DESIGN, THERMAL ANALYSIS AND OPTIMIZATION OF A PISTON USING ANSYS

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Abstract - *As the main heating part in the engine, piston works for a long time in high temperature and high load environment. The piston has the characteristics of large heating area and poor heat dissipation, so the thermal load is the most serious problem. This thesis presents a numerical method using thermos-mechanical decoupled FEM (Finite Element Method) to calculate the thermal stress only caused by the uneven temperature distribution. In this work, the main emphasis is placed on the study of thermal behavior of functionally graded materials obtained by means of using a commercial code ANSYS on aluminum alloy piston surfaces. The analysis is carried out to reduce the stress concentration on the upper end of the piston i.e. (piston head/crown and piston skirt and sleeve). With using computer-aided design, SolidWorks software the structural model of a piston will be developed. Furthermore, the finite element analysis is done using Computer Aided Simulation software ANSYS.*

***Key Words*: Piston, Aluminium Alloy, Stress, Thermos-mechanical decoupled FEM, ANSYS**

1. INTRODUCTION

Automobile components are in great demand these days because of increased use of automobiles. The increased demand is due to improved performance and reduced cost of these components. R&D and testing engineers should develop critical components in shortest possible time to minimize launch time for new products. This necessitates understanding of new technologies and quick absorption in the development of new products.

A piston is a component of reciprocating IC-engines. It is the moving component that is contained by a cylinder and is made gas-tight by piston rings. In an engine, its purpose is to transfer force from expanding gas in the cylinder to the crankshaft via a piston rod and/or connecting rod. As an important part in an engine, 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/crown cracks and so on. The investigations indicate that the greatest stress appears on the upper end of the piston and stress concentration is one of the mainly reason for fatigue failure. On the other hand, piston overheating-seizure can only occur when something burns or scrapes away the oil film that exists between the piston and the cylinder wall.

1.1 Problem Statement

Based on the literature survey performed, venture into this research is motivated by the fact that Pistons are required to have high performance characteristics and better precision as they are supposed to sustain high temperature and stresses. Piston skirt may appear deformation at work, which usually causes crack on the upper end of piston head. Due to the deformation, the greatest stress concentration is caused on the upper end of piston, the situation becomes more serious when the stiffness of the piston is not enough, and the crack generally appeared at the point A which may gradually extend and even cause splitting along the piston vertical. The stress distribution on the piston mainly depends on the deformation of piston. Therefore, in order to reduce the stress concentration, the piston crown should have enough stiffness to reduce the deformation.

Exponential analysis of piston is hectic and not very precise work. Exact theoretical analysis of piston characteristics is very difficult. With the use of high speed computers and the numerical techniques, the piston analysis can be made using CAE. That's why stress analysis is to be performed using simulation software. Thus, the FEA will be carried out for standard piston model used in diesel engine and optimisation of the same will be carried out.

1.2 Objective

The main objective of the present work is to find out and suggest optimum material for piston based on quality and economy considering material weight and dimensional issues at the same time. After generating an accurate finite element model, a strategy for the optimization workflow was defined. Target of the optimization was to reach at minimum thermal stresses in the piston.

The proposed work included following steps:

- ✓ Study of literature review of various work reported.
- ✓ The piston is designed according to the procedure and specification which are given in machine design and data hand books.
- ✓ CAD model of Piston is created using various tools in SolidWorks.

- ✓ FE analysis of the above geometry for different loading and boundary conditions is done as
  - Gas Pressure at top of the Piston (3MPa)
  - Temperature at the top of the Piston (200°C- 300°C).
  - Heat transfer Coefficient (5E-6 W/mm °C.)
  - Frictionless Supports.
- ✓ Comparison of the result obtained in above step for different materials.
- ✓ Choosing the optimum design based on the material and other parameter.

2. LITERATURE REVIEW

Dipayan Sinha, Susenjit Sarkar and Samar Chandra Mandal [1] (June 2017) presented the study of Thermo-Mechanical Analysis of a Piston with Different Thermal Barrier Coating Configuration. In the present work a piston has been analyzed numerically with FEA software named ANSYS Workbench to evaluate its thermos-mechanical capability under a predefined thermal and structural load. To enhance the performance of the engine, weight of the piston has been kept minimum by optimizing different dimensions. Yaohui Lu, Xing Zhang, Penglin Xiang, Dawei Dong [2] (Nov. 2016) presented the study of Analysis of Thermal Temperature Fields and Thermal Stress under Steady Temperature field of Diesel Engine Piston. This paper tries to present a new calculation method for the theoretical design of the piston. Vaishali R. Nimbarte, Prof. S.D. Khamankar [3] (Aug 2015) presented the study of stress analysis of piston using pressure load and thermal load. The main objective of this research work is to investigate and analyze the stress distribution of piston at actual engine condition. In this paper pressure analysis, thermal analysis and thermo-mechanical analysis is done. The parameter used for the analysis is operating gas pressure, temperature and material properties of piston. Muhammet Cerit*, Mehmet Coban [4] (2014) presented the study of Temperature and thermal stress analyses of a ceramic-coated aluminum alloy piston used in a diesel engine. The goal of this paper is to determine both temperature and thermal stress distributions in a plasmasprayed magnesia-stabilized zirconia coating on an aluminum piston crown to improve the performance of a diesel engine. R. Bhagat, Y. M. Jibhakate [5] (Aug-2012) presented the study of Thermal Analysis and Optimization of I.C. Engine Piston Using finite Element Method. This paper describes the stress distribution of the seizure on piston four stroke engines by using FEA. The finite element analysis is performed by using computer aided design (CAD) software. The main objective is to investigate and analyze the thermal stress distribution of piston at the real engine condition during combustion process. The paper describes the mesh optimization with using finite element analysis technique to predict the higher stress and critical region on the component.

3. ANALYTICAL CALCULATIONS

Analytical calculations are done for cast iron piston. For doing analytical calculation material properties and dimensional information should be known and so all the parameters consider for design of piston are calculated by using one analytical problem.

3.1 Procedure for Piston Design

The procedure for piston designs consists of the following steps:

a. Thickness of piston head (t_H)
b. Heat flows through the piston head (H)
c. Radial thickness of the ring (t_1)
d. Axial thickness of the ring (t_2)
e. Width of the top land (b_1)
f. Width of other ring lands (b_2)

TABLE -1: DESIGN SPECIFICATION FOR PISTON

SR. NO.	DESCRIPTION	NOTATION	UNIT	VALUE ARRIVED	VALUE USED
1	Length of Piston	L	Mm	--	75
2	Outside diameter of Piston	D	Mm	--	84
3	Thickness of Piston Head	t_H	Mm	7.75	10
4	Radial thickness of the ring	t_1	Mm	2.84	4
5	Axial thickness of the ring	t_2	Mm	4	4
6	Maximum Thickness of barrel	t_3	Mm	11.42	12
7	Width of the top land	b_1	Mm	12	12
8	Width of other ring lands	b_2	Mm	4	4

4. MATERIAL SELECTION

Pistons are produced from cast or forged, high-temperature resistant aluminum silicon alloys. There are three basic types of aluminum piston alloys. The standard piston alloy is a eutectic Al-12%Si alloy containing in addition approx. 1% each of Cu, Ni and Mg. Special eutectic alloys have been developed for improved strength at high temperatures. Hypereutectic alloys with 18 and 24% Si provide lower thermal expansion and wear, but have lower strength (see tabled property data on the following pages). In practice, the supplier of aluminum pistons use a wide range of further optimized alloy compositions, but generally based on these basic alloy types. The majority of pistons are produced by gravity die casting. Optimized alloy compositions and a properly controlled solidification conditions allow the production of pistons with low weight and high structural strength.

5. FINITE ELEMENT METHOD

5.1 Introduction

Finite Element Method (FEM) is a computer-based numerical technique for calculating the Strength and behavior of engineering structures. It can be used to calculate deflection, stress, vibration, Buckling behavior and many other phenomena. In the finite element method, a structure is broken down into many small simple blocks or elements. The behavior of an individual element can be described with a relatively simple set of equations. Just as the set of elements would be joined together to build the whole structure, the equation describing the behaviors of the individual elements are joined into an extremely large set of equations that describe the behavior of the whole structure. The computer can solve this set of simultaneous equations. From the solution, the computer extracts the behavior of the individual elements. From this, it can get the stress and deflection of all the parts of the structure. The stresses will be compared to allowed values of stress for the materials to be used, to see if the structure is strong enough.

5.2 Basic steps in FEM

- ✓ Discretization of the structure
- ✓ Selection of proper interpolation or displacement model
- ✓ Derivation of element stiffness matrices and load vectors
- ✓ Solution for the unknown nodal displacements
- ✓ Computational of elemental stress and strains

5.3 Optimization using FEA

Optimization of an engineering design is an improvement of a proposed design that results in the best properties for minimum cost. One of the simplest examples is determining the shape of a fence that will enclose the most area. If the fence can be any shape, but only a certain amount of fencing is available, then a circle will enclose the most area with the given amount of fencing. In order to minimize the amount of steel used in manufacturing a cylindrical tin can a certain relationship between the diameter of the can and the height of the can is found. This will enclose a volume with the least amount of steel used for the surface area.

5.4 Techniques for stress analysis

Stress Analysis as the name implies, stress analysis is the complete and comprehensive study of specimen under consideration. The main objective of stress analysis is to keep the working stresses within its limits for evaluating the factor for economical design criteria and to improve the product quality. Material characteristics can be predicted successfully through stress analysis. The techniques for stress analysis can be stated as follows

- ✓ Analytical techniques
- ✓ Experimental techniques
- ✓ Numerical Techniques
- ✓ Element Used in Finite Element Method

6. MESHING & BOUNDARY CONDITIONS

Steady-state thermal stress analyses are executed to study the thermal stress effect of on the piston of various materials. The variations of temperature and thermal stress on the piston are investigated for three materials named as Eutectic Alloy, hyper Eutectic alloy and Special Eutectic alloy. Thermal stress analyses are performed by using the general-purpose package software ANSYS, produced by ANSYS Inc.

6.1 Meshing

Before starting Finite element analysis, other factors must be determined first. These factors are discussed as follows.

6.1.1 Choice of element

For meshing purpose solid element has been selected. This type of element is used to mesh solid model in ANSYS. These volumes could be created in the ANSYS pre-processor or imported from a CAD system. Hexahedral elements (bricks) can be used to mesh regularly shaped rectangular type volumes, while tetrahedral element can used to mesh any volume three or four node points in a plane and experience bending deformation when loaded by forces transverse to their surfaces. There are different types of solid element used in ANSYS for different condition. Some of the elements are shown in table

TABLE -2: ELEMENT TYPE FOR STRUCTURAL ANALYSIS

Element Order	Line Elements	3D Shell	2D Solid	3D Solid
Linear	BEAM3/44 BEAM188	SHELL63 SHELL181	PLANE42 PLANE182	SOLID45 SOLID185
Quadratic	BEAM189	SHELL93	PLANE82/183 PLANE2	SOLID95/186 SOLID92/187

6.1.2 Discretization of element

In every analysis, very first step is to import geometry to the ANSYS environment. Discretize the model into elements and nodes. ANSYS workbench is selected for meshing. Automatic selection is done in ANSYS workbench in which solid element is selected. The piston is meshed into elements count 162329 and nodes 261533. Mesh of piston as shown in Fig. 1

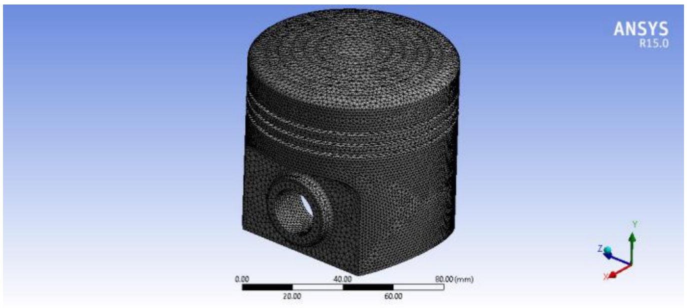

Fig -1: Meshing of piston

6.2 Boundary Conditions

6.2.1 Frictionless support at Piston Pin location

The small end of connecting rod attaches to the piston pin, gudgeon pin or wrist pin, which is currently most often press fit into the connecting rod but can swivel in the piston, a "floating wrist pin" design. Piston is connected to the connecting rod with the help of piston pin in such a way that it allows linear sliding of piston inside the cylinder and also allows to freely rotate. This boundary condition is achieved by using Frictionless support at the location of the piston pin as shown in Fig. 2

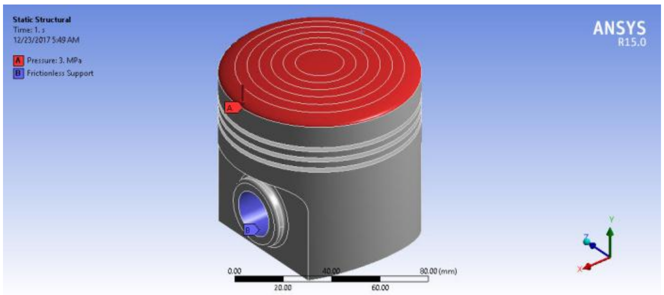

Fig -2: Frictionless Support

6.2.2 Pressure

Combustion of gases in the combustion chamber exerts pressure on the head of the piston during power stroke. The pressure force will be taken as boundary condition in structural analysis. Frictionless support has given at surface of pin hole. Because the piston will move from TDC to BDC with the help of fixed support at pin hole. So, whatever the load is applying on piston due to gas explosion that force causes to failure of piston pin (inducing bending stresses). Pressure acting on piston = 3 N/mm2 as shown in Fig.3

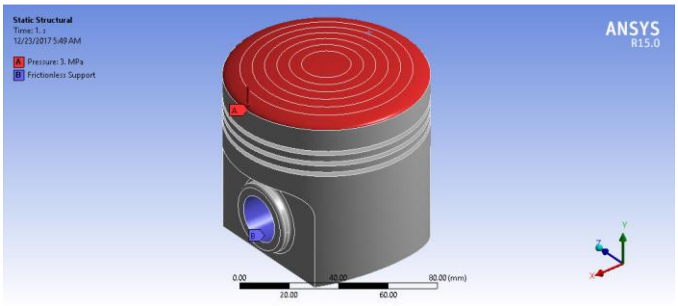

Fig -3: Gas Pressure on the head of the piston

6.2.3 Temperature

Along the axis of the piston, the temperature distribution is symmetrical. The temperature of the piston top surface is relatively high, especially at the center and the edge of the combustion chamber, meanwhile the temperature of piston skirt is relatively low. The maximum surface temperature of the piston (300°C) appears at the edge of the piston combustion chamber because the piston top experiences the highest thermal load and the edge of combustion chamber is subjected constantly to high temperature values of gas. The lowest temperature of the piston is 200°C and appears at the bottom of the piston skirt. The lower crankcase temperature and the presence of cooling oil also cause this phenomenon.

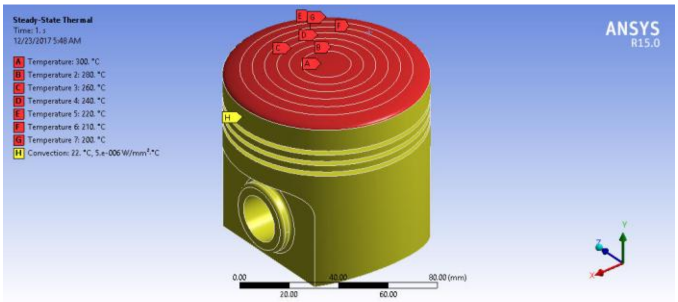

Fig -4: Temperature value for reference point on piston

7. RESULTS

After applying the complete mechanical load and thermal load (steady-state temperature field), the distribution of the thermo mechanical stress is shown below

7.1 Thermal mechanical coupling stress on the piston

According to the thermal mechanical coupling analysis results, it can be seen that the distribution of the thermal mechanical coupling stress is minimum in Hyper Eutectic Alloy.

The maximum stress is higher (97.90 MPa) for Eutectic Alloy (AISi12 CuMgNi) and appears in the pin hole region. However, this is not likely to cause structural damage or plastic deformation, since the stress is far less than the yield limit (230 MPa) of piston material. The piston meets the strength requirements of the structure.

The maximum stress is medium (94.07 MPa) for Special Eutectic Alloy (AISi18 CuMgNi) and appears in the pin hole region. However, this is not likely to cause structural damage or plastic deformation, since the stress is far less than the yield limit (280 MPa) of piston material.

The maximum stress is lower (90.78 MPa) for Hyper Eutectic Alloy (AISi12 Cu4Ni2Mg) and appears in the pin hole region. However, this is not likely to cause structural damage or plastic deformation, since the stress is far less than the yield limit (200 MPa) of piston material.

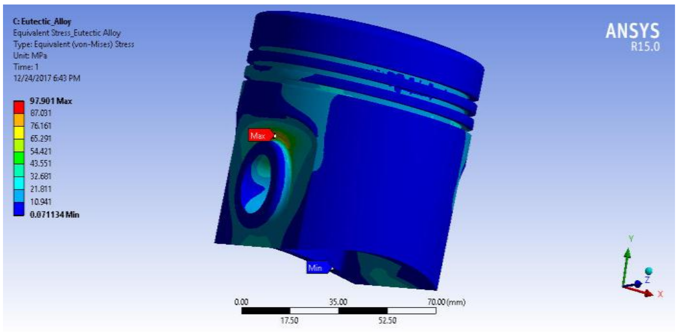

Fig -5: Thermal mechanical coupling stress on the piston for Eutectic Material

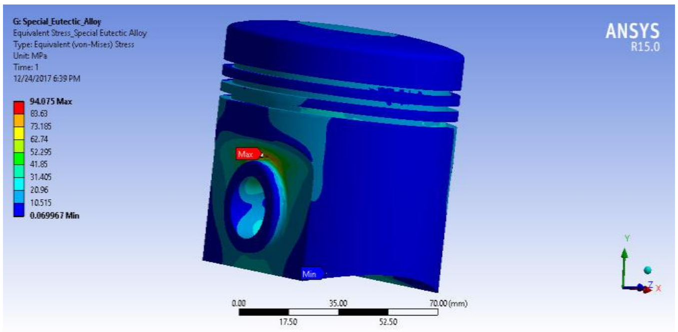

Fig -6: Thermal mechanical coupling stress on the piston for Special Eutectic Material

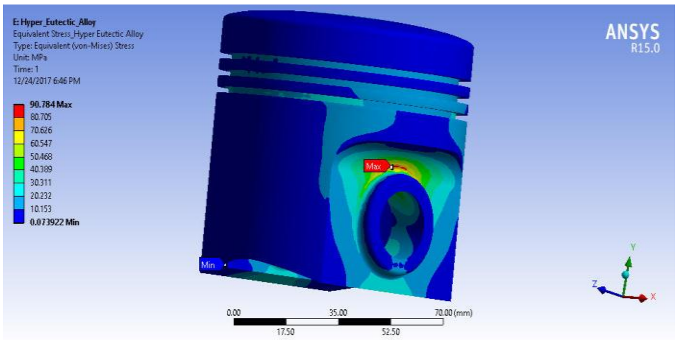

Fig -7: Thermal mechanical coupling stress on the piston for Hyper Eutectic Material

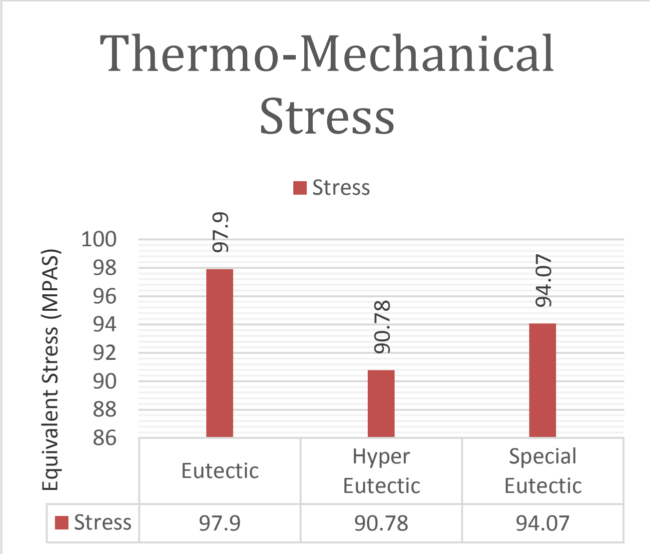

Chart -1: Thermal mechanical coupling stress on the piston

7.2 Thermal mechanical coupling strain on the piston

According to the thermal mechanical coupling analysis results, the distribution of the thermal mechanical coupling strain is minimum in Special Eutectic Alloy.

The maximum strain is higher (1.3396 mm/mm) for Eutectic Alloy and appears in the pin hole region. However, this is not likely to cause structural damage or plastic deformation. The maximum strain is medium (1.249 mm/mm) for special Eutectic Alloy and appears in the pin hole region. However, this is not likely to cause structural damage or plastic deformation.

The maximum strain is lower (1.255 mm/mm) for Hyper Eutectic Alloy and appears in the pin hole region. However, this is not likely to cause structural damage or plastic deformation.

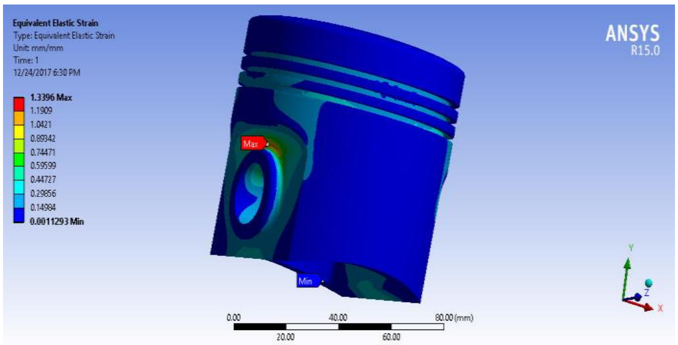

Fig -8: Thermal mechanical coupling strain on the piston for Eutectic Material

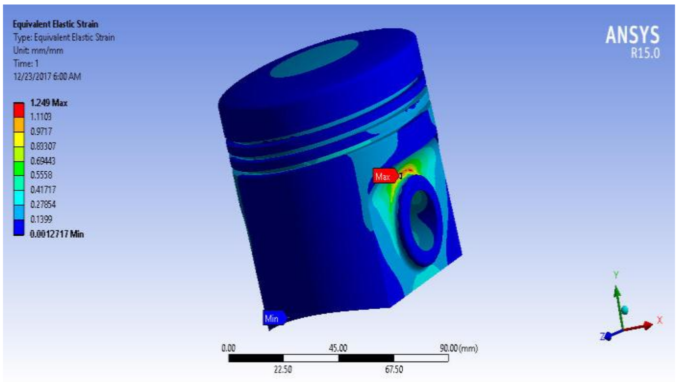

Fig -9: Thermal mechanical coupling strain on the piston for Special Eutectic Material

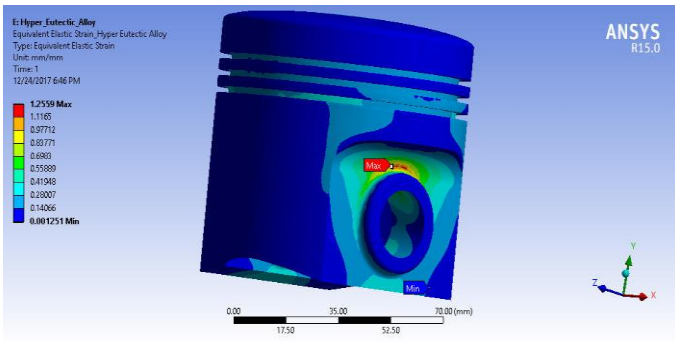

Fig -10: Thermal mechanical coupling strain on the piston for Hyper Eutectic Material

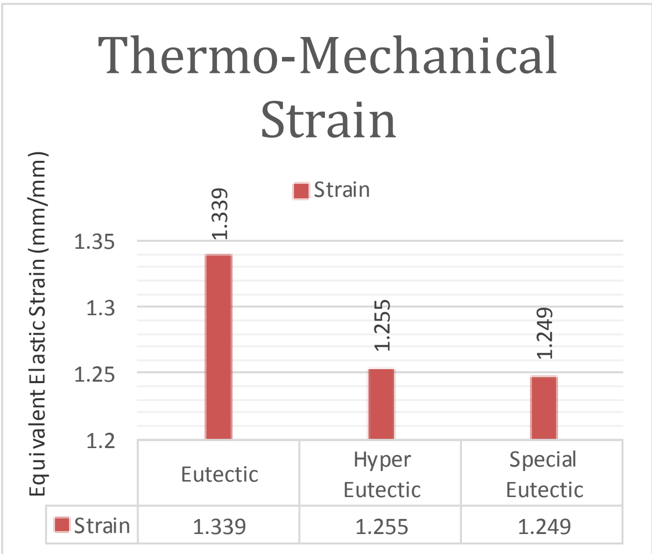

Chart -2: Thermal mechanical coupling strain on the piston

7.3 Heat Flux on the piston

According to the thermal analysis results, the distribution of the heat flow rate intensity is maximum in Eutectic Alloy.

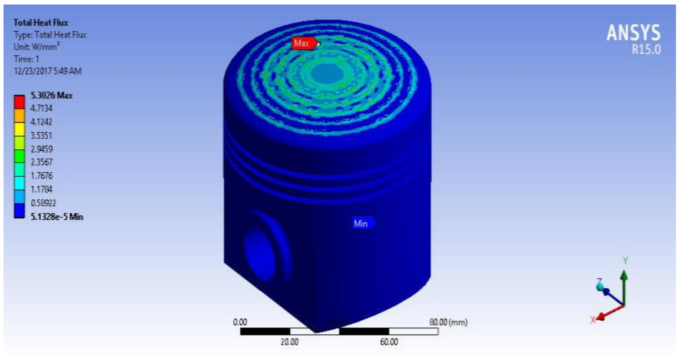

Fig -11: Heat Flux on the piston for Eutectic material

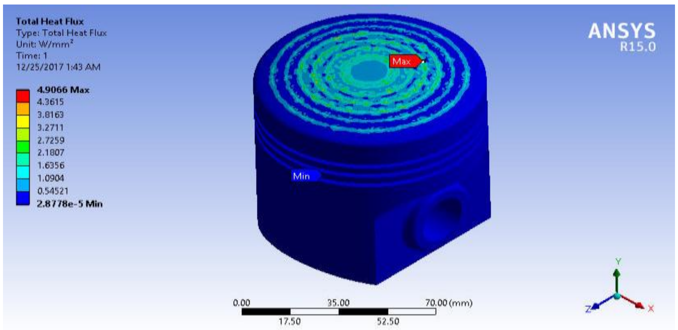

Fig -12: Heat Flux on the piston for Special Eutectic material

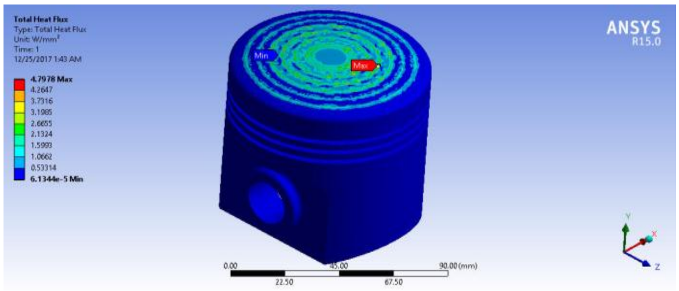

Fig -13: Heat Flux on the piston for Hyper Eutectic material

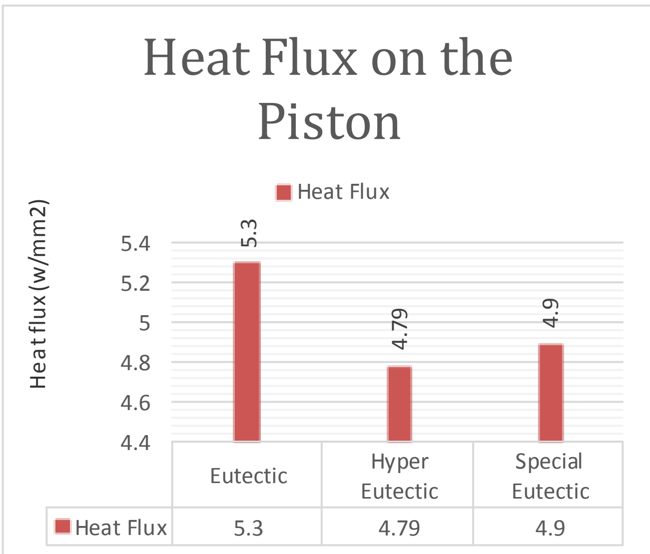

Chart -3: Heat flux on the piston

8. CONCLUSION

The thermal stress field only caused by the uneven temperature distribution was obtained in this study. To simulate the stress field, the steady-state temperature field was calculated. In thermal stress analysis, the overall constraint of the piston is achieved by fixing piston pin, which is consistent with the actual working condition of the piston. After all the works that have been done before, the simulation results of thermal stress are obtained properly. This thesis tries to put forward a thermal mechanical decoupling method, which is used to simulate the thermal stress field only caused by the uneven temperature distribution when piston works. The basic conclusions are presented below:

- ✓ The temperature distribution on the piston crown is relatively complex; the highest temperature appears in combustion chamber bottom, while temperature at the edge of combustion chamber is quite high too, but no more than the material allowable range. The temperature on piston ring is not high, since the external heat dissipating capacity is small leading to small heating load. The overall temperature of the piston skirt is low and the thermal load is low as well.
- ✓ In this thesis, a new constraint method is proposed in piston thermal stress analysis. The overall constraint of the piston is achieved by fixing piston pin with frictionless support, since the pin can indirectly constraints the piston by the contact between them, which is consistent with the actual working condition of the piston.
- ✓ It can be seen that the distribution of the thermal mechanical coupling stress is minimum in Hyper Eutectic Alloy. But for Special Eutectic Alloy (AISi18 CuMgNi) the maximum stress is medium (94.07 MPa) as compared to other two alloys. However, this is not likely to cause structural damage or plastic deformation, since the stress is far less than the yield limit (280 MPa) of piston material.
- ✓ According to the thermal mechanical coupling analysis results, the distribution of the thermal mechanical coupling strain is minimum in Special Eutectic Alloy.
- ✓ The distribution of the heat flow rate intensity is maximum in Eutectic Alloy. For hyper eutectic alloy it is 4.9 W/mm^2 which is also near to eutectic alloy.
- ✓ Comparing all above points (Point-4 to 6) It is observed that the Special Eutectic alloy (AISi18 CuMgNi) is best suitable material for the piston.

9. REFRENCES

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