Design and Analysis of Piston using Different Materials

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Abstract - *This paper describes the comparative study of pistons made of three different materials by using Finite Element Method (FEM) and attempts to figure out whether the material used in the piston of supercars can be used in a motorbike or not. The parameters used for the simulation are operating gas pressure, temperature and material properties of piston. The specifications used for the study of these pistons belong to four stroke single cylinder engine of Bajaj Pulsar 220 cc. This project illustrates the procedure for analytical design of two aluminum alloy and one titanium alloy piston. The dimensions are obtained and a 3-D CAD model on CREO 3.0 is prepared. Static structural and thermal stress analyses are performed by using ANSYS 16.0. The results predict the maximum stress and critical region on the pistons using FEA. The best material is then selected on basis of these results and a comparison is made with the titanium alloy to find out whether the titanium alloy is suitable for motorbikes or not.*

***Key Words*: Alloys, Pistons, A2618, Al-GHS 1300, Ti-6Al-4V, Stress, Deformation, Analysis**

1. INTRODUCTION

1.1 Background of Piston

Engine pistons are one of the most complex and important part of an engine. The function of the piston is bearing the gas pressure and making the crankshaft rotation through the piston pin. Piston works in high temperature, high pressure, high speed and poor lubrication conditions. Piston endures the cyclic gas pressure and the inertial forces at work, and this working condition may cause the fatigue damage of piston, such as piston side wear, piston head cracks and so on.

Piston in an IC engine must possess the following characteristics:

- Strength to resist gas pressure
- Must have minimum weight
- Must be able to reciprocate with minimum noise
- Must have sufficient bearing area to prevent wear
- Must seal the gas from top and oil from the bottom
- Must disperse the heat generated during combustion
- Must have good resistance to distortion under heavy forces and heavy temperature.

1.2 Design and Analysis

The main requirement of piston design is to predict the temperature distribution on the surface of piston which enables us to optimize the thermal aspects for design of piston. Most of the motorbike pistons are made of an aluminium alloy which has thermal expansion coefficient 80% higher than the cylinder bore material (cast iron). Also, to improve mechanical efficiency and reduce inertia force in high-speed machines, the weight of the piston also plays a major role.

Finite Element Analysis

Finite element analysis (FEA) is a computerized method for predicting how a product reacts to real-world forces, vibration, heat, fluid flow and other physical effects. The Finite Element Analysis (FEA) is the simulation of any given physical phenomenon using the numerical technique called Finite Element Method (FEM). It is used to reduce the number of physical prototypes and experiments and optimize components in their design phase to develop better products, faster.

Finite element analysis shows whether a product will break, wear out or work the way it was designed. In the product development process, it is used to predict what's going to happen when the product is used. FEA works by breaking down a real object into a large number (thousands to hundreds of thousands) of finite elements.

FEA helps predict the behaviour of products affected by many physical effects, including stress, vibration, fatigue, motion, heat transfer, fluid flow, etc.

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 few decades and required thorough examination of the smallest details.

2. PROBLEM DEFINITION

Titanium alloys are used in the pistons of supercars. The operating pressure and temperatures are very high in such cars and if this material can sustain and work in such conditions then it can also be used in motorbikes where the operating pressure and temperatures are comparatively very low.

The objective of the present work is to design and analyze piston made of A2618, Al-GHS 1300 and Ti-6Al-4V alloys, compare the analysis results, find the best material amongst them and figure out whether the titanium alloy is a suitable option.

3. METHODOLOGY

- Analytical design of pistons based on design formulae and empirical relations.
- 3-D piston models are created in CREO 3.0.
- Meshing and analysis of piston is done in ANSYS Workbench 16.0.
- Various stresses are determined by individually performing structural analysis, thermal analysis and thermo-mechanical analysis.
- Various zones or regions where chances of damage in piston are possible are analyzed.
- Comparison is made between the three materials in terms of stresses, deformation, strain, volume, weight, inertia force and factor of safety.

3.1 Design of Piston

Engine: Bajaj Pulsar 220 cc petrol engine.

Table-1: Engine Specifications

PARAMETERS	VALUES
Engine type	Four stroke, petrol engine
Induction	Air cooled type
No. of cylinders	Single cylinder
Bore (D)	67 mm
Stroke (L)	62.4 mm
Length of connecting rod	124.8 mm
Displacement volume	220 cm^3
Compression ratio	9.5+/-0.5:1
Maximum power	15.51 kW at 8500 rpm
Maximum torque (T)	19.12 N-m at 7000 rpm (N)
No. of revolutions/cycle	2

Mechanical efficiency of the engine (η) = 80 %.

η = Brake power (B.P.)/Indicating power (I.P.)
B.P. = 2πNT/60 = 2π*7000*19.12/(60*1000) = 14.015 kW

Therefore, I.P. = B.P./η = 14.015/0.8 = 17.518 kW

Also, I.P. = P*A*L*N/2 = P*π/4*D^2*L*N/2
17.518*1000 = P*π/4*(0.067)^2*(0.0624)*(7000)/(2*60)

So, P = 13.65*105 N/m^2 or P = 1.365 MPa

Maximum Pressure (p_{max}) = 10*P = 10*1.365 = 13.65 MPa

3.2 Analytical Design Calculations

For A2618 alloy

Thickness of the Piston Head
According to Grashoff's formula the thickness of the piston head is given by:

$$t_h = D\sqrt{(3p_{max}/16\sigma_t)}$$

where $\sigma_t = \sigma_{ut}/2.5 = 480/2.5 = 192$ MPa
and D = cylinder bore diameter

Therefore $t_h = 67*\sqrt{((3*13.65)/(16*192))} = 7.735$ mm
Empirical formula: $t_h = 0.032\ D + 1.5 = 3.644$ mm

The maximum thickness from the above formula (t_h) is 7.735 mm.

Piston Rings
The radial width of the ring is given by:

$$b = D\sqrt{(3*p_w/\sigma_p)} = 67*\sqrt{(3*0.025/100)} = 1.834 \text{ mm}$$

Axial thickness of the piston ring is given by:

$$h = (0.7\ b \text{ to } b) = 0.7*1.834 = 1.284 \text{ mm}$$

Width of Top Land and Ring Lands
Width of top land: $h_1 = (t_h \text{ to } 1.2\ t_h) = 7.735$ mm

Width of ring land: $h_2 = (0.75\ h \text{ to } h) = 0.75*1.284 = 0.963$ mm

Piston Barrel
Thickness of piston barrel at the top end:

$$t_1 = 0.03\ D + b + 4.9$$

Therefore $t_1 = 0.03*67 + 1.834 + 4.9 = 8.744$ mm

Thickness of piston barrel at the open end:

$$t_2 = (0.25\ t_1 \text{ to } 0.35\ t_1)$$

Therefore $t_2 = 0.25*8.744 = 2.186$ mm

Length of the skirt
$L_s = (0.6\ D \text{ to } 0.8\ D) = 0.6*67 = 40.2$ mm

Length of piston pin in the connecting rod bushing
L_1 = 45% of the piston diameter = 0.45*67 = 30.15 mm

Piston pin diameter
$d_o = (0.28\ D \text{ to } 0.38\ D) = 0.3*67 = 20.1$ mm

The center of piston pin should be 0.02 D to 0.04 D above center of the skirt = 0.03*67 = 2.01 mm above skirt center.

Similarly, analytical design for Al-GHS 1300 and Ti-6Al-4V alloy is also carried out and the dimensions of the three pistons are presented in the table below:

Table-2: Dimensions of Pistons

PARAMETERS	VALUES (mm)		
	A2618	Al-GHS 1300	Ti-6Al-4V
Thickness of piston head (t_h)	7.735	4.7	5.498
Piston rings radial width (b)	1.834	1.834	1.834
Axial thickness (h)	1.284	1.284	1.284
Width of top land (h_1)	7.735	4.7	5.498
Ring lands (h_2)	0.963	0.963	0.963
Thickness of piston barrel at top end (t_1)	8.744	8.744	8.744
Thickness of piston barrel at open end (t_2)	2.186	2.186	2.186
Length of skirt (L_S)	40.2	40.2	40.2
Length of piston pin in connecting rod bushing (L_1)	30.15	30.15	30.15
Piston pin diameter (d_o)	20.1	20.1	20.1
Piston boss diameter (1.5 d_o)	30.15	30.15	30.15

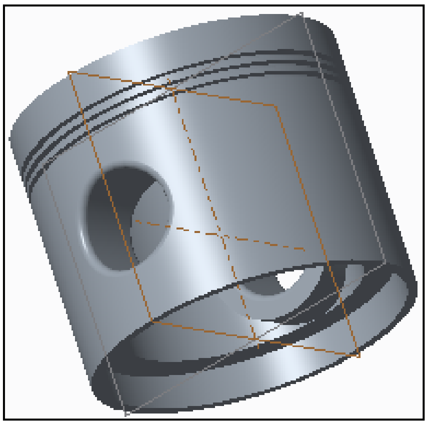


Fig-1: 3-D CAD Model of Piston

3.3 Analysis of Piston

3.3.1 Material Assignment

For analysis of piston, the 3-D CAD model prepared in CREO 3.0 is converted in to IGES format so that it can be imported in ANSYS 16.0. After importing the model in ANSYS, material properties are assigned in Engineering data.

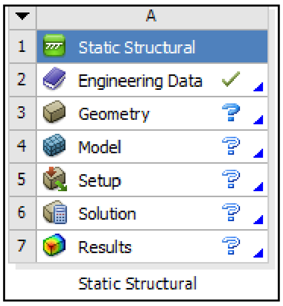


Fig-2: Static Structural Standalone System

Material properties of the three materials are mentioned in the table below:

Table-3: Material Properties

PARAMETERS	VALUES		
	A2618	Al-GHS 1300	Ti-6Al-4V
Elastic modulus (GPa)	73.7	98	113.8
Ultimate tensile strength (MPa)	480	1300	950
0.2% Yield strength (MPa)	420	1220	880
Poisson's ratio	0.33	0.3	0.33
Thermal conductivity (W/(m-C))	147	120	7.3
Coefficient of thermal expansion (1/K)	25.9 * 10^-6	18 * 10^-6	8.6 * 10^-6
Density (kg/m^3)	2767.9	2780	4430

3.3.2 Meshing of Piston Model

After assigning material properties, model is opened in mechanical. The whole body of the piston model is selected and meshing is performed. Tetrahedral elements are used and the element size is 2 mm.

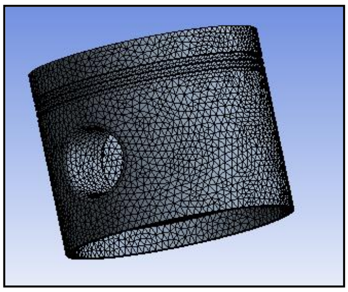


Fig-3: Meshing of Piston 3-D Model

3.3.3 Static Structural Analysis

In static structural analysis, boundary conditions like pressure and supports are applied. (refer Table 4)

- Pressure at the head of piston: 13.65 MPa
- Frictionless support is applied at piston pin hole as pin can freely rotate inside hole.
- Fixed supports are applied at edges of piston pin hole.

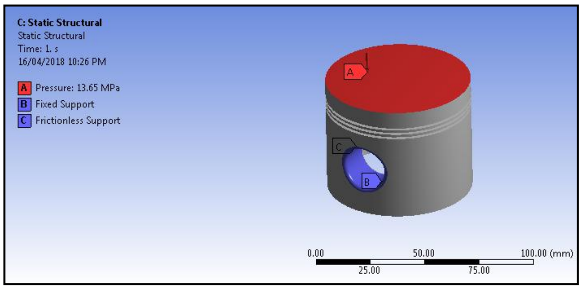
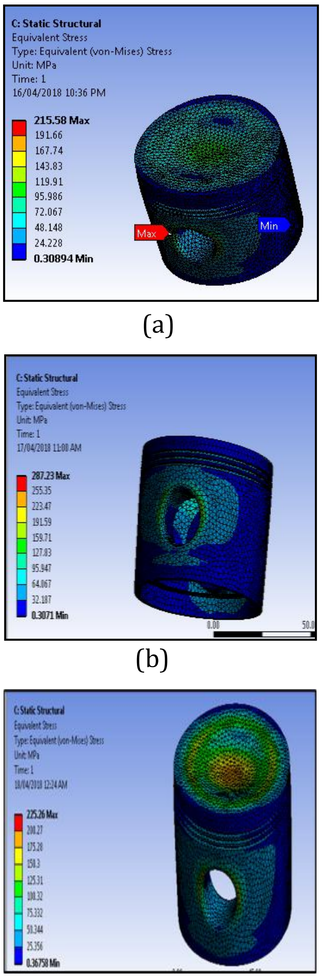


Fig-4: Applying Boundary Conditions



(a)

(b)

(c)

Fig-5: Equivalent Stresses (a) A2618 (b) Al-GHS 1300 (c) Ti-6Al-4V

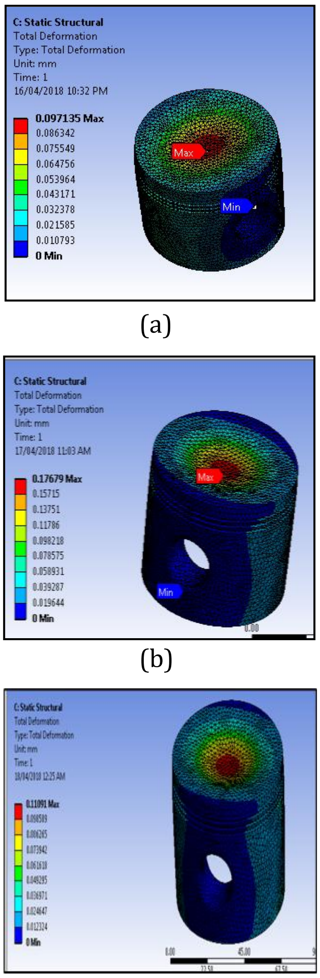


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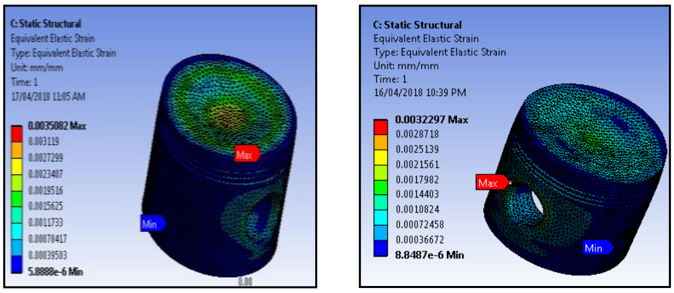
Fig-6: Total Deformation (a) A2618 (b) Al-GHS 1300 (c) Ti-6Al-4V



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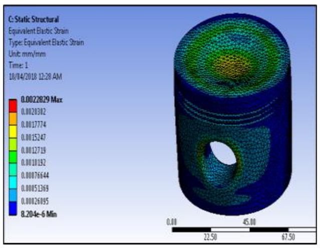


(c)

Fig-7: Equivalent Elastic Strain (a) A2618 (b) Al-GHS 1300 (c) Ti-6Al-4V

3.3.4 Steady State Thermal Analysis

In steady state thermal analysis, boundary conditions like temperature and convection are applied. (refer Table 5)

- Temperature at head of piston: 200°C
- Temperature at edges of piston: 125°C
- Film coefficients are applied to different regions of piston.

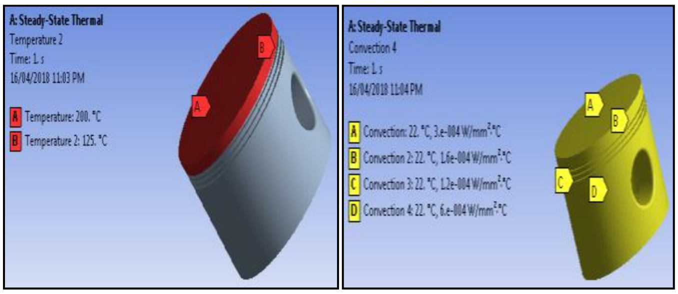
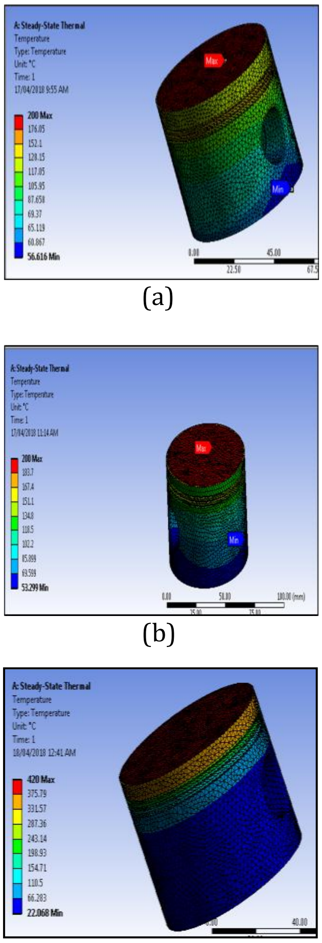


Fig-8: Applying Temperature and Convection Boundary Conditions



(a)

(b)

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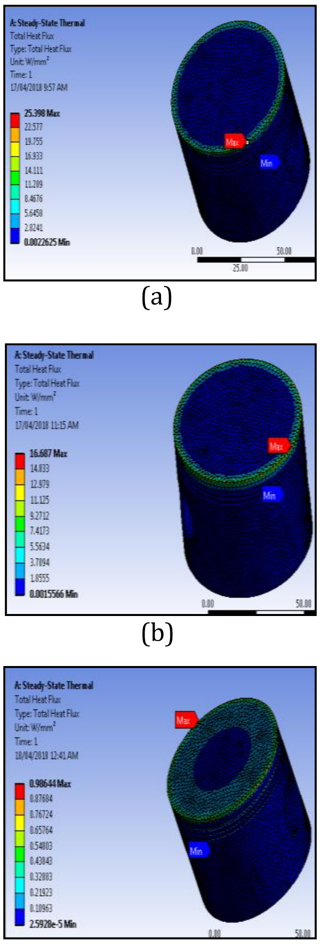
Fig-9: Temperature Distribution (a) A2618 (b) Al-GHS 1300 (c) Ti-6Al-4V



(a)

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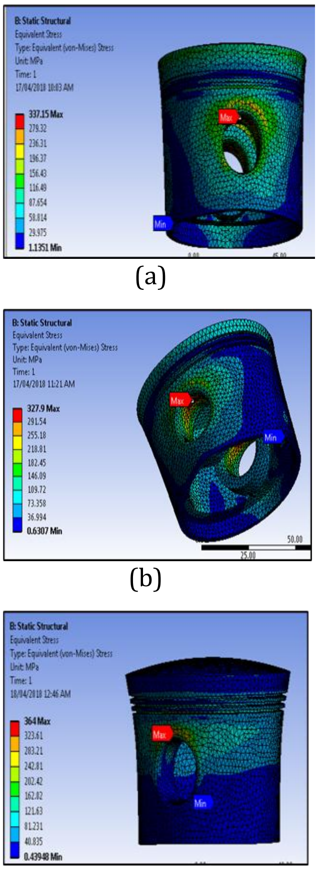
Fig-10: Total Heat Flux (a) A2618 (b) Al-GHS 1300 (c) Ti-6Al-4V



(a)

(b)

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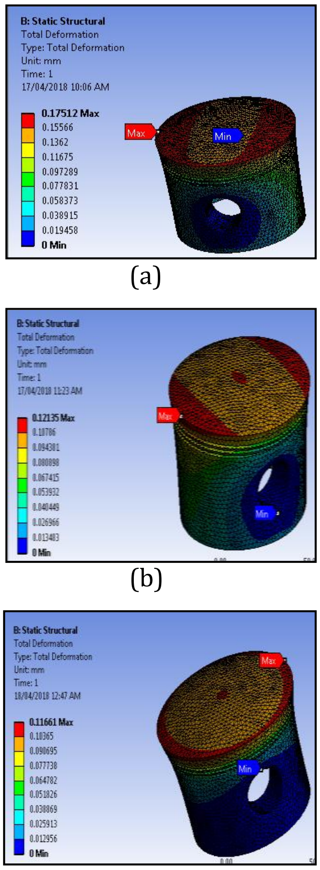
Fig-11: Equivalent Stresses (a) A2618 (b) Al-GHS 1300 (c) Ti-6Al-4V



(a)

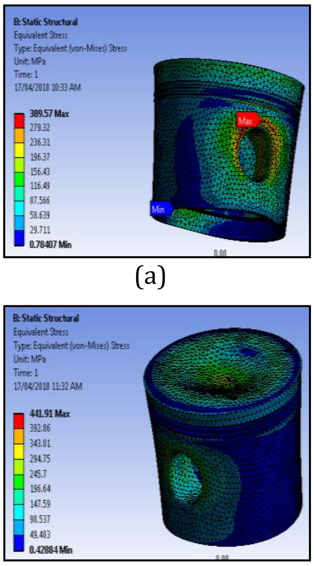
(b)

(c)

Fig-12: Total Deformation (a) A2618 (b) Al-GHS 1300 (c) Ti-6Al-4V

3.3.5 Combined Thermo-Mechanical Analysis

Here, both pressure and thermal loads are applied. (Table 6)



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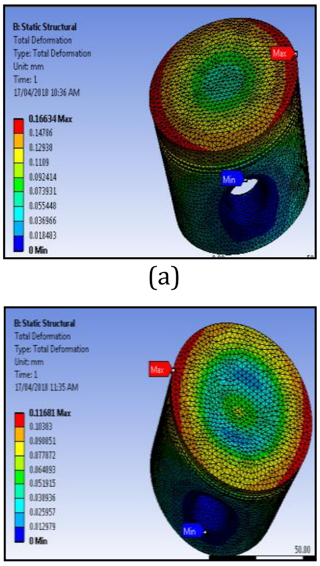

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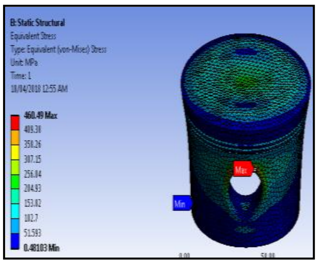

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Fig-13: Equivalent Stresses (a) A2618 (b) Al-GHS 1300 (c) Ti-6Al-4V

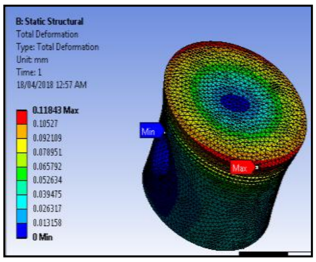

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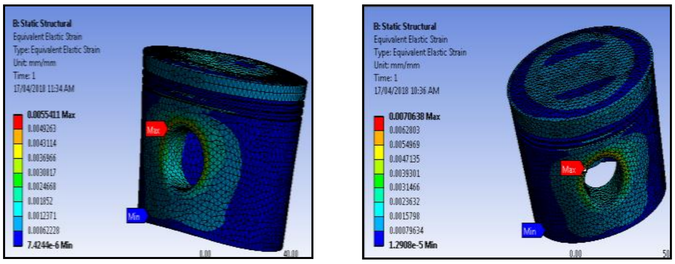
Fig-14: Total Deformation (a) A2618 (b) Al-GHS 1300 (c) Ti-6Al-4V



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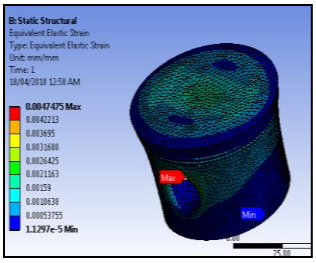

(c)

Fig-15: Equivalent Elastic Strain (a) A2618 (b) Al-GHS 1300 (c) Ti-6Al-4V

4. RESULTS

4.1 Static Structural Analysis

Table-4: Static Structural Analysis Results

PARAMETERS	**VALUES**		
	A2618	**Al-GHS 1300**	**Ti-6Al-4V**
Equivalent stress (MPa)	215.5	287.23	225.26
Total deformation (mm)	0.097135	0.17679	0.11091
Equivalent elastic strain (mm/mm)	0.0032297	0.0035002	0.0022829

4.2 Steady State Thermal Analysis

Table-5: Steady State Thermal Analysis Results

PARAMETERS	VALUES		
	A2618	Al-GHS 1300	Ti-6Al-4V
Equivalent stress (MPa)	337.15	327.9	364
Total deformation (mm)	0.17512	0.12135	0.11661
Heat flux (W/mm^2)	25.390	16.687	0.98644

4.3 Combined Thermo-Mechanical Analysis

Table-6: Combined Thermo-Mechanical Analysis Results

PARAMETERS	VALUES		
	A2618	Al-GHS 1300	Ti-6Al-4V
Equivalent stress (MPa)	389.57	441.91	460.49
Total deformation (mm)	0.16634	0.11681	0.11843
Equivalent elastic strain (mm/mm)	0.0070638	0.0055411	0.0047475
Heat flux (W/mm^2)	25.390	16.607	0.98644
Volume (mm^3)	91757	81059	83871
Mass (kg)	0.25398	0.22534	0.37155
Factor of Safety (F.O.S.)	1.23	2.94	2.06

As it can be seen from the tables above:

- The maximum stress occurs in Ti-6Al-4V alloy (460.49 MPa) while minimum is in A2618 alloy (389.57 MPa).
- The maximum total deformation is in A2618 alloy (0.16634 mm) and minimum in Al-GHS 1300 alloy (0.11681 mm).
- Mass is least in Al-GHS 1300 alloy (0.22534 kg) and maximum in Ti-6Al-4V alloy (0.37155 kg).
- The Factor of Safety (F.O.S.), which is ratio of ultimate tensile strength and maximum stress generated ($\sigma_{uts}/\sigma_{max}$), is maximum for Al-GHS 1300 alloy (2.94) and minimum for A2618 alloy (1.23).

5. CONCLUSIONS

The titanium alloy Ti-6Al-4V is widely used in pistons of supercars and this led us to the assumption that if it is used in such high-performance cars, then it's possible that it can also be used in motorbikes. The material properties of titanium alloy were also suggesting the same but our analysis clearly demonstrates that it isn't a feasible option. From our analysis results, it is concluded that Al-GHS 1300 aluminum alloy is the best material for piston of Bajaj Pulsar 220cc amongst the three. This is due to the following reasons:

- Its Factor of Safety (F.O.S.) is maximum amongst the three materials.
- Total deformation of Al-GHS 1300 alloy is least.
- Mass of Al-GHS 1300 alloy is also least.

This result is because of the design of the piston of Bajaj Pulsar 220cc. The piston design of supercars is significantly different from the piston design of motorbikes. To make titanium alloy a feasible option, we need to make a lot of changes in the design of piston which will result in a change in the overall design of the engine which is beyond the scope of this work.

Still, there's a lot that can be done. The same can be done for other motorbikes/vehicles too. Other analyses apart from thermal and structural can also be performed for these materials. Also, these materials can be compared on the basis of cost like cost of manufacturing, cost of machining, etc.

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