Static Structural Analysis of a Forged Aluminum High-Performance Piston

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Abstract - *The Piston is the main load bearing and moving component contained within cylinders. In an engine its significance is to transmit force generated from expanding gases in the cylinder to the crankshaft via connecting rod. Since for high performance engines developing higher power per stroke at higher speeds is indispensable, the piston needs to be made light, strong and reliable enough to withstand the peak mechanical stresses. In this study a forged aluminum piston pertaining to Subaru EJ20 WRX series turbo charged engine has been modeled on CATIA V5 R19 and analyzed for mechanical deformations at peak working conditions using Ansys Workbench 15.0*

Keywords–*Finite Element Analysis, Piston, Stress Analysis, Design*

I. INTRODUCTION

The Subaru EJ20 WRX series turbo charged engine is a 2.0 liter, 4 cylinder engine which conventionally uses hypereutectic cast aluminum pistons which is not designed to handle shock loads subjected upon knocking or detonation.

The structural design and operating conditions of pistons are very complicated and problematic. The piston undergoes stress and deformation due to periodic loading effect of high gas pressure, inertial force due to high speed reciprocating motion, other lateral forces, frictional force etc. Combustion of the high pressure fuel at high temperature causes the piston to expand due to which it develops thermal stresses and deformations. This thermal and mechanical deformation will cause residual stresses and eventual failure.

Another objective of the design criteria is to reduce the structural weight and hence reduce overall fuel consumption. This has been achievedby use of lightweight materials, such as advanced high strength steels, aluminum and magnesium alloys.

II. OBJECTIVE

The main purpose of this research is to design a piston with the following characteristics for it to be suitable for high performance engines

- Enormous strength to combatimmense pressures and forces.
- Less mass to reduce inertial forces.
- Form an effective oil and gas seal.
- Provide a sufficient load bearing area to prevent wear.
- Disperse heat quickly to the surroundings.
- High speed reciprocation with minimal noise.
- Rigid construction to prevent any distortions.

III. DESIGN FORMULAS

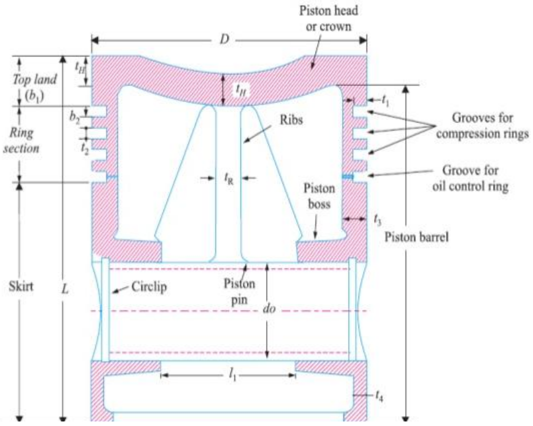

Fig 1: Parts of the Piston

A. *Piston Head*

Thickness of the piston: $t_H = \sqrt{\frac{3p.D^2}{16\sigma_t}}$

σ_t = Tensile strength of material of piston
D = Diameter of piston
p = Maximum gas pressure

Thickness for optimum heat dissipation:

$$t_H = \frac{H}{12.56k(T_C - T_E)}$$

H = Heat flowing through piston
k = Thermal conductivity
T_C = Temperature at center
T_E = Temperature at edge

Heat flowing through the piston:
$H = C \times HCV \times m \times B.P.$
C = Constant (0.05)
HCV = Higher Calorific Value of the Fuel
m = Mass of fuel used
$B.P.$ = Brake Power of engine per cycle

Thickness of the ribs: ${}^{t_H}/_3 \leq t_R \leq {}^{t_H}/_2$

Ribs are only provided if thickness of the head is greater than 6mm

B. *Piston Rings*

The piston rings are expandable split rings used to seal the gap between the piston and the cylinder. They are mainly categorized as:

- Compression Rings or Pressure Rings
- Oil Control Rings or Oil Scrapers

Radial thickness: $t_1 = D\sqrt{\frac{3p_w}{\sigma_t}}$
D = Cylinder bore in mm
p_w = Pressure of gas on Cylinder wall
Axial thickness: $0.7t_1 \leq t_2 \leq t_1$
Minimum Axial thickness: $t_2 = \frac{D}{10n_R}$
n_R = Number of Rings
Width of Top Land: $t_H \leq b_1 \leq 1.2t_H$
Width of Ring Lands: $0.75t_2 \leq b_2 \leq t_2$
Gap between rings and cylinder:
$0.002D$ to $0.004D$

C. Piston Barrel

Maximum thickness of piston barrel:
$t_3 = 0.03D + t_1 + 5\ mm$
Piston wall thickness: $0.25t_3 \leq t_4 \leq 0.35t_3$

D. Piston Skirt

The length of piston skirt should be selected in such a way that the side thrust pressure should not exceed $0.28N/mm^2$ for slow speeds and $0.5N/mm^2$ for high speeds

Side thrust force is given by: $P_s = p \times \frac{\pi D^2}{4}$
P_s = Max Gas load on piston skirt
p = Max Gas pressure
Length of skirt in actual practice: $0.65D \leq l \leq 0.8D$

E. Wrist Pin or Gudgeon Pin

Length between supports: $l_1 = 0.45D$
Total length of wrist pin: $l_2 = \frac{l_1 + D}{2}$
Max Bending moment at the center of the pin:

$$M = \frac{P}{2} \times \frac{l_2}{2} - \frac{P}{2} \times \frac{l_1}{4}$$

$$M = \frac{P \cdot D}{8}$$

Section modulus: $Z = \frac{\pi}{32}\left[\frac{{d_o}^4 - {d_i}^4}{d_o}\right]$
Max Bending moment: $M = Z \times \sigma_b$
σ_b = Allowable bending stress for piston pin

IV. MATERIAL SELECTION

Traditionally cast iron was used as piston material, but in the new engines which are being used nowadays develop higher power and are aimed to reduce emissions as well as to increase the engine's fuel efficiency, they are typically made of forged alloys of Aluminum and Silicon. Aluminum reduces weight and makes it compact in size, while Silicon diminishes the friction and increases its strength at higher temperatures.

Based on their Mechanical properties Aluminum 2618 and Aluminum 4032 have been selected. The varying Silicon content in these alloys determine the overall durability and toughness versus wear resistance characteristics of the piston. Silicon also checks the rate of expansion of the piston as the material becomes hotter as well as the material hardness. It enhances the machinability of the piston during the manufacturing phase.

A. Manufacturing Processes

Majority of the pistons employed in the engines nowadays are manufactured through gravity-die casting. In this process liquefied Aluminum-Silicon Alloy is poured in a constructed mold. In contrast to casting, forging takes a block of partly molten alloy and is stamped into the configuration of a piston using a die. Forged pistons divergesradically in production and inherent character.

Casting and forging result in diverse type of pistons. A forged piston must be devised in a way such that it can be easily extracted, hence the forged blank has a comparablyuncomplicated shape. Casting can attain a more complex blank and thus facilitates a more lightweight product.

B. Material Properties

In the Aluminum-Silicon system, eutectic point is reached at 12.5% Silicon. Aluminum 2618, containing 0.18% silicon and 2.3% copper is considered as hypoeutectic alloy. The low quantity of silicon causes increase in tensile strength due to which the piston can handle higher detonation forces. The copper and magnesium content increases the toughness of the alloy. Thus, 2618 is ideal for forced-induction engines, as their ability to resist pre-ignition is critically important under high boost. But it demands larger piston-to-wall clearance because of higher coefficient of thermal expansion, which results in growth of the piston up to 15% extra as compared to Aluminum 4032 alloy when exposed to heat.

On the other hand, Aluminum 4032 alloy contains 12.2% silicon which places it close to the Eutectic line on the phase diagram. The high quantity of silicon results in lower thermal expansion at elevated temperatures. Due to this the piston requires lesser piston-to-wall clearances and this results in lower noise, piston slap, compression loss. The density of this alloy is also lower which makes the piston lighter. The silicon content also improves the wear resistant properties of the piston and makes it ideal for daily usage in street cars with lower power and working temperatures. Only drawback of this material is that it has lower strength at higher temperatures.

TABLE I
VARIATION OF STRENGTH WITH TEMPERATURE

	297 K			422 K		477.6 K	
Material	UTS	YS	E (%)	UTS	YS	UTS	YS
Aluminum 2618	441.216	372.276	10	344.7	303.336	220.608	179.244

Aluminum 4032	379.17	317.124	9	317.124	275.76	234.396	220.608

UTS - Ultimate Tensile Strength in MPa
YS - Yield Strength in MPa
E – Elongation in %

TABLE II
COMPARISON OF MATERIALS

	Pros	Cons
Aluminum 2618	• Better Fatigue life • More Strength at high temperatures • Better Conductivity (faster heat transfer) • Higher Tensile Strength	• Higher expansion rate (larger clearance needed) • Poor wear index (lesser silicon) • Piston rattle or slap (more piston-to-wall clearance)
Aluminum 4032	• HigherWear index (due to presence of more silicon) • Lower expansion rate (lower clearance needed) • Lower density (lighter weight)	• Limited temperature strength (lower strength at high temperatures) • Lower Notch sensitivity (brittle)

V. DESIGN DATA AND CALCULATIONS

The piston design being analyzed belongs to a Subaru EJ20 WRX series turbo charged engine. It is a 2.0 liter, 4 cylinder engine with double overhead camshafts. The only drawback of this boxer engine are the hypereutectic cast aluminum pistons. These pistons cannot handle shock loads subjected upon knocking or detonation. In this design the material being used is forged Aluminum 4032 which has considerably higher strength and wear index. The following specifications have been used to design the piston

TABLE III
ENGINE SPECIFICATIONS

Parameters	Value
Diameter of Piston	92 mm
Stroke length	75 mm
Compression Ratio	8.5 : 1
Number of cylinders	4
Capacity	2000 cc
Pressure of gas on Piston	16 psi – 110316 Pa
Higher Calorific Value of Petrol	48000 kJ/kg

TABLE IV
MATERIAL PROPERTIES - ALUMINUM 4032

Property	Value
Density	2680 kg m^-3
Young’s Modulus	79 GPa
Poisson’s Ratio	0.3
Bulk Modulus	65.8 GPa
Shear Modulus	30.3 GPa
Yield Strength	317 MPa
Ultimate Strength	379 MPa
Coefficient of Thermal Expansion	0.00194 c^-1

TABLE V
DIMENSIONS OF PISTON DESIGN

Dimension	Value
Thickness of Piston Head	9 mm
Radial thickness of Compression Ring	1.2 mm
Radial thickness of Oil Ring	2.8 mm
Width of Top Land	10.8 mm
Width of Ring Lands	2.8 mm
Thickness of Piston Barrel	13 mm
Thickness of Piston Wall	4.5 mm
Length of Skirt	73.6 mm
Diameter of Wrist Pin	20 mm
Length between supports	41.5 mm

VI. MODELLING AND ANALYSIS

A 3D CAD model has been designed using the given parameters and calculations performed, on CATIA V5R19 and Stress Analysis has been done on ANSYS Static Structural 15.0

CATIA is an interactive application for modelling 3-dimensional parts. The sketcher tool was used to form a 2-dimensional view of the piston and was created into a solid 3-dimensional model by padding and revolving. Holes were created at the sides to accommodate the wrist pin by creating pockets.

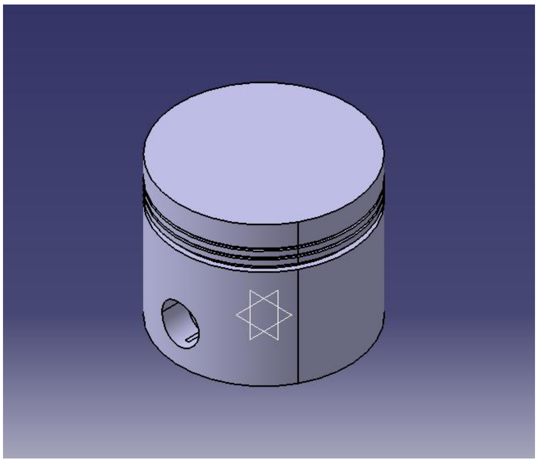

Fig 2: 3D CAD Model

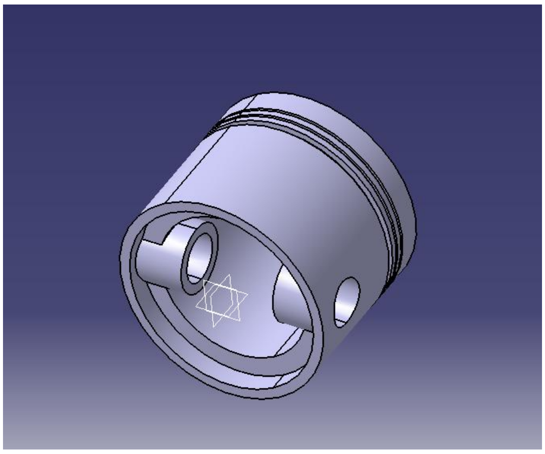

Fig 3: Internal View of 3D CAD Model

ANSYS is a finite element analysis package that can be used for problem solution as well as optimization. The forces on each element of the Piston generated through meshing is simulated by Ansys. By performing the calculation multiple times on each node and generate an accurate result of stresses and deformation and gauge the product's performance. The design can be optimized and tweaked based on the results obtained.

VII. BOUNDARY CONDITIONS

A gas pressure of 200 psi or 1378951.46 Pa has been applied on the top surface of the piston. The force is maximum during detonation. This pushes the piston downwards which in turn causes the rotation of the crankshaft via the connecting rod. The piston is attached to the connecting rod by a wrist pin or gudegeon pin. Thus, the fixed support on the piston is applied on the area which connects to the wrist pin.

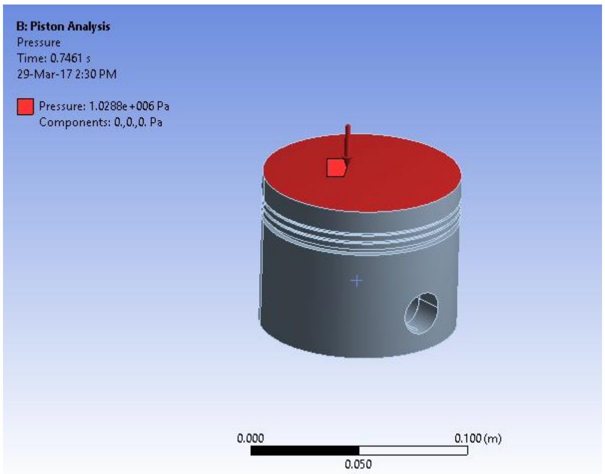

Fig 4: Application of Forces and Fixed Supports

Meshing is an integral part of the computer-aided engineering (CAE) simulation process. The mesh influences the accuracy, convergence and speed of the solution. The piston has been meshed using automated meshing and forms a tetrahedral mesh with high smoothening and a maximum cell size of 4.363e-003m for high accuracy of solution. The total number of nodes generated are 1380528 and elements formed are 974163.

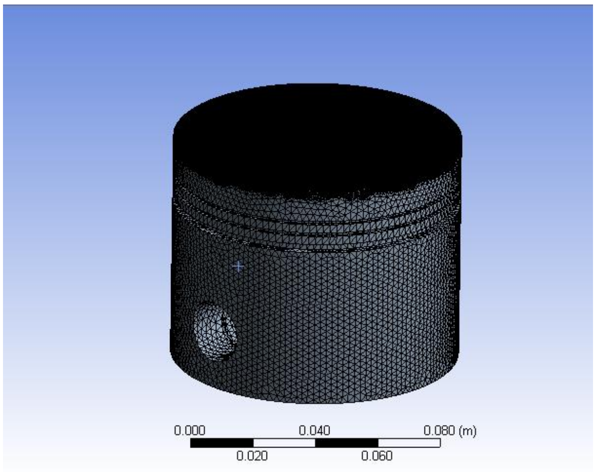

Fig 5: Meshed model for Finite Element Analysis

VIII. RESULTS

The piston ungergoes maximum deformation due to the pressure at the center of the top surface. But the deformation observed is only 1.5786e-005 m, which is practically negligible. If the deformation was more pronounced, ribs would be added for reinforcement of the structure.

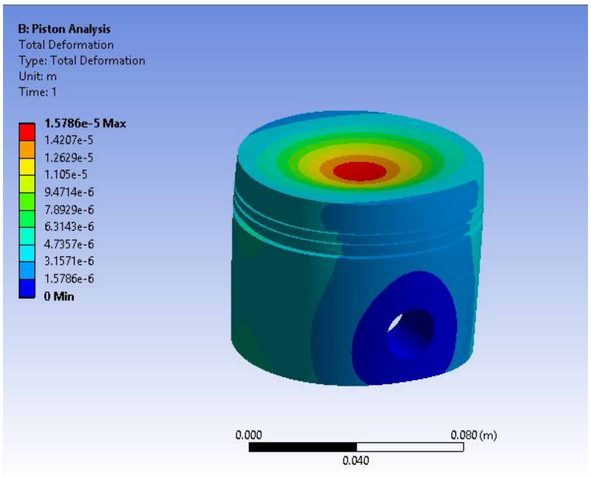

Fig 6: Deformation model

Unlike the deformation model, the regions of high stress concentration is above the support region which comes in contact with the wrist pin. The maximum stress reaches 1.9815e+007 Pa i.e. 19.81 Mpa which lies well below the yield strength of the piston and hence does not need further reinforcement.

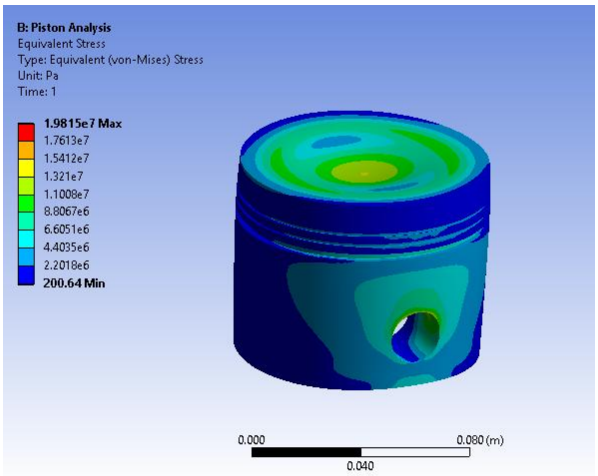

Fig 7: Von-Mises Stress model

IX. CONCLUSION

Simulating maximum load conditions of 200psi pressure on the designed piston yielded the following results:

TABLE VI
INFERENCE

Maximum Deformation	1.5786e-005 m
Maximum Equivalent stress (Von-mises)	1.9815e+007 Pa

From the results of the finite element analysis we can infer that Aluminum alloy 4032 is a suitable material for manufacturing forged piston for the given engine specifications under the intended operation conditions.

For higher loads and more rigorous loading conditions such as track focused cars, Aluminum alloy 2618 would be the preferred material but owing to the high wear index the piston may need to be inspected frequently and replaced if required.

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