KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING AND DESIGN

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INVESTIGATION OF CERAMIC PISTON FOR INTERNAL COMBUSTION RECIPROCATING ENGINE

Final project for Master degree

Supervisor
Prof. Dr. Vytautas Grigas

KAUNAS, 2015

KAUNAS UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Approved:
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Final project for Master degree
Master of Science (621H30001)

Supervisor
Prof. Dr. Vytautas Grigas

Reviewer
Prof. Artūras Keršys

Project made by
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KAUNAS, 2015

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The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

Investigation of Ceramic Piston for Internal Combustion Reciprocating Engine

Approved by the Dean 2015 y. May m.11d. Order No. ST17-F-11-2

2. Aim of the project

To investigate the behavior of I.C. engine piston made of ceramic composites viz., zirconia and silicon nitride and to compare the results of the analysis between one another and with the conventional piston.

3. Structure of the project

The type of study carried out is static coupled field analysis. As per this study type, thermal analysis was carried out and the results are the inputs for the static structural analysis. In this study, structural analysis was done in two categories: viz. 1. with combustion gas pressure and 2. without combustion gas pressure. Results are plotted and discussed for conclusion.

4. Requirements and conditions

1. Two ceramic materials viz. Zirconia and Silicon nitride are considered.
2. Temperature (heat source), convective heat transfer coefficients and combustion gas pressure

5. This task assignment is an integral part of the final project

6. Project submission deadline: 2015 June 1st.

Given to the student Maheshwaran Chockalingam

Task Assignment received Maheshwaran Chockalingam
(*Name, Surname of the Student*) (*Signature, date*)

Supervisor Prof. Dr. Vytautas Grigas
(*Position, Name, Surname*) (*Signature, date*)

KAUNAS UNIVERSITY OF TECHNOLOGY

Faculty of Mechanical Engineering and Design
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Mechanical Engineering 621H30001
(Title and code of study programme)

"Investigation of Ceramic Piston for Internal Combustion reciprocating engine" of final project
DECLARATION OF ACADEMIC HONESTY

12 June 2015
Kaunas

I confirm that a final project by me, **Maheshwaran Chockalingam**, on the subject "Investigation of Ceramic Piston for Internal Combustion reciprocating engine " is written completely by myself; all provided data and research results are correct and obtained honestly. None of the parts of this thesis have been plagiarized from any printed or Internet sources, all direct and indirect quotations from other resources are indicated in literature references. No monetary amounts not provided for by law have been paid to anyone for this thesis.

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SUMMARY

This thesis work investigates the replacement of aluminum alloy piston in an internal combustion engine with ceramic composite materials. The main criterion of the project work is to find the right choice of ceramic composite among the available composition viz., Silicon Nitride; Zirconia and alumina composite. The anticipated analysis predicts thermal stability and structural stability at real time scenarios as boundary conditions. The study also deals with the discussion of results between ceramic composite. The piston was modeled with the help of design data formulae. The model will be created in compatible CAD software and analysis will be carried out in Ansys package. The analysis performed is static coupled field. That means non-linear thermal and structural analysis, which is performed by applying approximately real time temperature and pressure parameters on the piston. The temperature and stress distribution plots on the piston are studied and discussed. And the conclusion will be drawn by comparing the results. The upcoming discussion will throw light on necessity of this project, followed by objective and goal.

Keywords: Internal Combustion engine, Piston, Ceramic composites, Aluminium Al 413.0, Thermal analysis, Structural analysis, Non-linear analysis, Catia V5, Ansys Workbench, Solidworks.

SANTRAUKA

Darbe nagrinėjamos vidaus degimo variklio stūmoklių, paprastai gaminamų iš aliuminio lydinio, pakeitimo stūmokliais iš kompozicinės keraminės medžiagos galimybės. Atliekant stūmoklio skaičiuojamąją analizę siekiama nustatyti labiausiai tinamą stūmokliui keraminę kompozitinę medžiagą. Tam nustatomas ir lyginamas tarpusavyje iš skirtingų medžiagų pagaminto stūmoklio įtempių-deformacijų būvis: silicio nitrido, cirkonio dioksido ir aliuminio kompozito. Tyrimui atlikti sudarytas tipinio vidaus degimo variklio erdvinis geometrinis modelis, kurio pagrindu baigtinių elementų analizės sistema ANSYS atlikti iš skirtingų medžiagų pagamintų stūmoklių įtempių-deformacijų būvio veikiant variklio darbo metu susidarančioms eksploatacinėms apkrovoms skaičiavimai. Atlikta statinė susietųjų uždavinių analizė analizė kartu sprendžiant netiesinį temperatūrinį ir struktūrinės analizės uždavinius nurodant stūmoklį veikiančių temperatūros ir slėgio apkrovas. Skaičiavimų rezultatų pagrindu suformuluotos išvados apie ištirtų keraminių kompozitinių medžiagų tinkamumą stūmokliams.

Raktiniai žodžiai: vidaus degimo variklio stūmoklis, keraminės kompozicinės medžiagos, temperatūrinė analizė, struktūrinė analizė, netiesinė analizė, įtempių-deformacijų būvis.

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INTRODUCTION

In the field of internal combustion engines (IC engines), so far the designers and manufacturers successfully commercialized IC engines made from metals. But as per the forecast, metals or ores from which they extracted from will become extinct in a century or so, whereas the demand for automobile and spares will be the same, while the recycling of the material may not cater the market's demand in terms of qualitative numbers. Also taking into account the commercial availability of various ranges of fuels that necessitates the flexibility in using all ranges of fuel effectively is up on the discussion within the automobile manufacturers.

Also, in the present scenario automobiles provide the better mode of transportation. But the combustion of fossil fuel in the automobile engine creates harmful effluents which has adverse effect on the environment that affects this very planet in terms of pollution. The principal pollutants emitted by automobiles are CO, NO_x, HC and particulates[7]. The modern day automobiles is a result of several technological improvements that have happened over a century and would continue the improvements to meet the performance demands of exhaust gas emissions, fuel consumption, power output, convenience and safety. In order to reduce emissions and increase engine performance, modern car engines carefully designed to control the amount of fuel the burn. Further to enhance reduction in emission and performance, engine piston made from low thermal conductivity material such as ceramics are considered [7].

So the focus for developing IC engines with alternative material which are available in surplus has been under discussion around the world. In this regards, based upon theoretical and practical studies done in various laboratories, ceramic materials like Zirconia, Silicon nitride and alumina have been considered as alternative material to make IC engine components. This thesis deals with the investigation of replacement of aluminum alloy piston with ceramic piston. The piston is designed in Catia V5. In this case, gudgeon pin or wrist pin with conventional structural steel is also considered for analyzing the expansion. So, an assembly of piston and wrist pin has been modeled.

The analysis is done in Ansys workbench 14.5 in the form of static coupled field by importing the assembly. In this analysis method, a steady state thermal and corresponding steady state structural analysis have been carried out, which means the analysis is purely non-linear considering convection at approximately real time temperature ranges. Conclusion has been drawn from the results and discussions are made.

OBJECTIVE

To investigate the behavior of I.C. engine piston made out of ceramic composites viz., zirconia and silicon nitride and to compare the results of the analysis between one another and with the conventional piston.

GOAL

To analyze stress distribution in the ceramic piston made out of different ceramic composites at nominal working condition of a diesel IC engine at pressure = 6.5 – 8 MPa at 350 – 360°C temperature which are the parameters at stoichiometric combustion, and to compare the results.

TASK

1. To collect and analyze data about the design of piston of a 4-Stroke internal combustion reciprocating engine, its operating conditions (loads, fixtures etc.) and materials used for manufacturing of such pistons.
2. To investigate the coupled field stress distribution, i.e., structural stress distribution due to thermal loading; and structural stress distribution due to both thermal loading and combustion gas pressure on conventional Al alloy piston and proposed ZrO_2, Si_3N_2 piston.
3. To compare the results of ZrO_2 and Si_3N_2 pistons with each other and to evaluate the possibility to use ceramic based piston in 4-stroke I.C. reciprocating engine.

1. PROPOSED CONCEPT

The concept can be well illustrated in fig (4.1), diasil cylinder will be used as engine cylinder which eliminates the use of bore or cylinder liner and also a smart cooling jacket can be designed which eliminates the use of heavy radiator and circulation pump. Since ceramic can withstand high temperature and dissipates less heat, conventional cooling is no more needed. This property of ceramics and elimination of conventional cooling system increases the combustion and thermal efficiency. Also it reduces total weight of the vehicle.

2. LITERATURE SURVEY

The concept about the ceramic engines is discussed[1]. The article briefly discusses about the various ceramic composites that can be used to manufacture engine components. So far there is no appreciable discussion around the world about the usage of ceramic piston material in reciprocating engine. Whereas the other components including engine cylinder, cylinder head are made of die cast aluminum silicon (Diasil) alloy; and valves, valve seats, cam followers, turbocharger rotors are

made of silicon nitride. Alternative ceramic composite for the considered ZrO_2 and Si3N4 with more or less similar properties are silicon carbide, aluminas and zirconia.
Zirconia does fulfill the requirements of piston's function and zirconia based coating used in aircraft jet engines to increase the turbine input temperature to improve the performance.

3. LITERATURE REVIEW

There are too many researches carried out by coating aircraft engine parts and automobile engine parts with ceramic materials in the name of Thermal barrier coating. Even students and professors in education institutions carried out extensive investigations on ceramic coatings on pistons. But there are no investigations out there on complete ceramic composite piston. So this thesis helps in investigating complete ceramic composite piston.
In 2007, NASA proposed project on carbon/carbon composite piston engines with ringless piston in Ref[2]. The proposal discusses about the predictive thermal efficiency in comparison to the conventional Al-alloy piston engines. And ref[3] discusses about research carried out in NASA's Glenn Research Center. The research was about the super thin silica coating on engine piston and cylinder wall; and other parts as well which are prone to high wear.
Vivek Zolekar under supervision of Dr.L.N.Wankhade carried out investigation to find out the temperature and stress distribution on the piston crown[4]. In this discussion, the analysis is carried out on the commercially manufactured aluminium alloy piston Al413.0 with thermal and mechanical boundary conditions. Further the analysis discusses about optimization which is out of this thesis discussion. The investigation draws conclusion by saying the stress distribution on the top surface and flexibility of CAD/CAE tools in analysis and optimization.
S. Srikanth Kumar, Dr. Sudheer Prem Kumar, Department of Mechanical Engineering, JNTU College of Engineering, Hyderabad have investigated on temperature distribution on conventional (uncoated) diesel piston and zirconium coated piston[5]. The investigates the thermal stress distribution on the piston at real time scenario during combustion process and describes mesh optimization by using finite element analysis technique. This work mainly stresses on the study of thermal behaviour of functionally graded coatings obtained by means of using a commercial code, ANSYS on aluminium and zirconium coated aluminium piston surfaces. The analysis is carried out to reduce the stress concentration on piston crown, skirt and sleeve. The conclusion drawn was piston skirt appears to be deforming the most while working, which usually causes crack on top part of the piston. Due to this deformation, stress concentration appears on the upper end of the piston. The thesis also emphasizes that to reduce this stress concentration the piston crown should have enough stiffness. Further the literature deals with the optimization of the design parameters which is out of this thesis context.

B. Praveena, Y.Suresh Kumar, Kalapal Prasad, Department of Mechanical Engineering, Nova College of Engineering and Technology, Jawaharlal Nehru technological University, Kakinada have investigated on four stroke single cylinder diesel engine piston using Ansys for static coupled field analysis Ref[6]. In this work, the distributions of stress and temperatures in the piston are found using finite element analysis package, ANSYS under two loading conditions i.e. only combustion pressure, and combination of thermal load and combustion pressure. Non-linear structural and thermal is performed by applying real time combustion temperature and pressure on the piston. The stress and temperature distributions on the piston are studied and the conclusions were drawn. From the analysis, the observation made was, in particular from the couple field analysis, the effect of gas temperature on the piston is significant along with loading. And the stresses obtained are very high indicating that, the material is in plastic state including experimental assumptions.

K. Sridhar, R. Reji Kumar, M. Narasimha, Lecturers, School of Mechanical and Industrial Engineering Bahirdar University, Bahirdar, investigated on Thermal barrier coatings for engines[7]. The paper discusses about, functionally graded coatings are used to increase performances of high temperature components in diesel engines. Thermal barrier coatings are being evaluated for better durability and lowering the heat rejection as well. The paper also emphasizes the use of a finite element model to analyze these thermal barrier coating systems. The numerical results of AlSi and steel pistons are compared with each other. It was shown that the maximum surface temperature of the functional graded coating AlSi alloy and steel pistons was increased by 28% and 17%, respectively. In this study, thermal behavior of functional graded coatings on Al-Si and steel piston materials was investigated by means of using a commercial code, namely Ansys. A comparative evaluation was made between ceramic coated and uncoated Al alloy piston. The maximum surface temperature of the ceramic coated piston is improved approximately 28% for Zirconia stabilised with magnesium oxide ($ZrMgO_3$) coating, 22% for Mullite coating ($3Al_2O_3$-$2SiO_2$) and 21% for Alumina (Al_2O_3) than the uncoated piston by means of ceramic coating.

S. Bhattacharya, A. Basu, S. Chowdhury, Y.S. Upadhyaya, Department of Mechanical Engineering, Manipal Institute of Technology, Manipal have done analysis of piston of two stroke engine[8]. In this analysis, Al alloy piston of two stroke S.I. engine considered. The piston made up of Aluminium 4032 alloy is designed by conventional approach and then both thermal and transient structural analysis have been carried out. The piston has been modeled in CATIA and analyzed using ANSYS Workbench. In order to improve the design of piston, two alternative designs have been considered by providing openings at the skirt region of the piston. The analysis showed that this modification improved the thermal performance of the piston. Conclusion has been drawn by comparing the results of preliminary design and two alternative designs. It is observed that by modifying the skirt region thermal performance of the piston could be improved without a major change in structural performance. Piston mass could be reduced. However between the two alternative designs, the one with large openings in the skirt region showed the best thermal performance.

4. METHODOLOGY

As per the proposed concept as shown in fig (4.1), the 3D model of the piston is created in CATIA V5R20 as shown in fig (4.1), neglecting the bore sleeve as discussed. Since all materials possess some value of expansion due to change in temperature. The created model of assembly is then imported to Ansys workbench 14.5. So, to make free expansion of the considered piston throughout, piston pin is also considered. Considering piston pin or wrist pin helped in constraining the piston easy.

The analysis process carried out as shown in fig (4.2). Fig (4.1) shows the basic nomenclature of a typical piston with exceptional that the considered piston for study have got reverse domed crown at thrust end. Since the considered piston has offset piston pin.

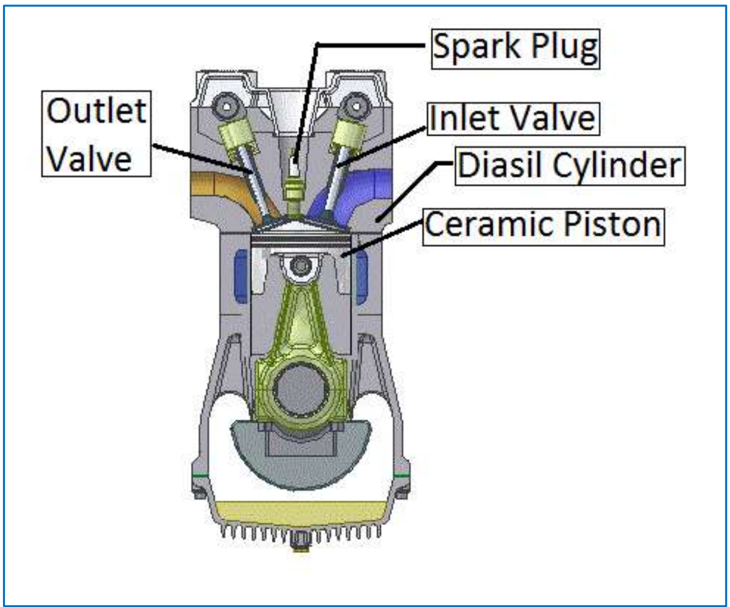


Fig 4.1: Sectional view of proposed

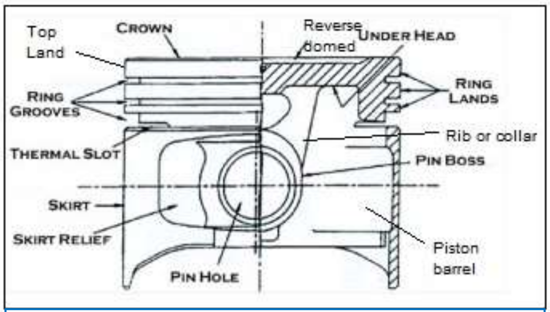


Fig 4.2: Piston nomenclature

To get start with the analysis, certain assumptions have to be made.

1. The engine chosen is four stroke diesel engine of 350cc with direct diesel injection, which could produce 17.25hp (considering a single cylinder of TATA Indica ev[9])
2. The cooling system is intact and working well with healthy coolant
3. Piston diameter(D) 69.86mm
4. Mean effective pressure of the combustion chamber is 8MPa (on piston crown)
5. Cylinder or cylinder sleeve is not considered

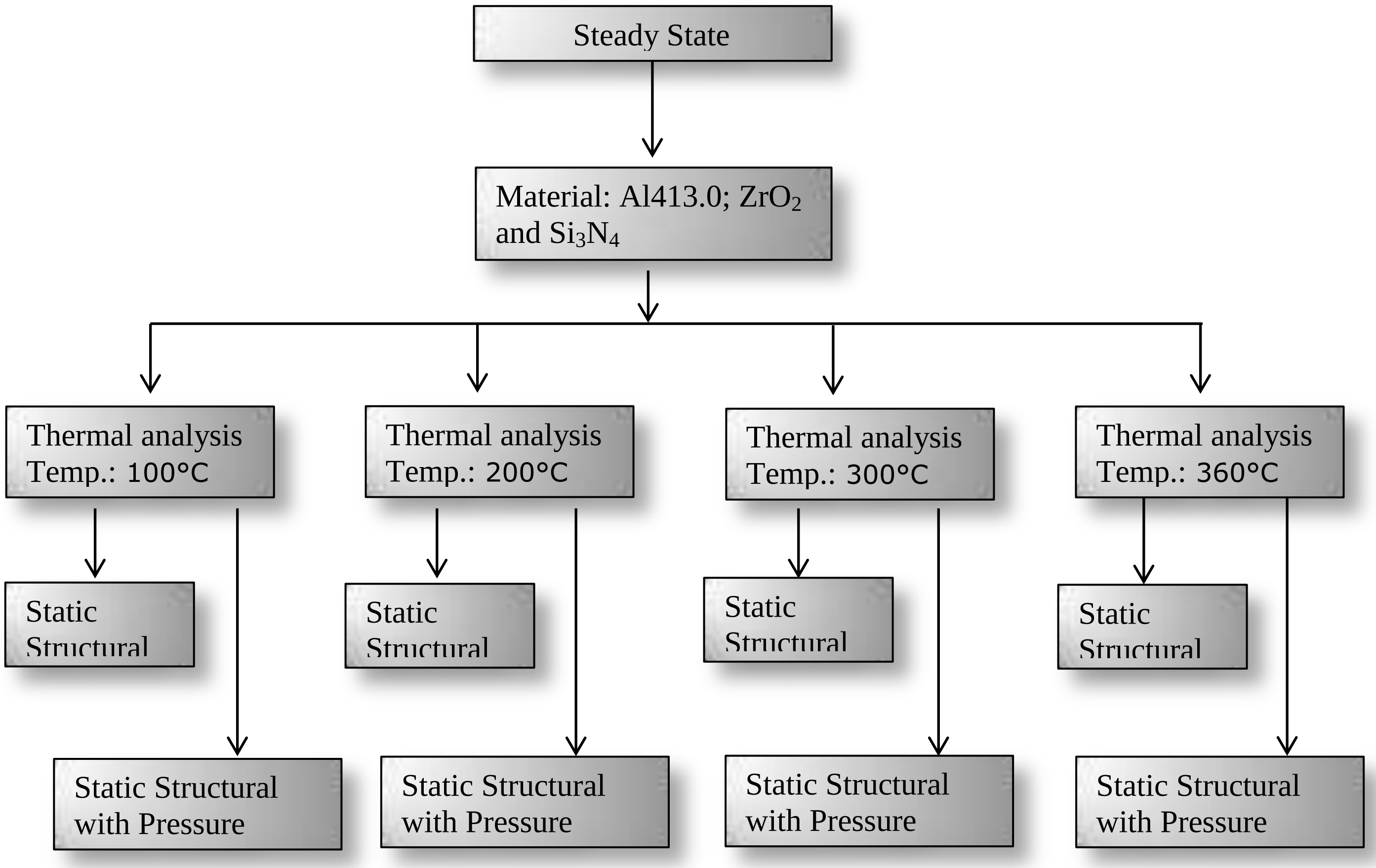


Fig 4.3: Flowchart of adopted analysis method

5. INVESTIGATION METHODOLOGY

The below flowchart illustrates the process methodology of this thesis.

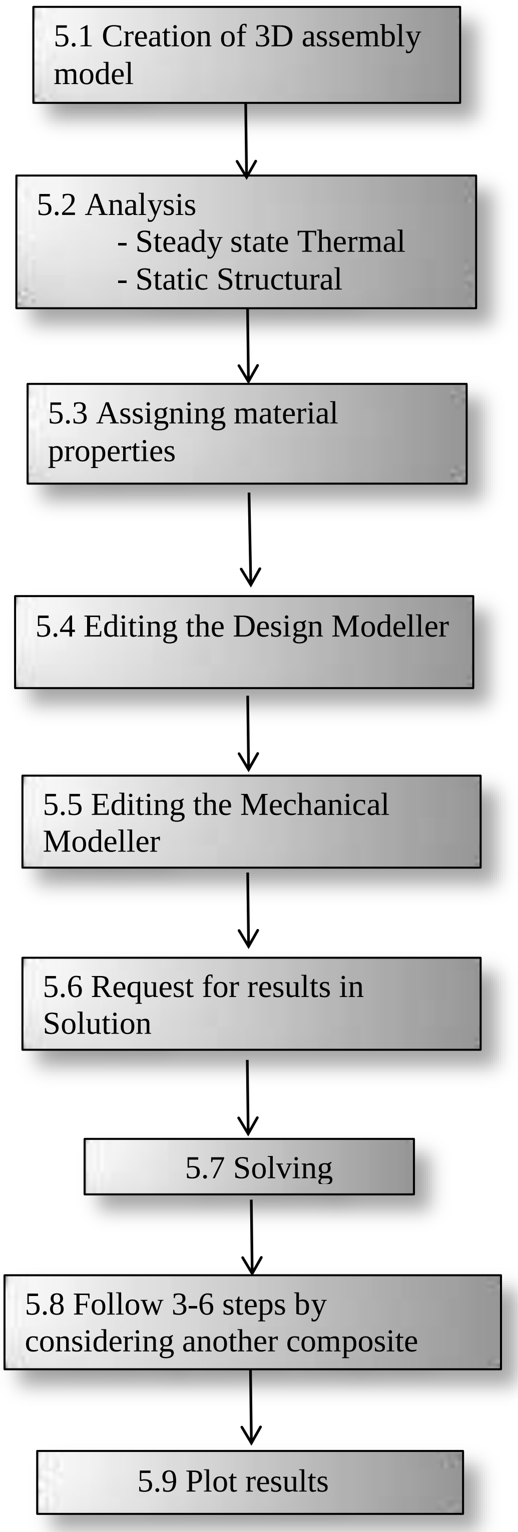


Fig 5.1 Process Methodology Flowchart

5.1 Creation of 3D model:

The 3D assembly model of piston and wrist pin is created in Catia V5R20. The piston considered belongs to a 70mm bore of a 4-stroke diesel engine. The design procedure adopted for modeling the piston is presented below and the design parameters are tabulated in the table 5.1

5.1.1 Piston Head –

Thickness of piston head is determined on basis of strength as well as on heat dissipation

$t_h = \frac{\sqrt{3P}}{\sqrt{16\sigma_t}}$ (5.1)

Cross-sectional area, $A = \pi r^2$ (5.2)

Indicated Power, $I.P = PLAN/60$ (5.3)

5.1.2 Radial Ribs –

Radial ribs may be two or four in numbers and the thickness of the ribs varies from $\frac{t_h}{3}$ to $\frac{t_h}{2}$

5.1.3 Piston Rings –

Out of three rings, two are compression and one is oil ring

1. Radial thickness of the piston rings, $t_1 = \frac{D\sqrt{3P}}{\sqrt{\sigma_t}}$ (5.4)
2. Axial thickness of the piston rings, $t_2 = 0.7t_1$ to t_1 (5.5)
3. Distance from top of the piston to first ring groove, that is

   Width of the top land, $b_1 = 1.2t_h$ (5.6)

   Width of other ring land, $b_2 = 0.75t_2$ to t_2 (5.7)

5.1.4 Piston Barrel –

Radial depth of piston ring grooves (b) should be 0.4mm more than radial thickness of piston (t_1).

$b = t_1 + 0.4$ (5.8)

Maximum thickness of barrel, $t_3 = 0.03D+b+4.5$ (5.9)

Piston wall thickness towards the open end, $t_4 = 0.25t_3$ to t_3 (5.10)

5.1.5 Piston skirt –

Maximum gas load = $\frac{\pi}{4}D^2P_{max}$ (5.11)

Length of the piston, L = Length of skirt + Length of ring section + Top land

$L = l + (3t_2 + 2b_2) + b_1$ (5.12)

5.1.6 Piston pin –

Load on the pin due to bearing pressure = Bearing pressure * Bearing ratio * Bearing area

= p_{b1} x d_o x L_1 (where, $L_1 = 0.45D$) (5.13)

Maximum load on the piston due to gas pressure = $\frac{\pi}{4}$ x D^2 x P (5.14)

Dimensional parameters of the piston which are derived from the above formulae are tabulated in the table 5.1

Table 5.1: Basic dimensional parameters of the piston

S. No.	Parameters	Values(mm)
1	Thickness of the piston head (t_h)	7.528
2	Radial thickness of piston	3.181
3	Axial thickness of piston	2.227
4	Width of top land(b_1)	7.528
5	Width of other land(b_2)	2.817
6	Radial depth of piston	3.581
7	Piston wall thickness towards	4.200
8	Length of piston (L)	58.54
9	Diameter of piston(D)	69.86
10	Diameter of piston pin(d_p)[10]	17.983
11	Length of the piston pin(L_P) [10]	53.28

So the basic geometry of a typical piston based upon the above formulae from design data[11][6] will be as shown in fig (5.2). Since the main goal of the thesis is to compare the analysis results of typical design of a piston with three different materials, the dimensional parameters of the other features of the piston like ribs, piston pin boss, piston pin lub hole and the like are approximated and modelled. And this could be assumption criterion for the modelling of piston in this thesis work.

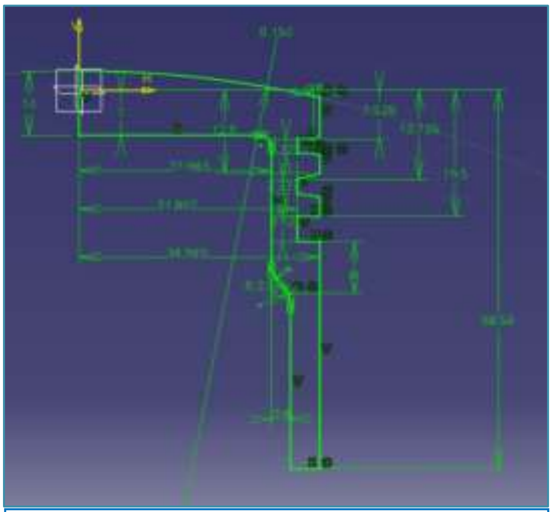


Fig 5.2 Typical design of an IC engine Piston

And the assembled model of the piston and piston pin is shown in the fig (5.3) amd fig (5.4). To make assembly more flexible with constraints, the piston and the piston pin are assembled in Solidworks.

Fig 5.3 Reverse domed

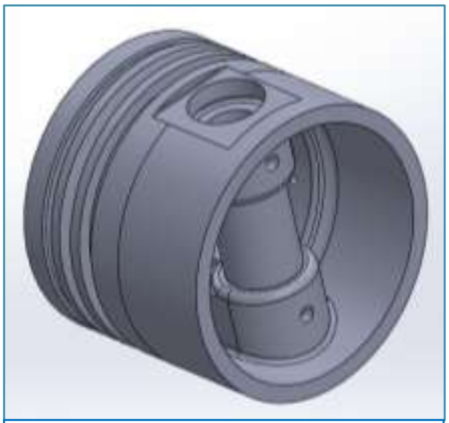


Fig 5.4 Piston – Piston pin

5.2 Analysis

The analysis has been carried out as illustrated in fig (4.3). For this analysis part, Ansys Workbench 14.5 is used as solver. For this purpose, the assembly model should be converted to compatible version and then imported to Workbench environment. Since Solidworks provides default ansys interface, importing the assembly into the Workbench environment was done with ease.

As discussed earlier, this analysis is coupled field analysis[6] consisting of thermal analysis and structural analysis with the thermal loading results as input; it is required to discuss static thermal and static structural in detail.

5.2.1 Thermal Analysis –

In this analysis part thermal loading alone was analyzed and temperature distribution throughout the piston assembly is plotted. Since the thesis compares the results of the two ceramic composites with the conventional aluminium composite piston, it is canny to consider the thermal loading constraints in comparison. Most of the I.C. engine pistons are made of an aluminum alloy which has a thermal expansion coefficient value at 80% higher than the cylinder bore liner material made of cast iron[8]. This leads to some differences between running and the design clearances. Due to the design consideration, the highest temperature at any point on piston must not exceed more than 60% of the melting point temperature of the alloy, because the alloy subjected to higher temperature undergoes change in the crystal structure which seriously hampers the long-run operation of the piston. Heat transfer coefficients for different surfaces of the piston were estimated as shown in the table 5.5. For the simplicity of calculations it is assumed that at high temperature the combustion (flue) gases behave as ideal gases.

The boundary conditions are evaluated as convection coefficients and temperature source and assumed as follows:

1. Heat transferred from the combustion to the piston crown is considered as temperature source
2. Heat transferred from combustion gas to the piston crown is considered under convection
3. Heat transferred and cooling by the engine motor oil from the body of the piston is considered under convection
4. Heat transferred by a healthy coolant with good Reynold’s number and Nusselt number at ideal working condition from 1000 rpm to 3600 rpm of engine speed.

5.2.1.1 Assigning Material Properties –

Since thermal loading is considered to evaluate temperature distribution, thermal conductivity as material property is provided. In fact, it is the only mandatory field to be filled in assigning material property.

Table 5.2, table 5.3 and table 5.4 contains the thermal conductivity of the three composites, viz., Aluminium alloy, ZrO_2 stabilized with MgO and Si_3N_2 respectively at considered working temperature as in fig (4.3). The table also contains approximated thermal conductivity value for piston pin or wrist pin, since it is meant for flexible constraint.

Table 5.2: Thermal Conductivity of Aluminium Al 413.0 alloy[12] and steel[13]

Component	Material	Parameter	Temperature			
			100°C	200°C	300°C	360°C
Piston	Al 413.0	Thermal Conductivity (W/m.K)	125.4	128.0	129.0	131.4
Piston pin	Structural Steel		60.5	58	53	49

In considering thermal conductivity for ZrO_2, since there is no appreciable data for thermal conductivity at specific temperature, the parameter is assumed arbitrarily within the range available. And the same applicable for Si_3N_2 composite which is tabulated in table 5.3

Table 5.3: Thermal Conductivity of ZrO_2[14][15] and steel[13]

Component	Material	Parameter	Temperature			
			100°C	200°C	300°C	360°C
Piston	Zirconia	Thermal Conductivity (W/m.K)	1.96	1.93	1.89	1.85
Piston pin	Structural Steel		60.5	58	53	49

Table 5.4: Thermal Conductivity of Si_3N_2[15][16] and steel[13]

Component	Material	Parameter	Temperature			
			100°C	200°C	300°C	360°C
Piston	Si_3N_2	Thermal Conductivity (W/m.K)	15	14.5	14	13.6
Piston pin	Structural Steel		60.5	58	53	49

5.2.1.2 Editing in Design Modeler –

Identification of model was done in the design modeler environment. Since the model is symmetric, half cut-section part of the assembly was considered for analysis. Symmetry was applied to appropriate plane and cut-section was made as shown in fig (5.5). Care should be taken to check whether the geometric properties contain appropriate information and checks.

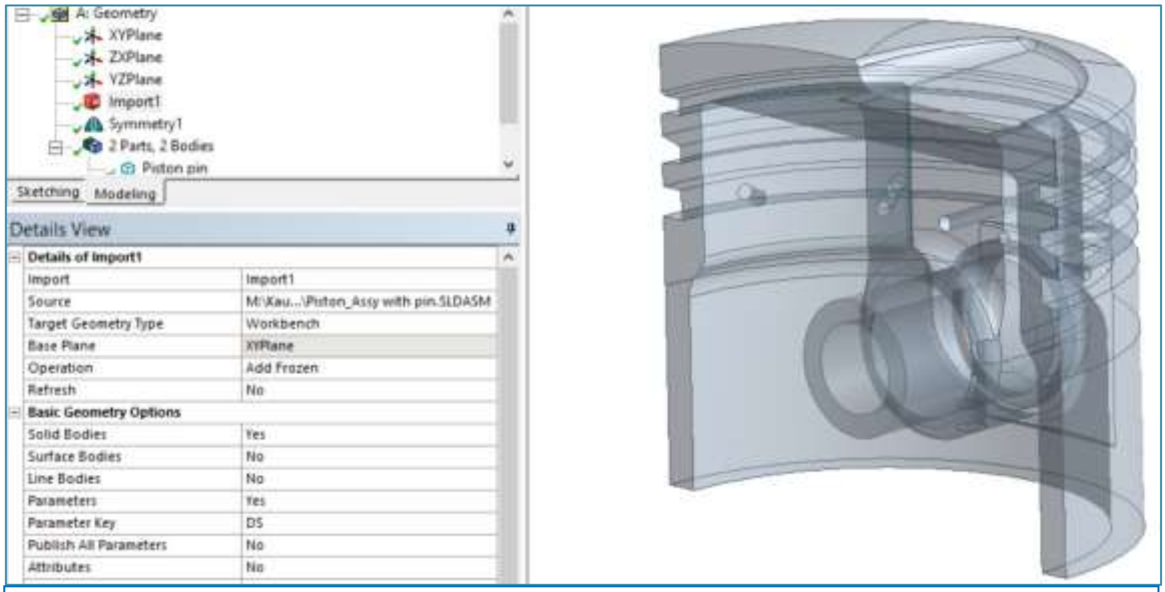


Fig 5.5 Symmetric cut-section of the piston-pin assembly

5.2.1.3 Editing Mechanical Modeler –

Preliminary checks are needed to be done before doing major editing. They are

1. Checking appropriate material are selected to the respective components
2. Coordinate system check
3. Checking the symmetry constraints
4. Checking the connections or contacts
5. Checking the named selection

But by default the above checks are taken account by workbench by default. Though there is demand to change the coordinate system and contact settings, since this design demands. These changes will be discussed in the upcoming topics. And the above points are the same for other temperature analysis as well.

5.2.1.3.1 Virtual Topology –

Topology need to be generated to provide the mesher and solver more smooth surface as in real scenario. Virtual topology is generated on the surface of the piston as shown in the fig (5.6)

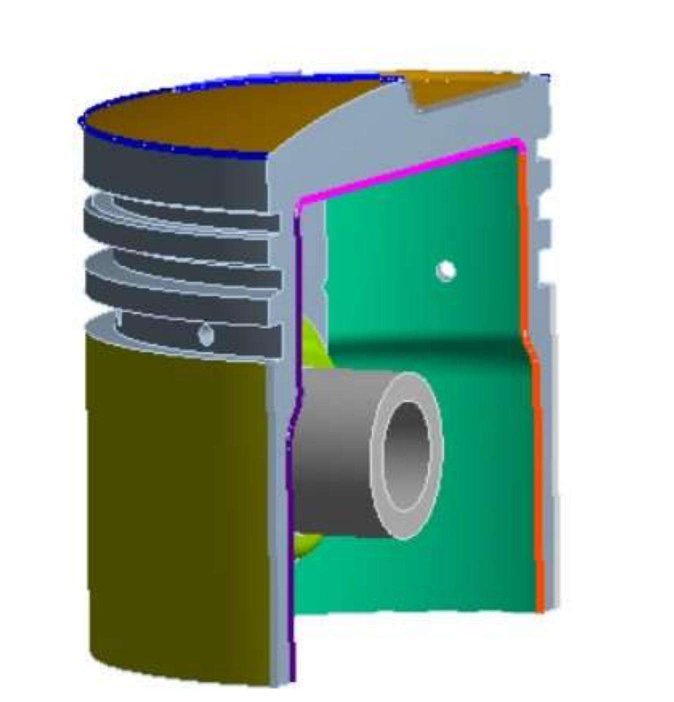


Fig 5.6 Virtual topology – Piston assembly

5.2.1.3.2 Coordinate system –

The default coordinate system already exists are Global coordinate system and a local coordinate system namely, zx-plane, which is the symmetry plane. But to make meshing elements of piston pin boss to match with the pin, it is mandatory to provide body sizing in the mesher in this case. For that, another local coordinate system should be created. A cylindrical pin coordinate system was created considering the piston pin as geometry selection and its internal diameter as face. The cylindrical coordinate system created can be seen in fig (5.7). As seen in the fig (5.7), x-z axis are perpendicular with y-axis is cylindrical as per the selection[41].

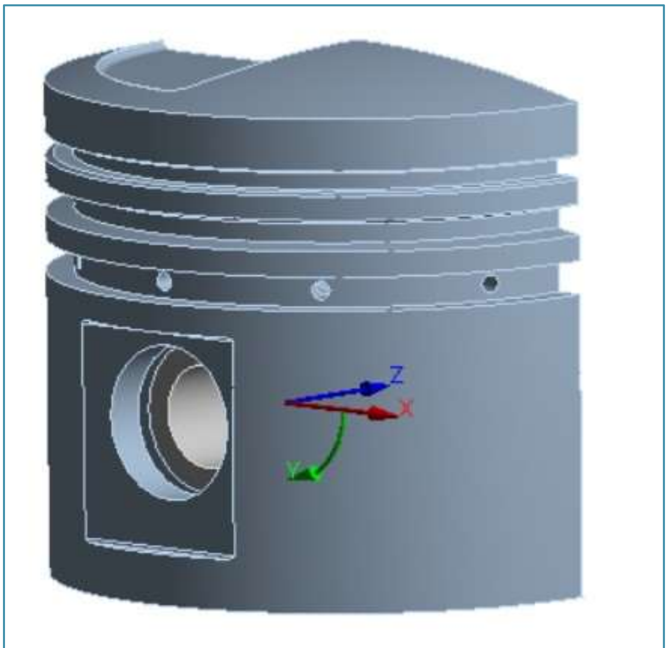


Fig 5.7 Cylindrical coordinate system

5.2.1.3.3 Connections –

Since the considered component is an assembly comprising of piston and piston pin, it is vital to establish perfect contact alike real time scenario. Workbench by default considers bonded. But for this assembly, non-linear contacts need to be established[39][41].

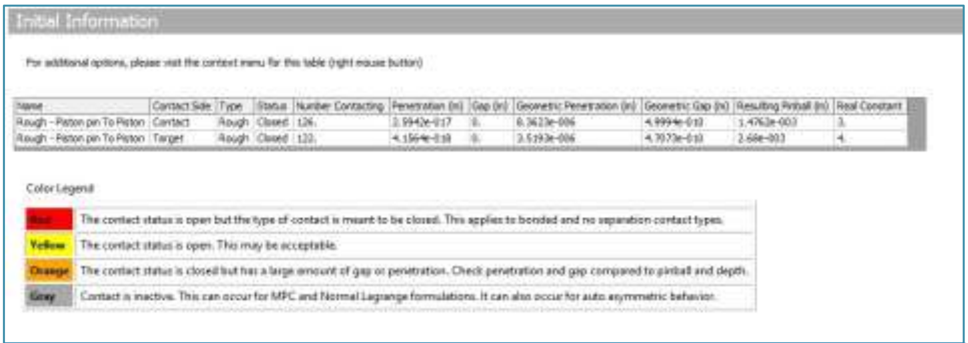
‘Rough’ contact was chosen for this purpose and contact parameters are edited in contact details as shown in fig (5.8). And fig (5.9) shows the piston-pin assembly with contacts. A contact tool can be called out and generated in order to evaluate the contact features like gap penetration, pin ball region, geometric penetration and to check the contact is a feasible one. And the connection tool is shown in fig (5.10).

Details of "Rough - Piston pin To Piston"

Scope	
Scoping Method	Geometry Selection
Contact	1 Face
Target	1 Face
Contact Bodies	Piston pin
Target Bodies	Piston
Definition	
Type	Rough
Scope Mode	Manual
Behavior	Symmetric
Trim Contact	Program Controlled
Suppressed	No
Advanced	
Formulation	Pure Penalty
Detection Method	On Gauss Point
Elastic Slip Tolerance	Program Controlled
Interface Treatment	Adjust to Touch
Thermal Conductance	Program Controlled
Pinball Region	Program Controlled
Time Step Controls	None

Fig 5.8 Contact

Fig 5.9 Piston – Pin contact



Initial Information

For additional options, please visit the context menu for this table (right mouse button)

Name	Contact Side	Type	Status	Number Contacting	Penetration (m)	Gap (m)	Geometric Penetration (m)	Geometric Gap (m)	Resulting Pinball (m)	Real Constant
Rough - Piston pin To Piston	Contact	Rough	Closed	126.	2.9942e-017	0.	6.3623e-006	4.9994e-010	1.4762e-003	3.
Rough - Piston pin To Piston	Target	Rough	Closed	122.	4.1564e-018	0.	3.5193e-006	4.7073e-010	2.68e-003	4.

Color Legend

Red	The contact status is open but the type of contact is meant to be closed. This applies to bonded and no separation contact types.
Yellow	The contact status is open. This may be acceptable.
Orange	The contact status is closed but has a large amount of gap or penetration. Check penetration and gap compared to pinball and depth.
Gray	Contact is inactive. This can occur for MPC and Normal Lagrange formulations. It can also occur for auto asymmetric behavior.

Fig 5.10 Contact tool information

5.2.1.3.4 Meshing –

The core of this analytical method is finite element method. As every engineer knows, this means break down of complete component into finite number of small elements in a process called meshing and solving.

For this thermal analysis, appropriate element type of 20 node solid 90 with tetrahedral shape as shown in fig (5.11). The element has 20nodes with single degree of freedom, temperature, at each node. This element is well suited for curvature components such as piston under discussion[6][36]. By default the element type selection is done by workbench. Without doubt, the workbench has chosen this element while solving. And the element shape can be defined by conforming method and selecting tetrahedral.

And body sizing need to be done in order to match the element size of piston elements near the pin boss with the pin. The body sizing of piston-pin assembly can be visualized in fig (5.12). And at the contacts, contact174 and target170 elements are chosen while solving. And the other meshing parameters which should be edited as per the requirement are shown in the fig (5.13). And mesh was generated and the completely meshed assembly could be seen in the fig (5.14)

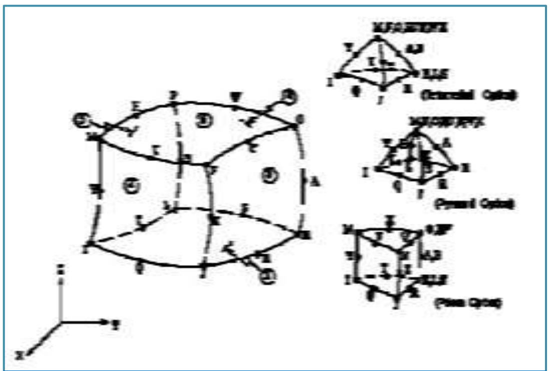


Fig 5.11 20node Solid90 tetrahedral element[36]

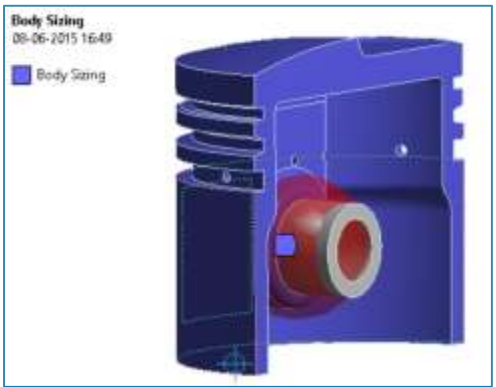
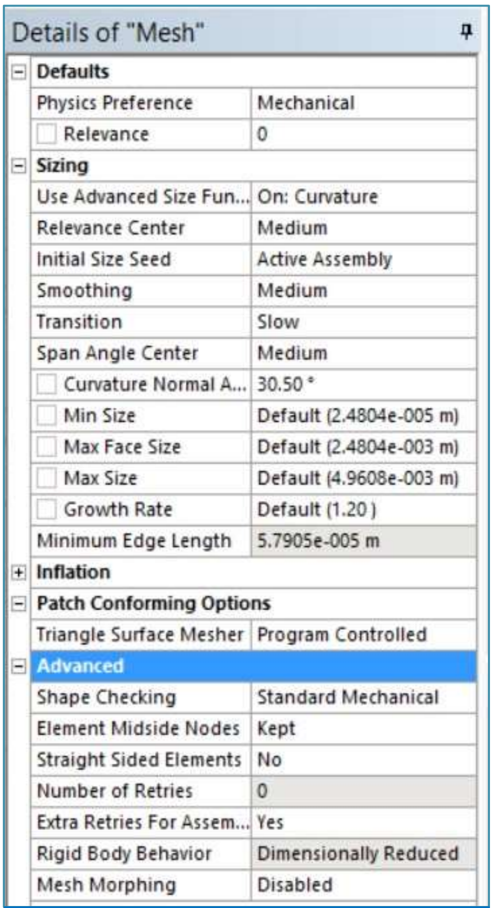


Fig 5.12 Body sizing



Details of "Mesh"	
Defaults	
Physics Preference	Mechanical
Relevance	0
Sizing	
Use Advanced Size Fun...	On: Curvature
Relevance Center	Medium
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Slow
Span Angle Center	Medium
Curvature Normal A...	30.50 °
Min Size	Default (2.4804e-005 m)
Max Face Size	Default (2.4804e-003 m)
Max Size	Default (4.9608e-003 m)
Growth Rate	Default (1.20)
Minimum Edge Length	5.7905e-005 m
Inflation	
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Advanced	
Shape Checking	Standard Mechanical
Element Midside Nodes	Kept
Straight Sided Elements	No
Number of Retries	0
Extra Retries For Assem...	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled

Fig 5.13 Mesh details

Fig 5.14 Meshing

5.2.1.3.5 Analysis settings –

The setup involves the analysis settings and numerical values (loads) to be made as input. In this study, analysis settings can be seen in fig (5.15) and the two important thermal loads acting on the piston are temperature and convective heat transfer coefficient are considered. Here temperature is assumed to be source of heat applied on the crown of the piston equivalent to the combustion load, and it is 360°C (60% of melting point of Al alloy[34]). The convective heat transfer coefficient can be arrived with the help of equation 5.15[37]. But to ease the work, the majority heat transfer coefficients were considered[6], since that journal also deals with the study of temperature distribution in a conventional piston with same dimensions. The areas which were not calculated are evaluated and tabulated in the table 5.5. Since the heat transfer coefficient is independent of material, the same can be used in the case of ceramic composites as well.

$$q = h_c A(T_s - T_a) \qquad (5.15)$$

where,

q – heat transferred per unit time (W)

A = heat transfer area of the surface (m^2)

h_c = convective heat transfer coefficient (W/m^2°C)

T_s = Surface temperature

T_a = Temperature of the coolant or air

Analysis setup inputs involves –

Initial temperature: Since the study carried out at that moment when the piston reaches 100°C, the initial temperature was assumed as 100°C. The same applies to other temperatures too.

Settings: This involves the selection of time steps, solver type and control of output parameters and the like. The fields which are of the interest have been changed from default settings and can be seen in fig (5.14)

Table 5.5: Convective heat transfer coefficient of various features of the piston[6][37]

Feature Description	Notation	Heat transfer coefficient (W/m^2°C)	Temperature °C
Piston Crown	h_1	1475	360
Piston Junk	h_2	155	150
Top face of the first circular groove	h_3	456	150
Radial face of the first circular groove	h_4	475	150
Bottom face of the first circular groove	h_5	331	150
Secondary compression ring face	h_6	127	145
Top face of the second circular groove	h_7	389	130
Radial face of the second circular groove	h_8	244	130
Bottom face of the second circular groove	h_9	389	130
O'ring face	h_{10}	125	120
Top face of the third circular groove	h_{11}	367	120
Radial face of the third circular groove	h_{12}	244	120
Bottom face of the third circular groove	h_{13}	367	120
Piston Skirt	h_{14}	532	110
Bottom of piston crown	h_{15}	1000	110
Inner surface of the piston skirt	h_{16}	1000	110

Piston pin boss	h_{17}	490	110
Contact surface of pin boss	h_{18}	40	110
Piston pin clip	h_{19}	240	110
Collar	h_{20}	620	120
Oil drain hole	h_{21}	220	75
Pin inner surface	h_{22}	264	110
Piston bottom surface	h_{23}	369	90

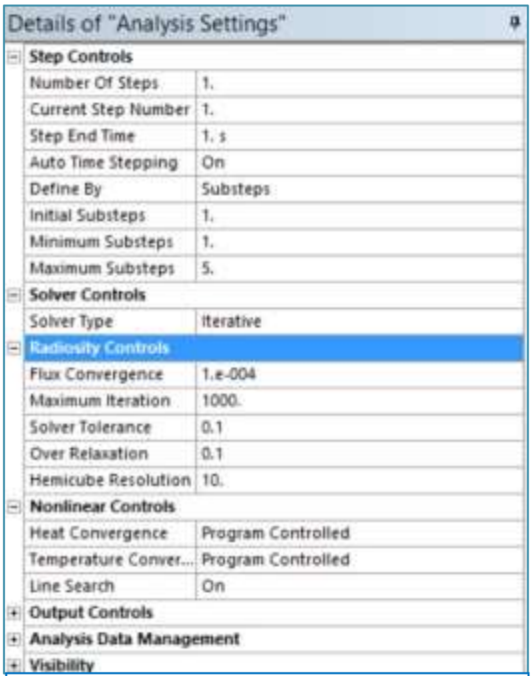


Fig 5.15 Analysis settings details

5.2.1.3.6 Solution –

The results required need to be picked before solving. The requisite result is temperature distribution plot. Then hit solve and check the convergence of the solution.

So, the temperature distribution plots at all the required temperature as in fig (4.3) are solved as discussed in the above methodology and results(plots) are shown in fig (5.16), fig (5.17), fig (5.18), fig (5.19)

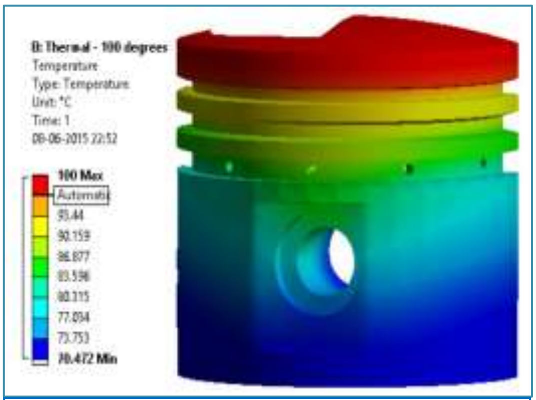


Fig 5.16 Thermal analysis - 100°C

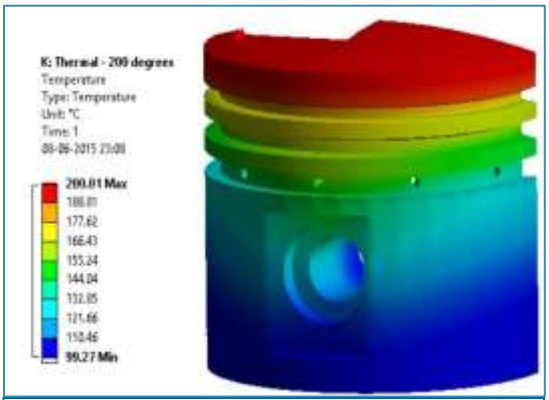


Fig 5.17 Thermal analysis - 200°C

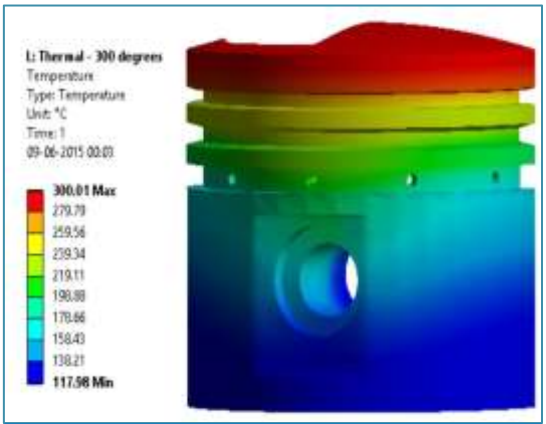


Fig 5.18 Thermal analysis - 300°C

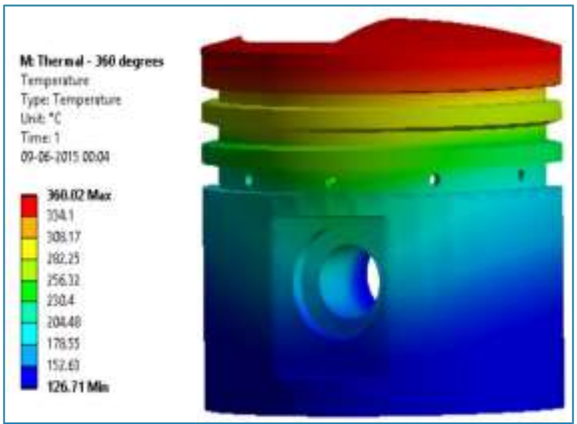


Fig 5.19 Thermal analysis - 360°C

And hence the temperature distributions for Al 413.0 alloy have been plotted. Then, the thermal study for ZrO_2 and Si_3N_4 composites are carried out in the same method by assigning the respective composite's material property (refer table 5.3 and 5.4) in engineering data and solved for solution. And the temperature distributions plots for ZrO_2 and for Si_3N_4 are shown:

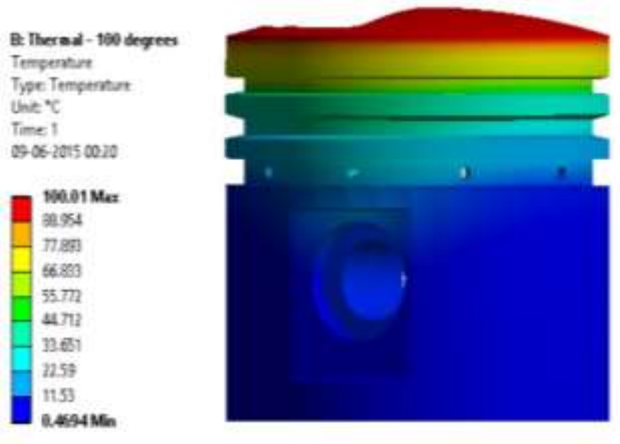


Fig 5.20 Thermal analysis - 100°C

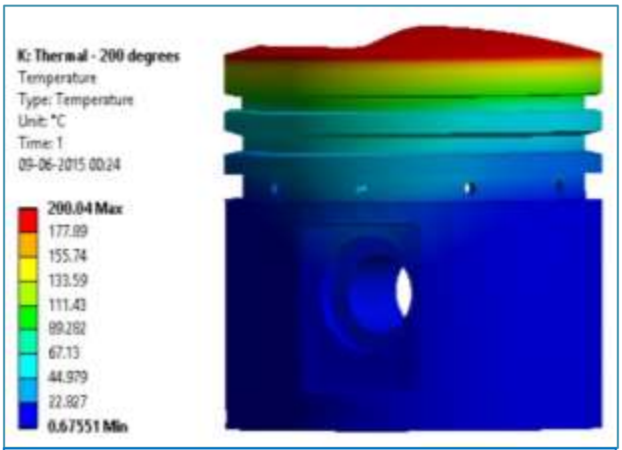


Fig 5.21 Thermal analysis - 200°C

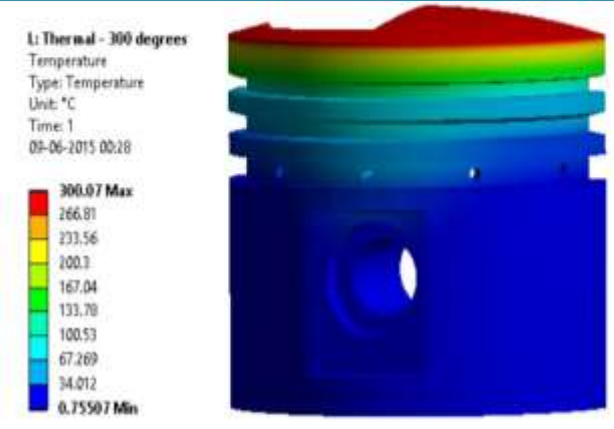


Fig 5.22 Thermal analysis - 300°C

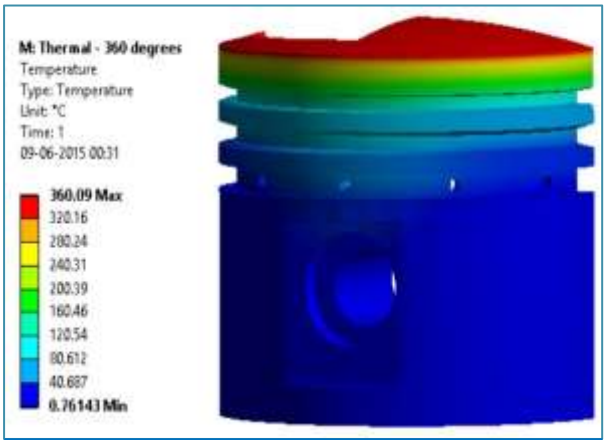


Fig 5.23 Thermal analysis - 360°C

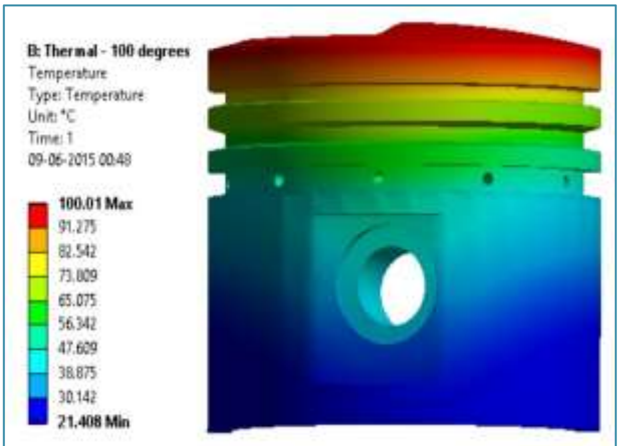


Fig 5.24 Thermal analysis - 100°C

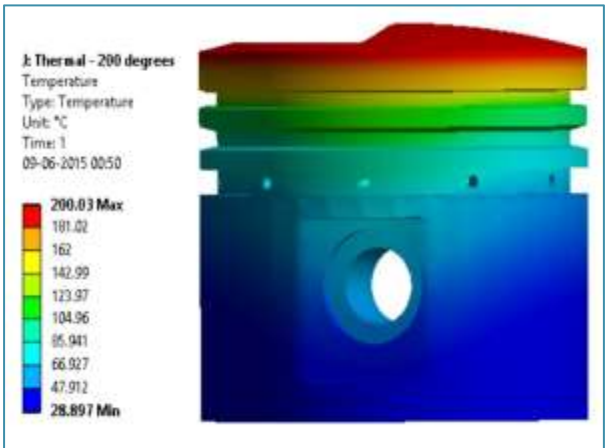


Fig 5.25 Thermal analysis - 200°C

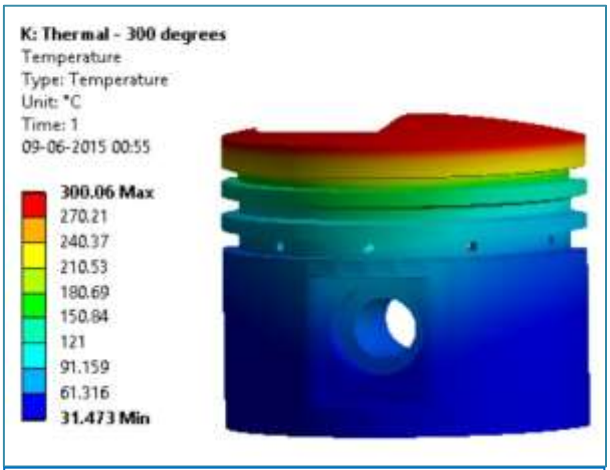


Fig 5.26 Thermal analysis - 300°C

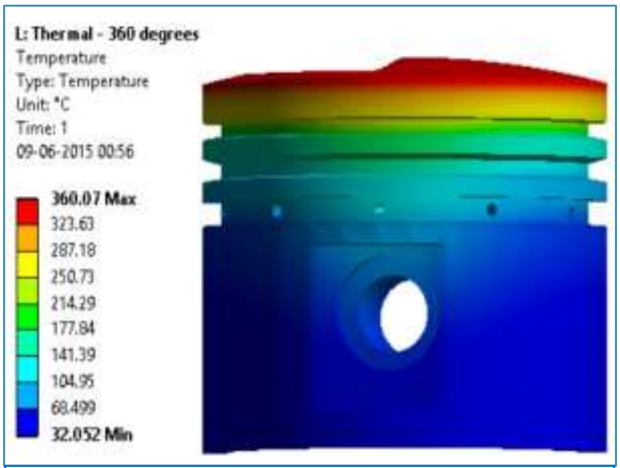


Fig 5.27 Thermal analysis - 360°C

5.2.2 Structural analysis –

Steady state static structural analysis is carried out in this part of study. The analysis consists of two categories, viz.

- Considering combustion gas pressure with thermal loading from the above made thermal study and to evaluate the results viz., stress distribution.
- Without considering combustion gas pressure but with thermal loading from the thermal study and the results were evaluated. This is to investigate the material expansion from thermal loading alone. And stress distributions are plotted.

To get start with the study, considering the combustion process and forces acting on the piston is a thoughtful one. During combustion process, gudgeon pin experiences force that gets transmitted through the piston. In addition, shock loads also get acted on the piston. The piston is designed to withstand the shock loads and with repeated cycles or transient loading. Design criterion should be kept in place that the piston should not undergo fatigue failure. The gudgeon pin (which connects the piston to the connecting rod in a conventional internal combustion engine) is subjected to a combination of shearing and bending loads. At combustion cycle, the piston is subjected to distortion and the energy stored inside the piston serves as a determining factor to know the yield and failure conditions of a piston when subjected to static loading. Von Mises yield criterion can be formulated in terms of the von Mises stress or equivalent tensile stress, σ_υ, a scalar stress value that can be computed from the stress tensor as shown in eq. 5.16 [18]. In this case, a material is said to start yielding when its von Mises stress reaches a critical value known as the yield strength as shown in eq – (5.16). And there is considerable body of opinion Von mises yield criterion does only complies with ductile material like aluminum, copper, steel, but when dealing with the brittle materials or composites like ceramics or glass, Maximum principal stress theory or Coulomb-Mohr theory should be considered. But how about comparing failure criteria of ductile material with brittle composites? This thesis deals with a tricky combination of material and the comparison criterion upon which the results are discussed which will be dealt under results and discussion.

$$\sigma_v^2 = \frac{1}{2} [(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{11} - \sigma_{33})^2 + 6 (\sigma_{23}^2 + \sigma_{31}^2 + \sigma_{31}^2)] \quad (5.16)$$

Alike thermal analysis, same procedure followed for evaluating the results for all the three composites. But with some exceptions, mechanical material properties are assigned to engineering data; and mechanical loading and constraints have to be placed. So whatever assumptions are made during the analysis applies to all the three composites.

To start with the analysis, the assembly model should be imported into geometry modeler of steady state static module. This is done by just linking the geometry modeler of thermal module, since workbench provides such flexibility. Since this thesis deals with static study, boundary conditions or numerical values assumed are pressure and thermal loading alone (temperature distribution from thermal study), because there are numerous loads would act upon the piston in real time scenario.

The important assumption to be made here is, the piston pin is only meant for fixture and constraint purposes. It does not consider for analysis.

5.2.2.1 Assigning Material Properties –

Since structural loading is considered in this part of study, physical and mechanical properties of the composites viz. Al 413.0, ZrO_2 stabilized with MgO and for Si_3N_4 composites are collected and entered in the engineering data. The properties of the three composites pertaining for this study are listed in table 5.6, table 5.7 and table 5.8 respectively at considered working temperature as in fig (4.3). The table also contains approximated properties for piston pin, since it is meant for flexible constraint, to evaluate the amount of expansion imparted in piston due to loads. Since this study is non-linear, because the mechanical properties depend upon environmental temperature change and source of heat, thermal expansion values at the considered temperatures are tabulated. Because of long research and experimentation, thermal expansion of aluminum alloys is available in abundance and exact, whereas the thermal expansion of zirconia and silicon nitride are arbitrarily assumed within the available thermal expansion range with respect to temperature change which are tabulated. And the properties of piston pin or wrist pin are tabulate in table 5.9

Table 5.6 – Physical and Mechanical properties of Al 413.0[22]

S.No.	Property	Values				Units
1	Density	2660				kg/m^3
2	Reference Temperature	100	200	300	360	°C
	Coefficient of Thermal Expansion[22]	$1.875E^{-5}$	$1.915E^{-5}$	$1.972E^{-5}$	$2.001E^{-5}$	$°C^{-1}$
3	Young's Modulus	71000				MPa
4	Max. service Temperature (°C)	574 - 582				°C
5	Poisson's ratio	0.33				-
6	Yield stress	280				Mpa
7	Tangent modulus	500				Mpa
8	Tensile yield strength	150				Mpa
9	Compressive yield strength	280				Mpa
10	Tensile ultimate strength	310				Mpa

Since ceramics does not comply to yield stress criterion, mechanical strength for ceramic composites has to be dealt with different tensile and compression strength which are tabulated below:

Table 5.7 – Physical and Mechanical properties of ZrO_2[14][15][16][21]

S.No.	Property	Values				Units
1	Density	5750				kg/m^3
2	Reference Temperature	100	200	300	360	°C
	Coefficient of Thermal Expansion[14]	$1E^{-5}$				$°C^{-1}$

3	Young's Modulus	205000				MPa
4	Max. service Temperature (°C)	~2000				°C
5	Poisson's ratio	0.32				-
6	Tensile yield strength	480				Mpa
7	Compressive yield strength	1200				Mpa
8	Ultimate tensile strength	711				Mpa
9	Ultimate compressive strength	5200				Mpa

Table 5.8 – Physical and Mechanical properties of Si_3N_4[15][16][23][24]

S.No.	Property	Values				Units
1	Density	3290				kg/m^3
2	Reference Temperature	100	200	300	360	°C
	Coefficient of Thermal Expansion[23]	$3.4E^{-6}$				$°C^{-1}$
3	Young's Modulus	317000				MPa
4	Max. service Temperature (°C)	~1250				°C
5	Poisson's ratio	0.29				-
6	Tensile yield strength	360				Mpa
7	Compressive yield strength	690				Mpa
8	Ultimate tensile strength	525				Mpa
9	Ultimate compressive strength	2760				Mpa

Table 5.9 – Physical and Mechanical properties of structural steel alloy [25][26]

S.No.	Property	Values				Units
1	Density	7850				kg/m^3
2	Reference Temperature	100	200	300	360	°C
	Coefficient of Thermal Expansion	$1.18E^{-5}$	$1.22E^{-5}$	$1.23E^{-5}$	$1.25E^{-5}$	$°C^{-1}$
3	Young's Modulus	200000				MPa
4	Max. service Temperature (°C)	900				°C
5	Poisson's ratio	0.29				-
6	Yield stress	250				Mpa
7	Tangent modulus	1450				Mpa
8	Tensile yield strength	250				Mpa
9	Compressive yield strength	250				Mpa
10	Tensile ultimate strength	460				Mpa

Material properties from table (5.6) to piston and table (5.9) to wrist pin are assigned to engineering data and editing the mechanical modeler was done. While analyzing the ceramic composites, material properties from table (5.7) and table (5.8) were assigned to piston and solved by the same approach.

5.2.2.2 Editing the Mechanical Modeler –

Since no editing of design modeler is needed, the study jumps to editing the mechanical modeler. Though editing the mechanical modeler is similar to the 5.2.1.3, specific features in static structural module and inputs need to be discussed.

Virtual topology, coordinate system and connections follow the same procedure as discussed under the topic 5.2.1.3.1 – 5.2.1.3.3. So it is from meshing that demands some light to throw upon.

5.2.2.2.1 Meshing –

Though the user has no control over the type of element selection in workbench environment, the appropriate elements for this structural analysis have to be discussed. The element which is compatible for structural analysis when 20node solid90 opted for thermal analysis in a coupled field analysis is 20node solid186 and solid187. solid186 and solid187 are higher order 3-D node elements defined by 20node that have three degree of freedom per node that exhibit quadratic displacement behavior[36]. The element behavior is shown in fig (5.28). And the element shape compatible for this coupled field analysis is 10node tetrahedron. This element also supports non-linearity of this analysis [6].

During meshing, nodes and 119788 elements are generated.

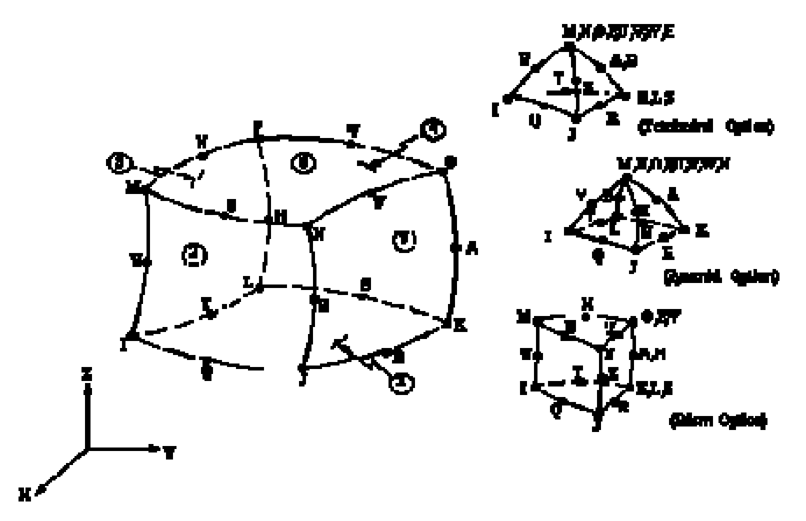


Fig 5.28 10node Tetrahedron – Solid 186 element[36]

Satisfactorily, the workbench has chosen the above elements viz. 10node tetrahedron solid186 and solid187 by default while solving. And the element shape can be defined by conforming method and selecting tetrahedral.

As discussed under 5.2.1.3.4, body sizing is carried out in order to match the element size of piston elements near the pin boss with the pin as visualized in fig (5.12). And at the contacts, contact174 and target170 elements are chosen while solving. And the other meshing parameters which should be edited as per the requirement are shown in the fig (5.13). And mesh was generated and the completely meshed assembly could be seen in the fig (5.14)

5.2.2.2.2 Analysis Settings –

Since the thesis deal with extracting as many results possible to arrive with legitimate discussion that is loading at various specific combustion chamber temperature within the operating limit as in fig (4.3), the environment temperature have to be assigned. So at 100°C, the environment temperature is the same. Fig (5.29) shows the detailed analysis settings for this static structural study.

The piston-pin assembly is constrained in piston pin in order to prevent displacement of piston in the radial direction and rotation about piston pin axis as shown in fig (5.30) approximately to real scenario alike small end of the connecting rod. For this purpose, with the real tolerance the wrist pin was splined while modeling and assembled with the piston. Since every known structural analysis package consists of this unique feature called frictionless support, complexity in modeling an assembly with cylinder sleeve to the required tolerance was avoided. Fig (5.31) shows the frictionless support assigned to the piston-pin assembly. To continue with, working pressure or real time combustion chamber pressure was assigned. Table 5.10 contains the pressure at various features of the piston.

Details of "Analysis Settings"

Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	On
Define By	Substeps
Initial Substeps	1.
Minimum Substeps	1.
Maximum Substeps	10.
Solver Controls	
Solver Type	Iterative
Weak Springs	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Restart Controls	
Nonlinear Controls	
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Conve...	Program Controlled
Rotation Convergen...	Program Controlled
Line Search	On
Stabilization	Off
Output Controls	
Stress	Yes
Strain	Yes
Nodal Forces	No
Contact Miscellaneo...	No
General Miscellaneo...	No
Store Results At	All Time Points
Max Number of Res...	Program Controlled
Analysis Data Management	
Visibility	

Fig 5.29

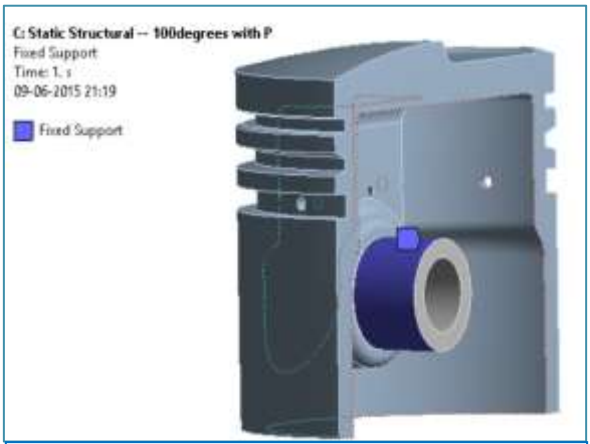


Fig 5.30 Fixed Support

Fig 5.31 Frictionless support

Table 5.10 – Combustion gas pressure values applied on various features of the piston[27][6]

S.No.	Feature surface	%percentage	Pressure (MPa)
1	Piston crown	P (inclusive of atm. pressure)	8.2013
2	Primary compression ring – top surface	P x 76%	6.233
3	Primary compression ring groove – bottom surface	P x 70%	5.7409
4	Top and bottom surface of secondary compression ring groove	P x 25%	2.0503
5	Top and bottom surface of O'ring groove	P x 25%	1.2302

The same approach discussed under 5.2.2.2.1 and 5.2.2.2.2 was followed in meshing and analysis setting while analyzing ceramic composites. And the same was followed while carrying out structural study without considering combustion gas pressure at respective temperature and for the two material ceramic composites.

5.2.2.2.3 Solution –

The results required need to be picked before solving. The requisite results are normal stress plot and strain energy plot. Then hit solve and check the convergence of the solution. To ease with the discussions based upon the results and to be little crisp, strain energy for 100°C and 360°C alone are depicted for all the cases.

The study at all the considered thermal loading under the two listed categories viz.

1. with combustion gas pressure
2. without combustion gas pressure, i.e., stress due to thermal loading alone

as discussed earlier under 5.2.2 are solved following the same analysis settings and results are plotted. The plots which are shown in fig (5.32) – fig (5.35) depicts the normal stress with combustion gas pressure for Al 413.0. And the strain energy plots for the same at two agreed temperatures (100°C and 360°C) are shown in fig (5.36) and fig (5.37). And fig (5.38) – fig (5.41) depicts the normal stress under the second category that is without combustion gas pressure. And fig (5.42) and (5.43) represents the strain energy plot for the same.

The same approach was followed while solving for zirconia and silicon nitride composites and the results are plotted. Fig (5.44) – fig (5.47) represents normal stress plots under first category for zirconia. And the strain energy plots are shown in fig (5.48) and fig (5.49). Fig (5.50) – fig (5.53) depicts the normal stress plots under second category. Fig (5.54) and fig (5.55) represents strain energy. And fig (5.56) – fig (5.59) and fig (5.62) – fig (5.65) depicts the normal stress distribution under first and second categories respectively for silicon nitride. Fig (5.60) – fig (5.61) represents strain energy under first category while fig (5.66) and fig (5.67) represents the strain energy under second category for Si_3N_4.

Fig 5.33 Al 413.0 Normal stress with combustion pressure @ 100°C

Fig 5.33 Al 413.0 Normal stress with combustion pressure @ 200°C

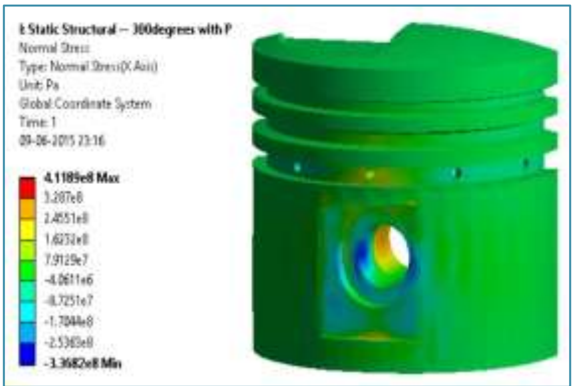


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Fig 5.34 Al 413.0 Normal stress with combustion pressure @ 300°C

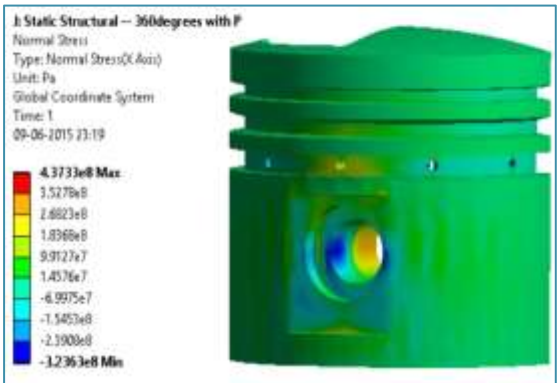

Fig 5.35 Al 413.0 Normal stress with combustion pressure @ 360°C

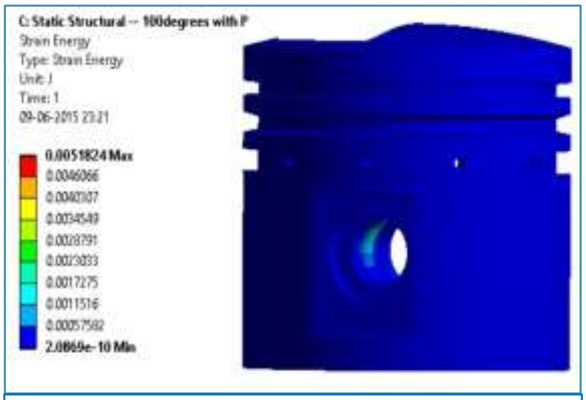

Fig 5.36 Al 413.0 Strain Energy with combustion pressure @ 100°C

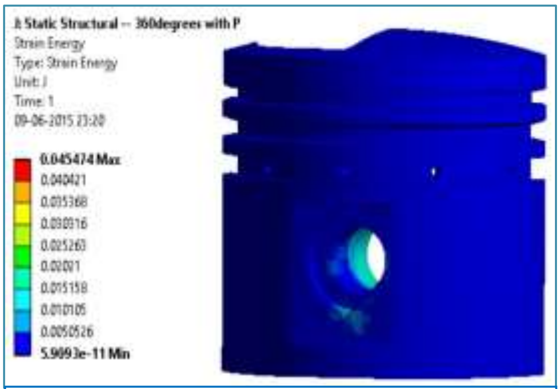

Fig 5.37 Al 413.0 Strain Energy with combustion pressure @ 360°C

Fig 5.38 Al 413.0 Normal stress without combustion pressure @ 100°C

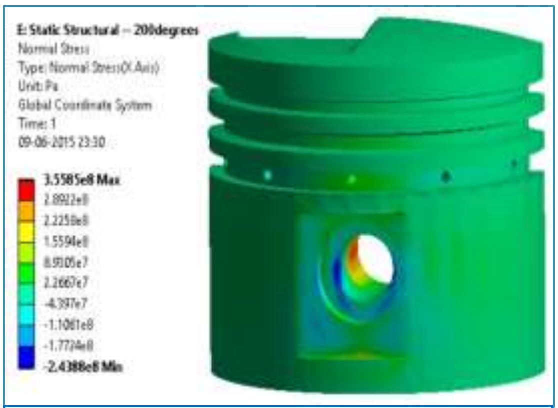

Fig 5.39 Al 413.0 Normal stress without combustion pressure @ 200°C

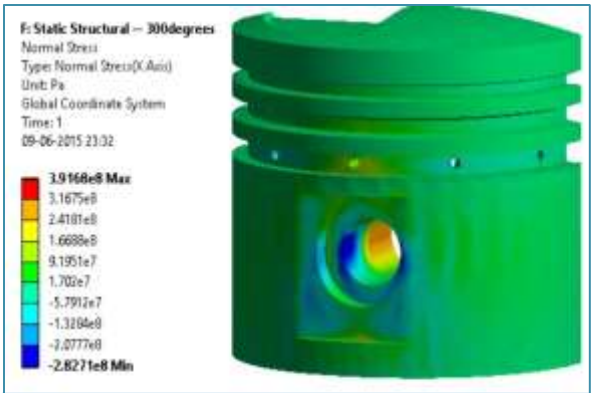

Fig 5.40 Al 413.0 Normal stress without combustion pressure @ 300°C

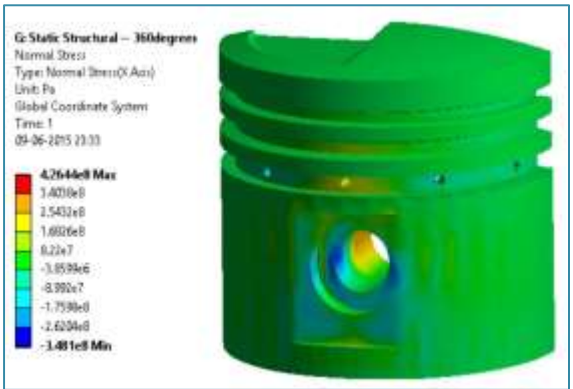

Fig 5.41 Al 413.0 Normal stress without combustion pressure @ 360°C

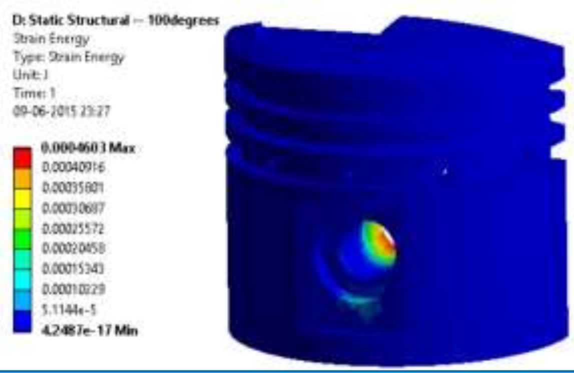

Fig 5.42 Al 413.0 Strain Energy without combustion pressure @ 100°C

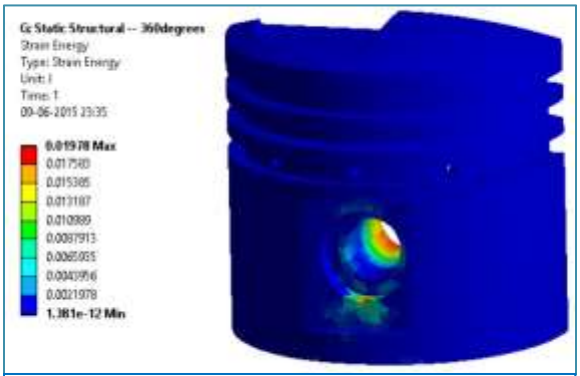

Fig 5.43 Al 413.0 Strain Energy without combustion pressure @ 360°C

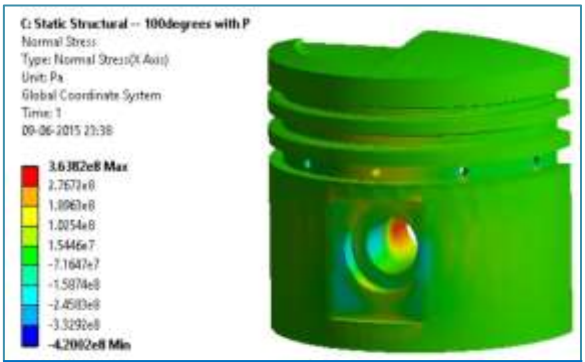

Fig 5.44 ZrO_2 Normal stress with combustion pressure @ 100°C

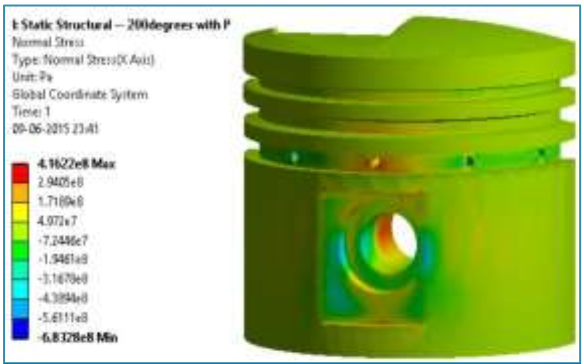

Fig 5.45 ZrO_2 Normal stress with combustion pressure @ 200°C

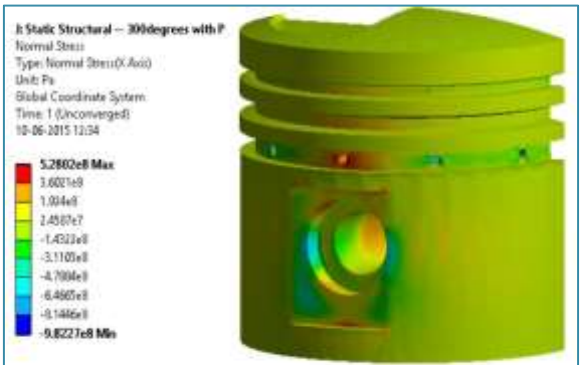

Fig 5.46 ZrO_2 Normal stress with combustion pressure @ 300°C

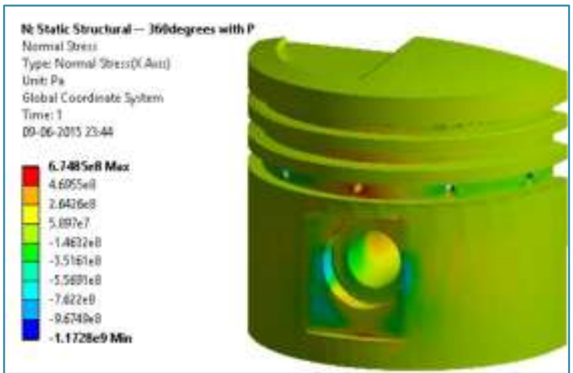

Fig 5.47 ZrO_2 Normal stress with combustion pressure @ 360°C

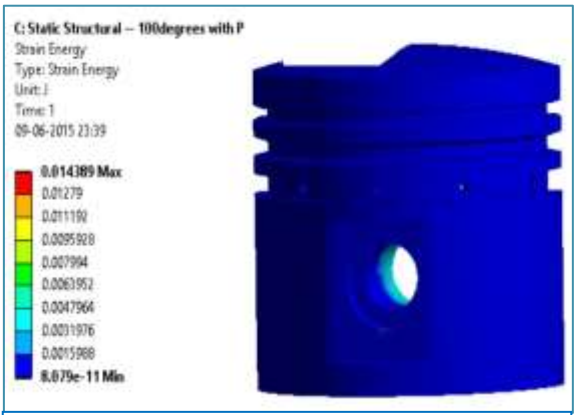

Fig 5.47 ZrO_2 Strain Energy with combustion pressure @ 100°C

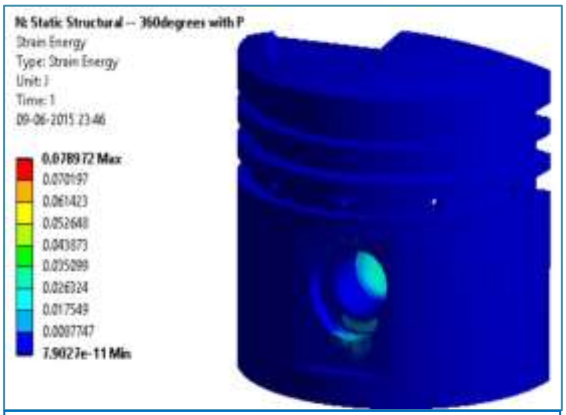

Fig 5.48 ZrO_2 Strain Energy with combustion pressure @ 360°C

Fig 5.49 ZrO_2 Normal stress without combustion pressure @ 100°C

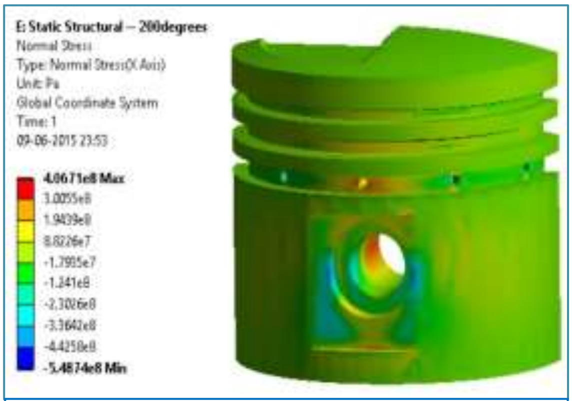

Fig 5.50 ZrO_2 Normal stress without combustion pressure @ 200°C

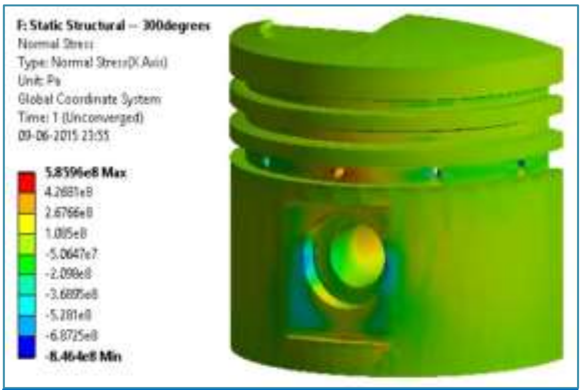

Fig 5.51 ZrO_2 Normal stress without combustion pressure @ 300°C

Fig 5.52 ZrO_2 Normal stress without combustion pressure @ 360°C

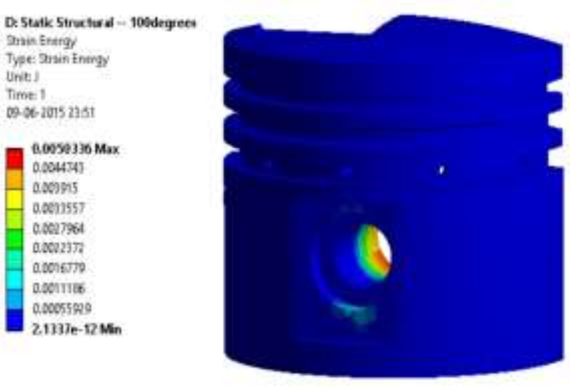

Fig 5.53 ZrO_2 Strain Energy without combustion pressure @ 100°C

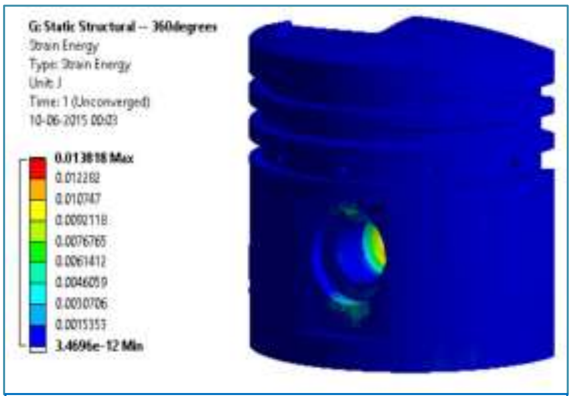

Fig 5.54 ZrO_2 Strain Energy without combustion pressure @ 360°C

Fig 5.55 Si_3N_4 Normal stress with combustion pressure @ 100°C

Fig 5.56 Si_3N_4 Normal stress with combustion pressure @ 200°C

Fig 5.57 Si_3N_4 Normal stress with combustion pressure @ 300°C

Fig 5.58 Si_3N_4 Normal stress with combustion pressure @ 360°C

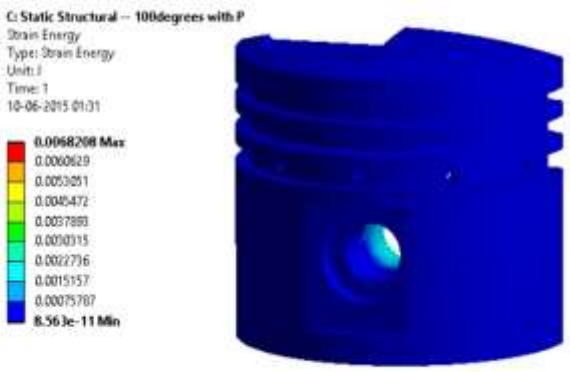

Fig 5.59 Si_3N_4 Strain Energy with combustion pressure @ 100°C

Fig 5.60 Si_3N_4 Strain Energy with combustion pressure @ 360°C

Fig 5.61 Si_3N_4 Normal stress without combustion pressure @ 100°C

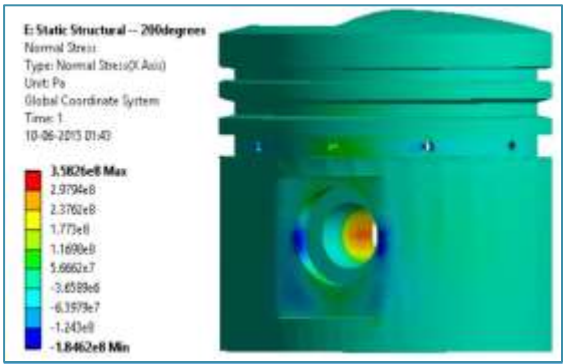

Fig 5.62 Si_3N_4 Normal stress without combustion pressure @ 200°C

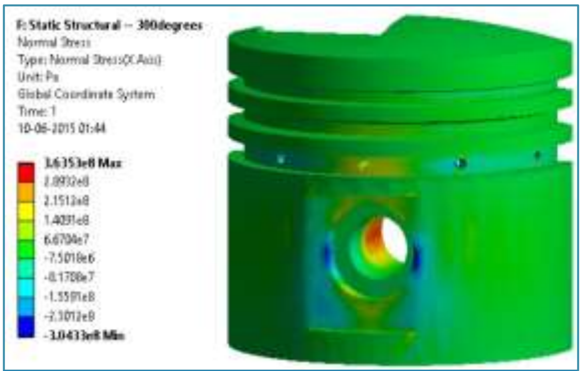

Fig 5.63 Si_3N_4 Normal stress without combustion pressure @ 300°C

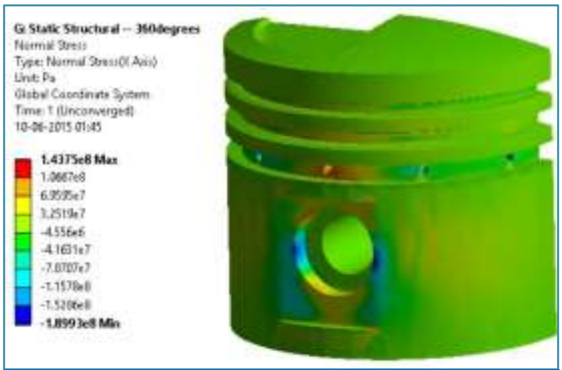

Fig 5.64 Si_3N_4 Normal stress without combustion pressure @ 360°C

Fig 5.65 Si_3N_4 Strain Energy without combustion pressure @ 100°C

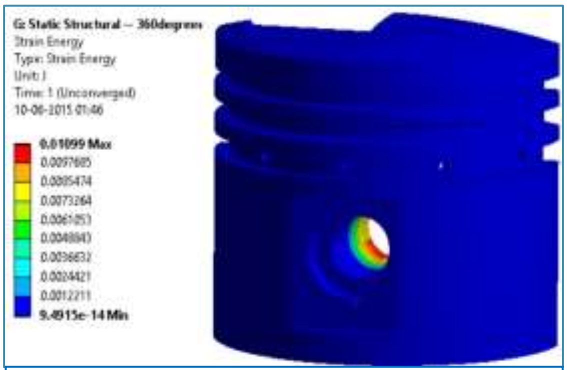

Fig 5.66 Si_3N_4 Strain Energy without combustion pressure @ 360°C

6. RESULTS AND DISCUSSIONS

As discussed, this thesis deals with the tricky combination of materials that demands unique criterion for comparing the aluminium alloy with the ceramic composites. Unfortunately the famous Von mises or equivalent stress criterion does not holds good with the failure criterion of brittle materials which is discussed as suggestive criteria upon which to some extent brittle materials failure can be analyzed[19][20]. So in order to compare the results precisely strain energy based normal stress criteria is considered[28], which is the same reason why normal stress plots and strain energy plots are depicted for the considered thermal loads. And this normal stress criteria was considered knowing the fact that equivalent stress of Al 413.0 is well within the limit, and infact it is the conventional alloy which is proven to have stresses within the limits for the given loading conditions.

Since pistons are intended to be in working environment inside the combustion chamber experiencing combustion temperature and pressure, it is thoughtful in just comparing the results obtained from first category, i.e., static structural analysis with combustion pressure. Though the static analysis of piston due to thermal loading without considering combustion gas pressure also depicted, discussions on those results will not get any productive results which is away from real time scenario.

According to the above considered criteria, strain energy is same as work done in any component. Normally strain energy stored in a material when it is subjected to normal stress. And maximum distortion energy theory depends upon strain energy that distorts the material[28].

By normal stress theory, strain occurs due to compression and tensile loading on the component. And hence it is apt to take account of the arrived normal stress plots of ZrO_2 and Si_3N_4 composites to be within the range and low in comparison to the Al 413.0 alloy. To be concise with the discussion from the adequate result datum available, a random result can be picked and discussed. For consideration, analysis under 360°C is taken into account. Since 360°C is the peak service temperature of the aluminium alloy piston, it is considered as benchmark. Though ceramic can have thrice the service temperature of aluminium, it is arbiturarily assumed as benchmark because of conventional cooling system (heat transfer coefficient) is considered.

Calling fig (5.35), (5.45) and (5.57), maximum and minimum values of normal stress and strain energy from which conclusion can be arrived have been tabulated in table 6.1. The maximum and minimum values of strain energy considering fig (5.37), (5.49) and (5.61) for the same maximum service temperature of the piston, arbiturarily assuming aluminium alloy piston as benchmark in maximum service .

Table 6.1 – Maximum and minimum values of normal stress on piston

S.No.	**Composite**	**Thermal loading and combustion pressure**			
		Normal Stress (Mpa)		Strain Energy	
		Maximum	Minimum	Maximum	Minimum
1	Al 413.0	437*	-323	4.54E-2*	5.90E-11
2	ZrO_2	675*	-1172	7.89E-2*	7.9E-11
3	Si_3N_4	358*	-590	2.83E-2*	1.131E-10

Note - * indicates values that occur on piston pin which can be neglected.

From the above table 6.1, solution can be arrived to suggest which composite piston experience less stress in comparison. In this investigation, Al 413.0 alloy experience less normal stress than the two ceramic composites. Its minimum value (compression stress) at thermal loading and combustion pressure is the least in comparison. Table 6.1 shown during thermal loading and combustion pressure, the minimum value of strain energy imparted in Al 413.0 piston is least when compared to zirconia and silicon nitride. As discussed earlier, maximum distortion energy theory depends upon this strain energy, aluminium alloy composite piston experiences least stress during peak working conditions with conventional cooling.

Note that, this investigation turn in favor of aluminium alloy piston due to lack of absolute experimental values available for ceramics.

But, what if the percentage of normal stress value with respect to the compressive stress of the material? Al 413.0 normal stress is 13.3% of the compressive stress of the alloy itself. So as 77.5% for Zirconia and 78.6% for Silicon Nitride. Above means Si_3N_4 is arguably stronger than the Al 413.0 alloy. On the other hand, Al 413.0 alloy has the less strain energy value which is attributed by the stiffness of the material, whereas the ceramic material has least stiffness in comparison.

7. CONCLUSION

1. Thus piston of an 4-stroke I.C. reciprocating engine has been designed. Engine data pertained to a type of diesel engine was collected and analyzed. Ceramic materials which possess close properties to aluminium and that could be used for manufacturing piston were chosen. Operating conditions and boundary conditions were studied. Material properties of all the composites were collected.
2. In the thermal and structural analysis part coupled field stress distribution were investigated and results were generated in the form of plots; and minimum and maximum values.
3. The generated results were been compared with each keeping aluminium alloy composite piston as benchmark. The possibility of using ceramic based piston have been made and discussed below. From the above discussion made from table 6.1, it is suggested to go with aluminium composite piston though the maximum and minimum values of the normal stress are within the limit of tensile and compression strengths accounting the stiffness factor, the aluminium alloy inherited with since the piston is the critical component that withstands not only heat and combustion pressure, but also thermal and mechanical shocks as well due to detonation and engine loading respectively. But suggestion can be made from the above results, because in future, if engineers get idea of experimenting or manufacturing full ceramic piston or fibre re-inforced ceramic piston, this investigation could throw some light. So the ceramic composites are graded, which one can be preferred in place of aluminium alloy. It is suggested to choose silicon nitride composite to produce piston, because it is better next to the aluminium alloy composite in both normal stress and stress energy criterion.

8. FUTURE PROSPECTS OF THE INVESTIGATION

1. Fibre re-inforced ceramic composite can be considered by studying the material properties and crystal matrices which will account the stiffness factor, that this investigation lacking in.
2. Graphite or graphene can be considered for future investigation.

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