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Topology Optimization in 3D Printed Piston

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Abstract: Piston is the main alternating mass of a single cylinder 4 stroke engine and hence contain most of the inertial forces, also modern advancement in the automotive industry for the sake of pollution control and fuel economy many of the techniques such as Downsizing of engine (turbo charging), advance spark ignition, port injection, VVA and many more are adapted and hence results in high specific loading, including thermal and mechanical loads on the several parts of engine. This paper presents the re-designing of the piston, the topology optimization techniques have been used for increasing strength and decreasing mass of the piston which is our main objective. Traditionally pistons were manufactured by casting of aluminum and grey cast iron, aluminum was used in performance oriented vehicles as it was light in weight and have addition thermal properties and also it was easy to manage the inertial forces, whereas cast iron pistons were used in industrial purpose engine (heavy duty engine) today methods are replaced with 3-D printing, as a topology optimized piston cant be manufactured with traditional methods. The procedures in the paper are done for a generalized case and not for a particular so that the same methodology can be implemented in specific cases. Also it will cover a lot about the Material selection and additive manufacturing process used for this specific application.
Keywords: Topology optimization, 3-d printing, rapid prototyping, piston

I. INTRODUCTION

Reduction in the reciprocating mass of a engine can provide better kinematic conditions, and also helps in engine balancing. Which eventually is point of concern for the single cylinder engine. from decades this was achieved with the help of aluminum and its traditional manufacturing process. But when we further go for more optimized design it becomes light weight, more complex and hard to manufacture. To resolve this problem additive manufacturing is chosen as a process, in this case aluminum cant be represented as a best choice and steel can be a valid alternative for manufacturing. . Schreer et al. [4] analysed the consequences of employing a steel piston: a better kinematic behaviour of the crank mechanism, a comparable weight, more homogeneous surface temperatures, a lower dead volume at the top land, a lower blow-by and a more efficient combustion process are the main advantages registered. In comparison of aluminum and steel to achieve same configuration, thickness of the steel piston is reduced by 1-1.5 mm. to attain this thin feature additive manufacturing is the promising technology. Further Du and Tao [6] and Zhao et al. [7] adopted the topology optimization for an engine piston lightening, but there aim was only to understand which parts of the piston were redundant, without ascribe any focused design validity. Also Brackett et al. [8] analyzed the complexity of manufacturing the topology optimized piston and studied about the mesh parameters and loading conditions. With this configuration topology optimization with finte element analysis of piston is employed, load conditions such as displacement of specific nodes on piston top, skirt and pin are considered for better results,

II. METHODOLOGY

A. Design of Piston

Modern engine is designed in a way to rave up to a certain RPM and produce a desirable torque and power output also, norms of pollution control and fuel economy is to be considered, to attain those requirements techniques such as turbo charging, advance spark ignition, Variable Valve timing, high compression, etc. are practiced, resulting in heavy thermal and mechanical loading on the piston thus it is very necessary to design piston accordingly. Parameters such as Shape and thickness of piston head, thickness of atop land, scraper and compression ring section, size of piston, circlip section for piston pin, thickness of skirt , piston barrel and all the other norms are to be consider while designing. Because in the running condition this reciprocating mass have to withstand the forces such as side thrust resulting from obliquity of the connecting rod, compression of gas, axial thrust caused by combustion and induction stroke also It dissipates large amount of heat from the combustion chamber to the cylinder wall. In our case we have refer the book Machine Design by Prof. V B Bhandari sir. For calculations of piston.

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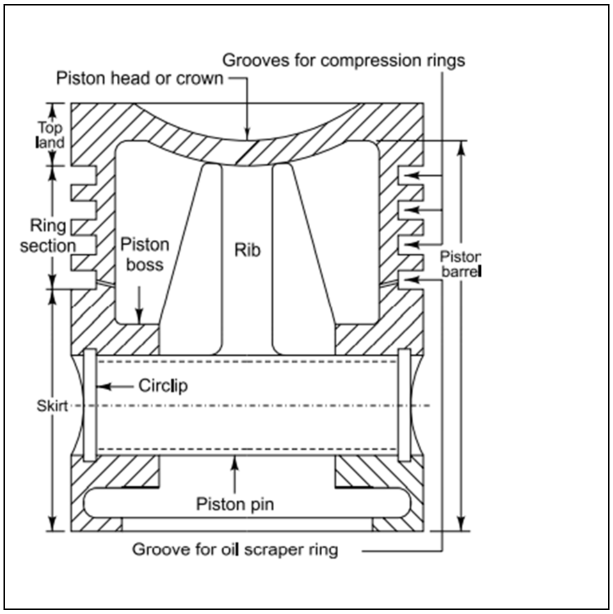


Figure.1

Figure.1 shows the basic nomenclature of the piston.
Bhandari, V. B. Design of machine element. Tata McGraw-Hill Education, 2010

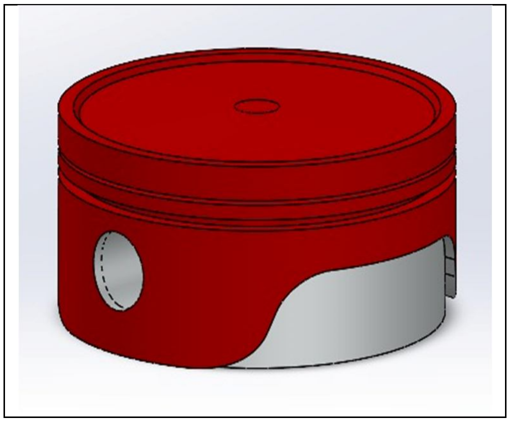
B. Design for Topology Optimization.

A generic optimization problem can be written in the form

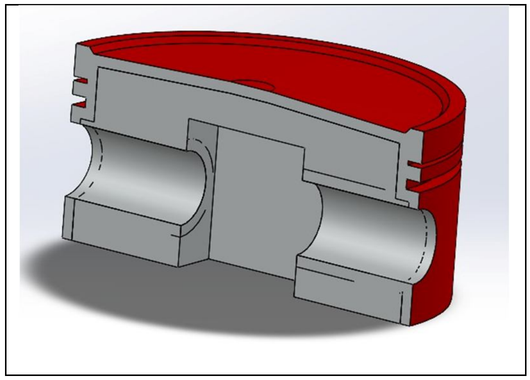
$$\text{minimize}_{x \in D}\, f(\boldsymbol{x})$$
$$\text{subject to } c(\boldsymbol{x}) \geq 0$$

where the vector x represents a suitable parameterization of the problem, D is the design space, f (x) is the objective function, and c(x) are the constraints of the optimization. The functions f(x) and c(x) are usually computed via a suitable numerical technique while the optimization algorithm iteratively looks for the best configuration. In topology optimization, since gradient information is readily available from the Finite Elements analyses, a large number of variables can be easily handled, accepting that a gradient-based optimization algorithm is adopted. The most popular methods for topology optimization are the homogenization methods. In particular, in this paper the solid isotropic material with penalization methods, SIMP, is employed. The theory of this method is described extensively by Bendsøe and Kikuchi [5] and Bendsøe and Sigmund [10]. The main scope of the method is to find the optimum material distribution in a structure. In barbieri 2017 paper [1] they have described more about deign space and its meshing parameters.

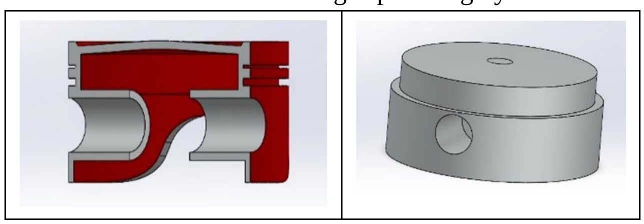
As described above our design also have a non designe space in which basically the wall of piston can be seen and a design space which is kept solid for the software to iterate and remove the part which has the minimum density of material.



Above given figure is of a piston with design and non design space. The red colored part is the piston wall including piston crown, skirt, and connecting rod pin, and rings seats which is considered as non design space with a thickness of 2mm.



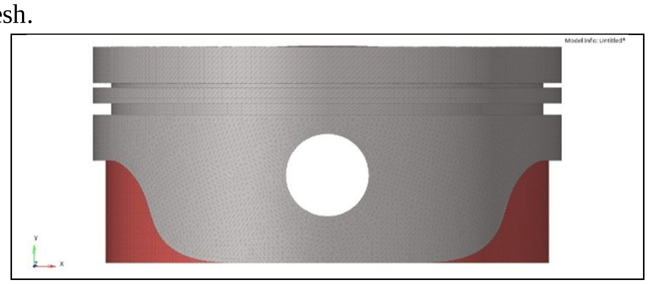
To be more precise the cross section view shows us the non design space in grey color which is a solid block of material.



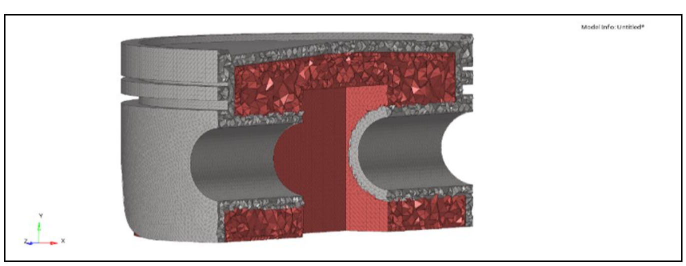
Above picture gives the clear idea of design and non design space.

C. Model Setup

For setting up the optimization problem Domain (design space) and governing parameters such as load constraints are to be specified and and resolved accordingly. The domain area should be as wide as possible just to provide the freedom for the optimization process to chose the optimum material distribution The adoption of a geometry as simple as possible is very important to achieve a regular high quality mesh.



Following figure the red shows the domain of the topology optimization. Grey elements describe the crown, the ring belt, the skirt and the pin boss and they are fixed, so that their density cannot be modified (non-design space). This layer two millimeter thick and consists of tetrahedral elements . Red elements form the bulk of the piston and represent the design space. The design space consists of tetrahedral elements, the average element size being one millimeter. Here the default setting of mesh is used for the basic analysis.



In the above cross sectional view, design and the non design phase can be observed, also the tetrahedral geometry of mesh with minimum and maximum size of mesh can be observed. The material considered for the analysis is a generic steel: Young modulus equal to 210000 MPa, density equal to 7.8 kg/dm3 and Poisson's ratio equal to 0.3 It could seem wrong to use the property of a bulk isotropic material, because Additive Manufacturing techniques always produce anisotropic components due to their lay-up style process in few research by providing the better envoirment such as thin warfare of layers quick scan time can make the printed part properties close to the classic bulk module , but the anisotropic properties are always observed.

D. Loading Conditions

In the present optimization prime objective is to reduce the mass of piston. In this the finite analysis of classic aluminum piston provides major three types of loading parameters which are as following

- top dead center during combustion (TDCC)
- top dead center at the beginning of the induction stroke (TDCI)
- instant of maximum piston thrust force (PT)

At TDCC maximum force is applied due to the ignition resulting in combustion of gases ,here major forces impact can be measured on the piston crown and the top half of connecting rod pin. Total force acting on the crown is about 40800 N. As a consequence, a pressure of about 5.23 MPa has been applied on the piston top while a pressure of about 71.8 MPa has been applied on the top half of the pin.

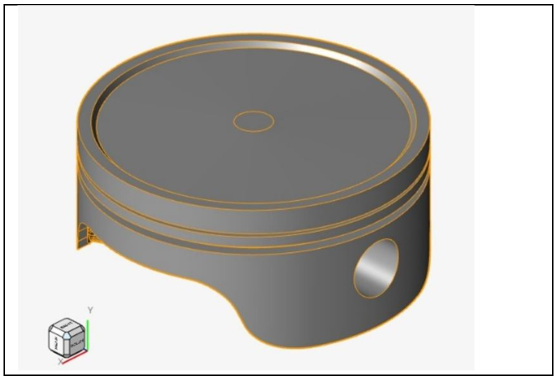
At TDCI also considered as suction stroke where majority of force acts upon the bottom half of the connecting rod pin nearly 18600 N. As a consequence, a pressure of about -2.4 MPa has been applied on the piston top while a pressure of about 27.17 MPa has been applied on the bottom At PT the total force acting on the piston is about 4200 N. As a consequence, a pressure of about 42.2 MPa has been applied on the piston skirt while a pressure of about 7.9 MPa has been applied on a half side of the pin boss, this way piston self balance each other and The solver has been then forced to give a symmetric relative density distribution with reference to the piston.

E. Optimization Process

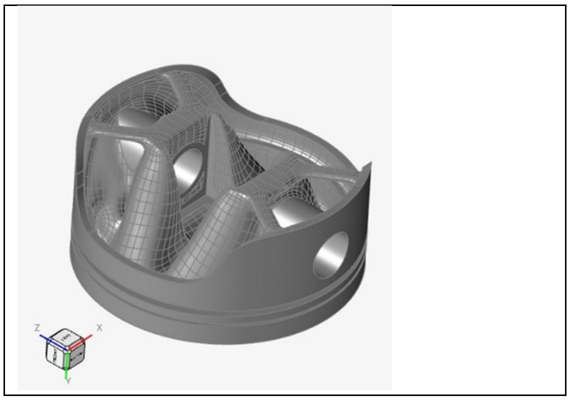
The software package employed for the optimization is Altair Inspire where the default size of mesh is first applied along with the loading constraints, the iteration of optimizing have started with the default solver, In order to better calibrate the process, a sensitivity analysis on the optimization parameters DISCRETE (corresponding to the penalty factor, p) and MINDIM (related sensitivity filter, r) has been performed initially the solution was converged at 44 iteration with the resulting mindim value of 5.further with more iteration the mindim value was set at 4 and the process was repeated this time the results was converged at 54 iterations.

The choice of the parameters has been driven by the following considerations: the solution achieved is more clearly defined, the number of intermediate density elements is lower, the convergence is achieved more easily In result the high density counters can be observed and the solver have removed a sufficient amount of mass from the design space result in better light weight geometry. Further more refined cad model was made.

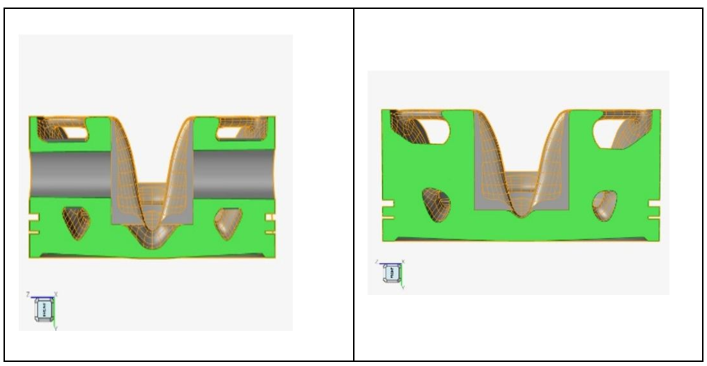
III. RESULTS CONCLUSIONS



Following figure visible mass reduction can be observed.



Optimization clearly satisfy the loading conditions at connecting rod pin and at the piston crown.



Cross section view of optimized geometry

The re-designed piston shows a better strength to mass ratio as compared to a normal piston with same working conditions, which have been discussed in the Results section. Further the use od 3D Printing has been discussed. It is clear that a topology optimized is better than the originally used one, and with use of 3D printing, the manufacturing is more accurate and precise but comparatively costly. Also reduction in mass increases the surface area resulting in better potential for forced cooling, and reduction in weight of piston results in minimal efforts for balancing the mass yielding the best power to weight ratio for a specific engine

IV. FUTURE WORK

Virtual comparison between actual and optimized geometry can be done using software such as Ricardo wave and MATLAB which can save the cost of actual manufacturing and real life testing

thermal analysis can be done of piston to simulate the mechanical and dynamic loading conditions to be more precise about the geometry.

Iteration of meshing and loading conditions can be done.

V. CONCLUSION

A method for a computer aided steel piston design has been proposed. In particular, the presented methodology aimed at finding more efficient layout solutions for the piston framework feasible with Additive Manufacturing techniques. The authors employed topology optimizations to define the optimal structural topology. Special care has to be taken in setting up the optimization process since the choice of the constraints, i.e. the performance targets, of the mesh size and quality and of the optimization parameters directly affect the outcome of the process.

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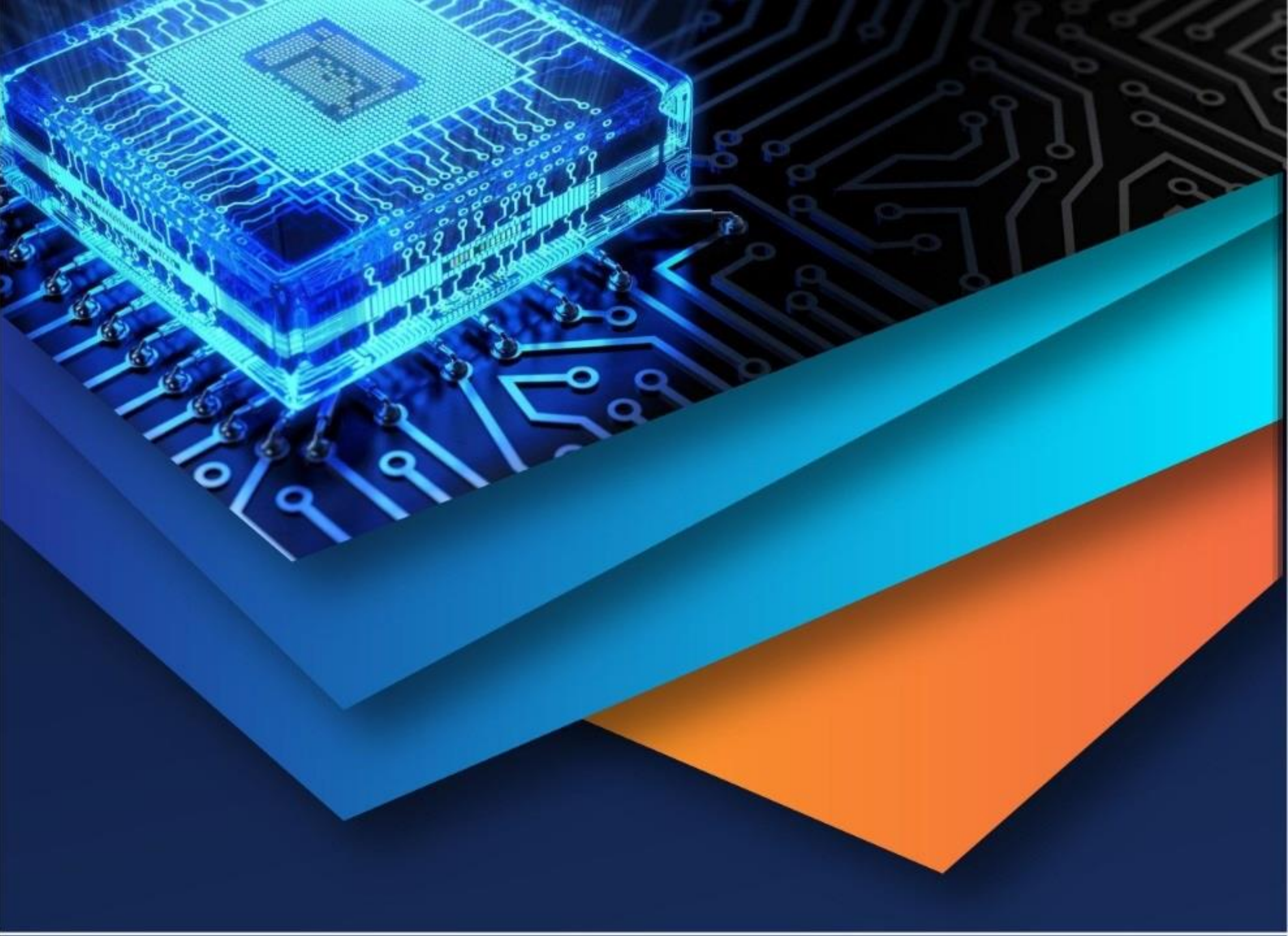

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