The heat is being dissipated from the piston through the lubricant cooling system. To simplify the calculation of the heat transfer coefficient, stagnant water with 40° C ambient was chosen as a lubricant. ANSYS 15 was used to conduct the simulation process.

Different reductions in the thickness of piston crown and piston boss were studied and the optimal design was selected. We stopped reducing the crown thickness when the piston deformation began to form an oval shape. Also, due to wear resistance we stop at 2 mm piston boss thickness.

First, the boundary condition was applied to the unmodified model (4 mm crown thickness and 3 mm piston boss thickness) and then to the modified one. Every percentage of comparison was held in reference to the first study on the unmodified model.

F. Meshing

In meshing processes, a 3D unstructured mesh with an element size of 1 mm was used. Such size was obtained from a simulation using 370,643 nodes and 244,483 elements with an average element quality of 0.83.

The mesh was applied to the model in Fig.2 without dividing the model and using the axisymmetric technique. as shown in Fig. 3.

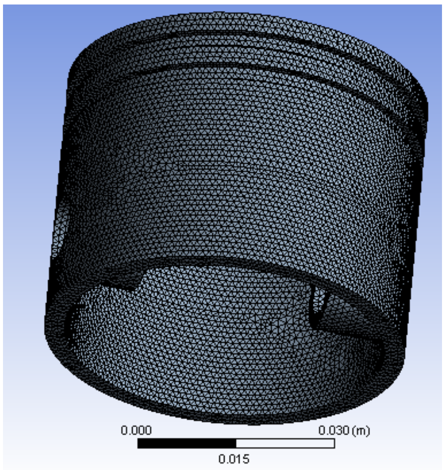

Figure 3. 3D Mesh of the model

IV. Results

In order to evaluate the effect of changing the piston design on the developed stresses, two main piston’s portions dimensions were investigated.

A. Piston Crown Thickness

The following Fig. 4 displays the variation of piston crown thickness with the Von-Mises stress and mass values. Fig. 5 portrays the variations of piston crown thickness with the Von-Mises stress and temperature.

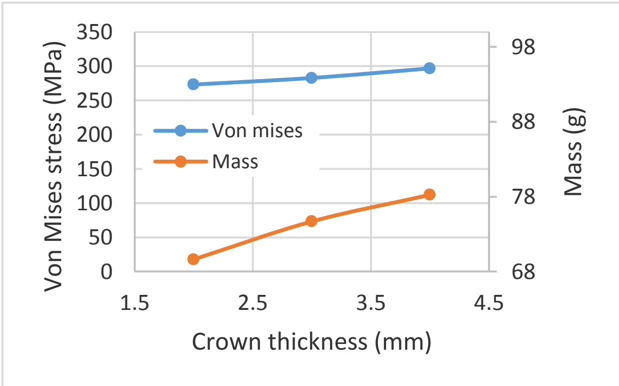

Figure 4 Variation in stress and mass with respect to crown thickness

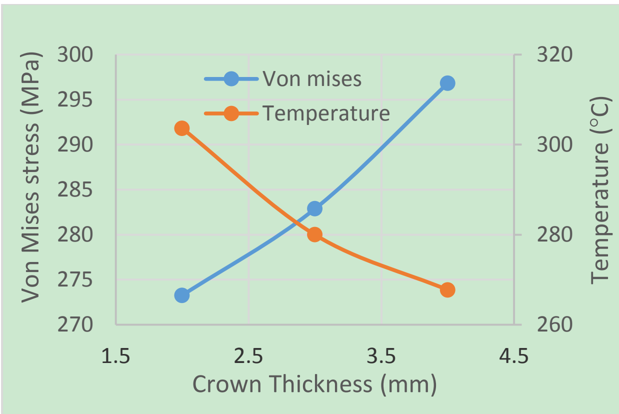

Figure 5. The effect of crown thickness on the Von-Mises stress and crown temperature

TABLE III. COMPARISON OF DIFFERENT PISTON CROWN THICKNESS

Crown thickness (mm)	4	3	2
Von-Mises (MPa)	296.82	282.87	273.25
Reduction in stress	-	5%	8%
Mass (gram)	79.258	74.704	69.643
Stress reductions	-	5%	8%
Reduction in mass	-	6%	12%
Safety factor	1.06	1.11	1.15
Temperature (℃)	267.71	279.97	303.63
Temperature increase %	-	5%	13%
Deformation (mm)	0.13443	0.13564	0.13815

The results of the previous investigation clearly show that the piston crown thickness is proportional to the stress. Moreover, the reduction in the crown thickness was found to cause a little decrease (8%) in the maximum equivalent stress. This is mainly due to mass reduction, as shown in Table III. On the other hand, a decrease in the crown thickness leads to an increase of the maximum piston temperature, which affects the aluminum A4032 stresses and became uncertain. Therefore, the optimum piston crown thickness for Bajaj 150 cc was found to be 3 mm.

B. Piston Boss Thickness

The boss thickness is smaller than the piston crown thickness. Therefore, the reduction step of the boss thickness at which the stresses were observed was considered to be 0.5 mm (Fig. 6).

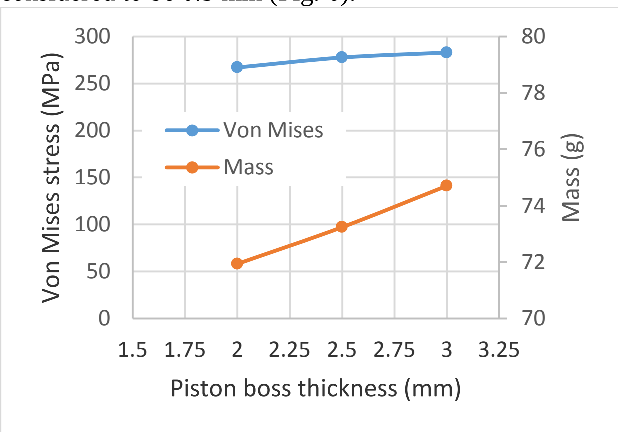

Figure 6. The effect of piston boss thickness on Von-Mises stress and piston mass

Results values are shown in the table and figures below:

TABLE IV. RESULTS OF DIFFERENT PISTON BOSS THICKNESS

Piston boss thickness (mm)	3	2.5	2
Von-Mises (MPa)	282.87	277.59	267
Mass (g)	74.704	73.24	71.94
Change in stress %	-	2%	6%
Change in mass %	-	2%	4%
Safety factor	1.11	1.13	1.18
Deformation (mm)	0.13564	0.13569	0.13562

The reduction in the Von-Mises stress is proportional to the decrease in the piston boss thickness, similarly to the crown, as mentioned in Table IV. Although reducing piston boss will generate more reduction on the equivalent stress and the piston mass, the probability of wear to take place in the piston structure will increase. Therefore, for safety considerations, we stop calculations at 2 mm piston boss thickness. We take 2 mm piston boss thickness for the Bajaj 150 cc pulsar.

Therefore, our optimal design for the piston has 3mm piston crown thickness and 2 mm boss thickness.

C. Simulation Results

The final piston design simulation results are shown in Figs. 7, 8, and 9.

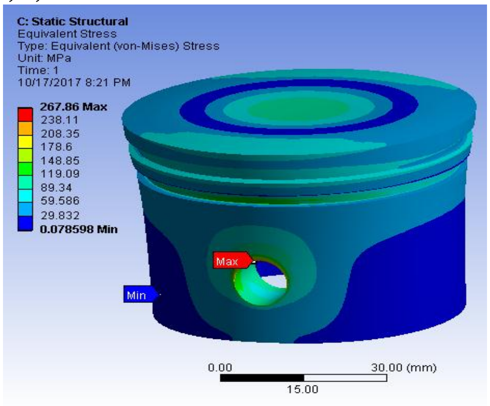

Figure 7. Von-Mises stress on the piston

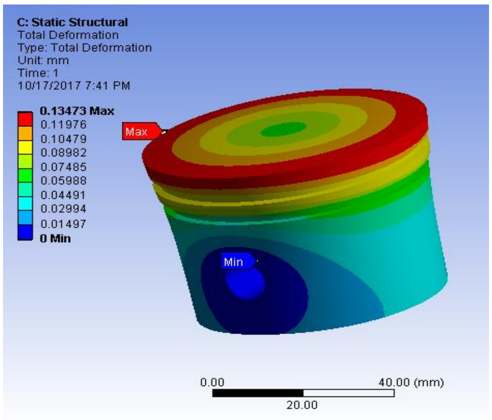

Figure 8. Total deformation

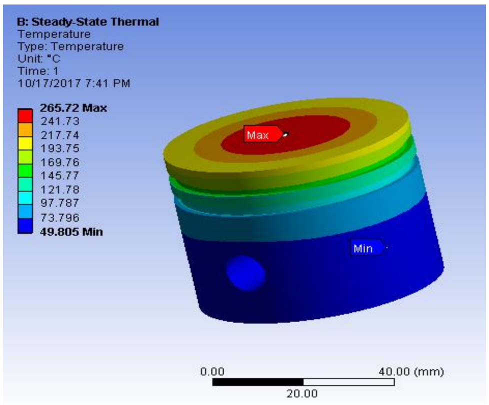

Figure 9. Temperature distribution

V. Conclusion

The decrement in the piston crown and piston boss thickness reduces the stresses and mass but increases the thermal diffusivity. Safety considerations should be taken in the piston boss analysis to avoid wear failure. The optimal piston design (3 mm piston crown and 2 mm piston boss thicknesses) was found to reduce the total stress by 10% and mass by 9%, but it increased the temperature generated in the piston by 4.4%. Proper optimization processes through non-destructive test techniques like simulation software will give the same results of destructive tests and save time and money.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Yousif Badri and Ahmed Shamseldin has drawn the 3D Solidworks piston model; did the thermal analysis using Ansys; conducted the static and thermal structural analysis using Ansys, and wrote the paper. Yousif Badri rearranged the paper to fit the conference template. Dr. Jamil Renno reviewed the paper and provided supervision for the static structural analysis. Dr. Sadok Sassi provided supervision during the rewriting and resubmission status of the paper. All authors had approved the final version.

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References

[1] P. Carvalheira and P. Gonçalves, "Fea of two engine pistons made of aluminium cast alloy a390 and ductile iron 65-45-12 under service conditions," presented at the 5th International Conference on Mechanics and Materials in Design, Coimbra, Portugal, 24-26 July, 2006.

[2] A. Dorga, P. Singh, and M. K. Agrawal, "Analysis of pulsar 150cc piston by material optimization," *International Research Journal in Advanced Engineering and Technology (IRJAET)*, vol. 4, no. 5, pp. 3972–3977, 2018.

[3] A. R. Singh and P. K. Sharma, "Design, analysis and optimization of three aluminium piston alloys using FEA", *Journal of Engineering Research and Applications*, vol. 4, no. 1, pp. 94–102, 2014.

[4] A. R. Bhagat, Y. M. Jibhakate, and Kedar Chimote, "thermal analysis and optimization of I. C. engine piston using finite element method," *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 2, no. 4, pp. 2919–2921, 2012.

[5] M. H. W. Wunderlich, "Thermal cyclic fatigue analysis of three Aluminum piston Alloys," *International Journal of Material and Mechanical Engineering*, vol. 1, no. July 2012, pp. 57–60, 2012.

[6] "Bajaj Pulsar 150 CC DTS-i." [Online]. Available: https://www.globalbajaj.com/media/2026/pulsar-150-om_export-small-12.pdf.

[7] R. S. Khurmi, J. K. Gupta, "A text book of machine design,', Eurasia Publishing House, 2005, Chapter 32, pp. 1135.

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