Design, Modeling and Analysis of Structural Strength of Cylinder and Cylinder Head of 4-stroke (10 H.P.) C.I. Engine – A Review

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Abstract — *The proficiency of any automobile engine is deals with the structural strength of its cylinder and cylinder head. Cylinder and cylinder head are most important parts of an engine because the piston moving inside the cylinder, so friction between cylinder wall and piston is very higher and due to this the mechanical load or fatigue load acting on the cylinder. So that structure of cylinder should be stronger. The combustion chamber, crank case, piston, connecting rod, crankshaft and cylinder are placed under the cylinder head. Cylinder head provides the protection against the high thermal and mechanical load on an engine, so the cylinder head is "a protector" of an engine and its parts.*

The review of existing literature on design, modeling and analysis of cylinder and cylinder head is presented. 3D-model of cylinder and cylinder head were created using Pro/Engineer software and ANSYS was used to analyze the thermal and structural analysis. So finally design considerations, material specifications, failure analysis, these all are reviewed successfully over here.

Keywords—Cylinder, cylinder head, FEM, Pro/Engineer, ANSYS, fatigue load, thermal load, structural strength.

I. INTRODUCTION

The diesel engine is one kind of Internal Combustion engine. An internal means "Inside" and combustion is similar word for "Burning", So an Internal Combustion engine is simply one where the fuel is burned inside the cylinder where power is produced. That's very different from an External Combustion engine such as those used by old fashioned steam locomotives.

CYLINDER

The cylinder of an I.C. engine contains the working fluid and guides the piston. The cylinder has to withstand high temperature due to the combustion of fuel; So that, some arrangement must be provided to cool the cylinder. The cylinder engines are generally **Air Cooled** and **Water Cooled.**

AIR COOLED CYLINDER: Air cooled cylinder is commonly applicable for small engines say up to **20KW.** In this type of cylinder fins are provided on the cylinder walls. Heat produced due to combustion in the engine cylinder and heat will be easily dissipated to air by help of provided fins.

WATER COOLED CYLINDER: In this type of cylinder water jackets are provided around the cylinder. The water when circulated through the jackets, It absorb heat of combustion. The water cooled cylinders mainly used in heavy engines having capacity above **20 KW.**

CYLINDER HEAD

In an Internal combustion engine the cylinder head located above the cylinder on top of the cylinder block. It closes the top of the cylinder and forming the combustion chamber. This joint is sealed by use of head gasket. The head also gives space for the passages that feed air and fuel to the cylinder and that allow the exhaust to escape. The cylinder head can also be a place to mount the valves, fuel injectors and spark plugs. The cylinder head are also either **Air cooled** or **Water cooled**.

AIR COOLED CYLINDER HEAD: In this type of cylinder head fins are provided on the outer surface of cylinder head. Heat produced due to combustion in the engine cylinder and heat will be easily dissipated to air by help of provided fins on cylinder head.

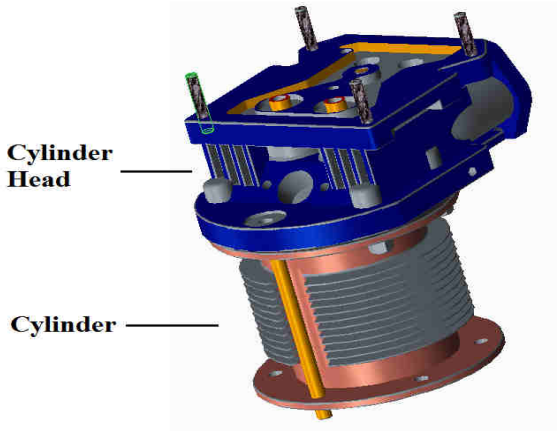


Fig.1: Assembly of the Cylinder and Cylinder Head

WATER COOLED CYLINDER HEAD: In this type of cylinder head water jackets are provided around the outer surface of cylinder head. The water when circulated through the jackets, It absorb heat of combustion.

II. LOADS ACTING ON CYLINDER AND CYLINDER HEAD

I.) Inertia force on cylinder due to unbalance forces from piston and connecting rod setup.
II.) Vibration force in cylinder due to the speed variation in crankshaft.
III.) Thermal load on cylinder and cylinder head due to improper temperature distribution.
IV.) Mechanical load on cylinder head due to the improper stress distribution.
V.) Fatigue load due to cyclic load on cylinder head.
VI.) Load on cylinder due to the explosion of fuel gases.
VII.) Load on cylinder due to compression of fuel gases.

III. MATERIALS AND MANUFACTURING PROCESSES

The fundamental concepts and surface coating method, Air Plasma Spray (APS) concerned with cylinder and cylinder head of an I.C. engine had studied by **Peter Ernst** et al.**[14]** At a here they had marked the results under full load conditions of an engine the APS coating showed a reduction in friction of over 20% compared to the cast iron baseline. They have also studied that the improvement of heat transfer from the combustion chamber into the water jacket and weight reduction are carried out by using Aluminum alloys in place of cast iron sleeves and also this technique is a leading edge choice of Original Equipment Manufacturer (OEM) from the last few years.

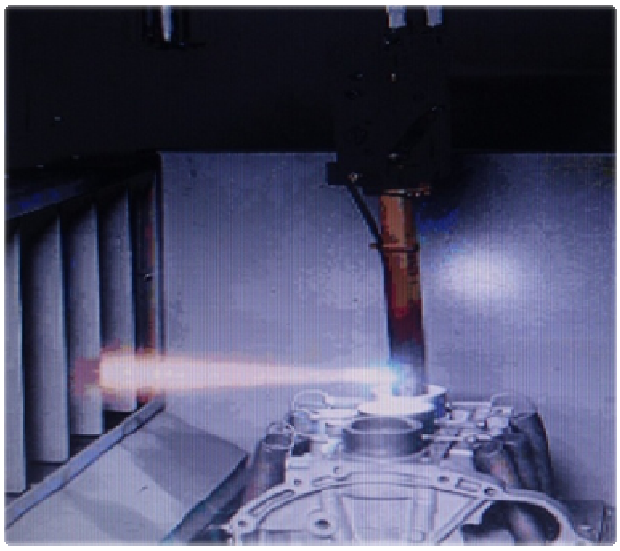


Fig.2: One SM F210 plasma torch in an aluminum 3-cylinder engine block [14]

G.Karthik et al.**[7]** obtained result for a cylinder and cylinder head for passion plus 100cc motorcycle is that the current used material for cylinder and cylinder head is Stainless Steel with 3mm thickness. But they had observed results by using Cast iron, Aluminum 6061 alloy with 1.5 mm thickness as a material in place of stainless steel based on their thermal conductivity and densities. The density of an Aluminum 6061 alloy is less in compare to Stainless steel and Cast iron, So weight of the body reduced due to application of an Aluminum 6061 alloy. And also they had observed that the thermal flux is more for Aluminum 6061 alloy than the other two materials and the overall weight is also less than the Stainless steel and Cast iron, So here Aluminum 6061 alloy is better in place of Stainless steel and Cast iron.

T.Hejwowski et al.**[19]** studied about effects of thin thermal barrier coating on the performance of a diesel engine. This gives results of thermally insulated piston and cylinder liners. Here the temperature and stress distribution within the piston and cylinder liners evaluated by using FEM code. The performance of the modified engine was found satisfactory and ceramic coating did not produce observable knock in an engine and also there is no significant wear of piston skirts or cylinder liners was found.

Replacement of the cast iron liners in Aluminum engine cylinder bores was carried out by **John Lenny Jr.[8]** In this project, He studied about to improve the tribological characteristics of Aluminum cylinder bore by using following four alternatives:

I.) By using Hypereutectic Al-Si alloy in cylinder bore surface.
II.) By using Fiber Reinforced Aluminum matrix composite on cylinder wall.
III.) By applying thermal spray coating on hypoeutectic Aluminum bore surface of cylinder.
IV.) By Electrochemical deposition coating on hypoeutectic Aluminum bore surface of the cylinder.

So, from study of above four alternatives, obtained conclusion that the thermal spray coating on hypoeutectic Aluminum bore of cylinder gives the best result in the all required tribological characteristics of cylinder of an engine.

Nitesh Mittal et al.**[12]** investigated that the performance of an engine improved by coating the surfaces of cylinder head and valves with ceramic material including Zirconium Dioxide (ZrO_2) having 8% by weight of Yttrium Oxide (Y_2O_3) with a thickness of 0.3mm by plasma spray method.

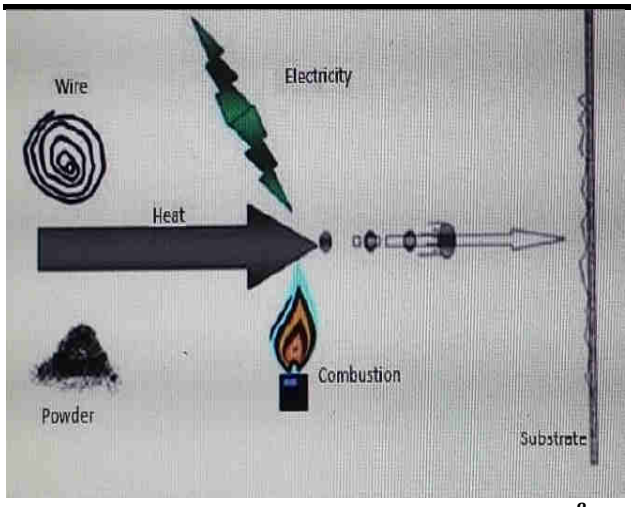


Fig.3: Scheme of Thermal spray Coating process[8]

IV. DESIGN CONSIDERATIONS AND ANALYSIS

The FEM analysis of cylinder head was carried out by **Shixiong Li** et al.**[17]** They had found that the nose bridge area between the inlet and exhaust valves was very fragile on the cylinder head. For improving the overall structure of the cylinder head they had prepared the model first in the Pro/Engineer Wildfire 2.0 and after they had predicted the critical area and failure mode on cylinder head by help of finite element simulation. Finally the structure of nose bridge and other parts of cylinder head improved by using Finite Element Analysis software ANSYS 9.0.

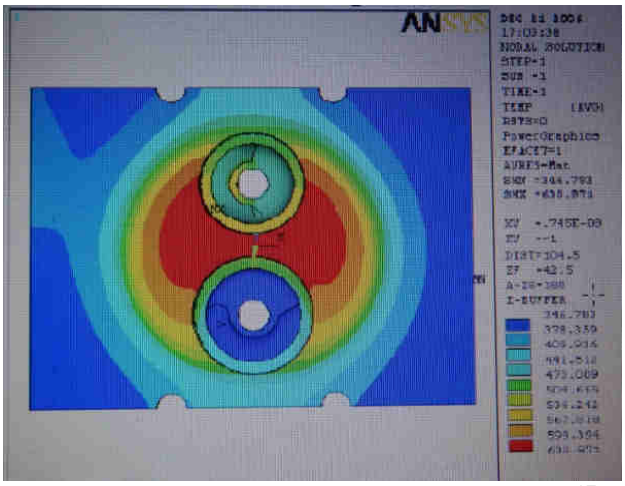


Fig.4: Temperature distribution of original design[17]

Cheng x. et al.**[5]** analyzed on the cylinder head of the heavy diesel engine by performing 3-dimensional CFD analysis with the cylinder combustion and an engine cooling jacket, stress and strain analysis under thermal-mechanical coupling conditions and high cycle fatigue analysis and also they had measured temperature distribution on the engine head and predicts the danger region through calculation matches the crack in actual experiment. Finally they had obtained as the results that the stress at the crack region decreased from 245Mpa to 230Mpa after the increased wall thickness and the stress drop significantly after changed the cylinder material from gray iron to compacted graphite iron. Either replacing the material or increasing the wall thickness solved the crack failure problem easily.

New thermo-mechanical analysis of cylinder head was investigated by **M.Fadaei** et al. **[11]** In this paper the 3D model created by using Solid Works 2008. The mesh and analysis of cylinder head are constructed in ANSYS. Also here the uniforms fire deck cooling and the flow characteristics of the water jacket improved by using CFD analysis in ANSYS 10.

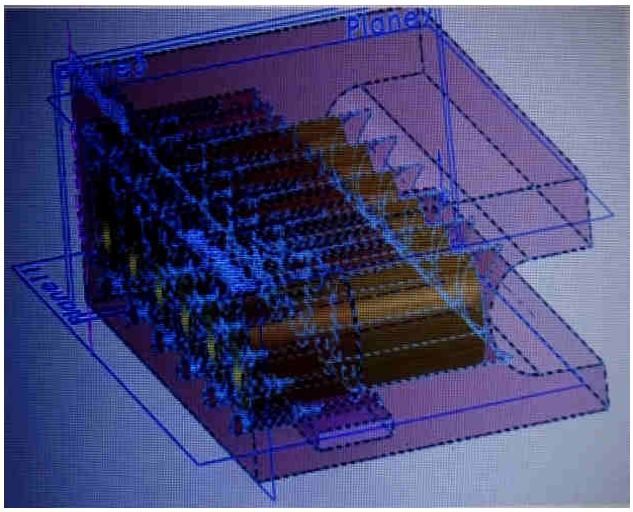


Fig.5: The cylinder water jacket for CFD analysis [11]

Baoxin Zhao et al.**[2]** evaluated that the problem of super heat generation in cylinder head. So, that the experiment and simulation done at the temperature field of the cylinder head of GW4D20 diesel engine. The simulation of heat transfer was taken out for the combustion chamber by help of the coupled finite element method (FEM). After that the temperature distribution at cylinder block, cylinder, cylinder head, cylinder gasket, valve seat and valve guide measured. The experimental results compared with the results of simulation based on hardness plug method. In this study they had offered that is new that the nucleate boiling was applied to research how to influence the heat transfer coefficient (HTC) of coolant side. So, that the temperature field of cylinder head was calculated through 3D fluid solid coupled simulation analysis and the problem of superheat of cylinder head was solved with the change of increasing baffle for each cylinder.

The heat transfer rate of cylinder body by varying it's geometry and material were calculated by **B N Niroop** et al.**[3]** They had calculated heat transfer rate for a 150cc

motorcycle which is modeled by using parametric software Pro/Engineer and after that they had changed three materials are Aluminum alloy 7075, Magnesium alloy and Beryllium in place of the Aluminum alloy 204 and also they had changed the thickness of fins from 3mm to 2.5mm for the weight reduction and finally they had obtained better heat transfer rate by performing total analysis with rectangular fins, circular fins and curved fins by help of analysis done in ANSYS.

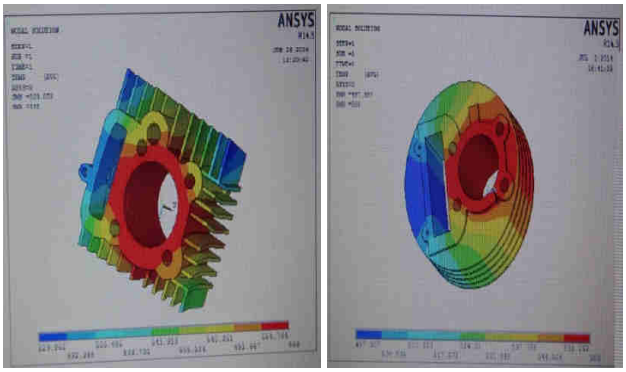


Fig.6: Curve shaped and circular shaped Beryllium at nodal temperature with 2.5mm thickness[3]

Mandloi P. et al.**[10]** talks by involving in their paper that how a simulation driven process for cylinder head design can be developed. So, first of all for new design or revamping an old design of the cylinder head many parameters are considered like material non-linearity,combustion, fluid flow, heat transfer and structural strength analysis. And also other parameters like designing of valves, jacket and combustion chamber improves to cylinder head design and it helps to test the durability and strength of the cylinder head. So they had developed a simulation driven process for cylinder head design.

Design and analysis of cylinder and cylinder head were carried out by **G.Karthik** et al.**[7]** In this paper the cylinder and cylinder head modeled using parametric software Pro/Engineer and here the original thickness of the cylinder and cylinder head reduced from 3mm to 1.5mm. Finally they had observed the thermal flux of Aluminum alloy is more than the Cast iron and Stainless steel as a part of thermal analysis. At a here the thermal analysis was done in COSMOS.

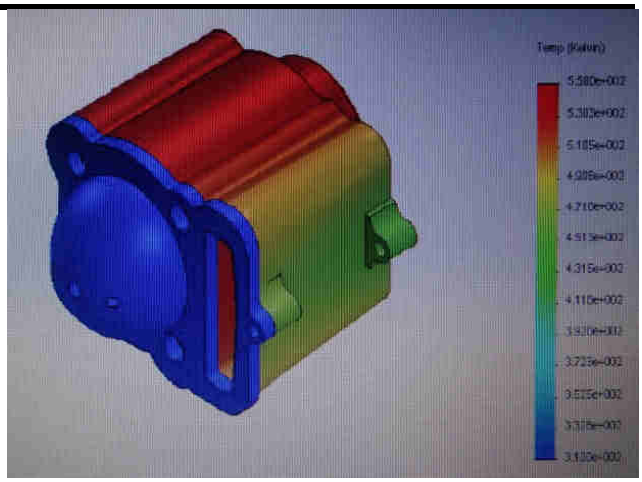


Fig.7: Temperature distribution on the model[7]

C.D.Rakopoulos et al.**[4]** investigated experimentally and theoretically that the phenomenon of short term cyclic response of temperature transients in the combustion chamber walls of an air cooled four stroke direct injection (DI) diesel engine. In which new pre-amplification unit developed for the fast response wall thermocouples and an object oriented code for fast data acquisition. Also at a here simulation code developed for the thermodynamic cycle of an engine for specially the closed and the open parts of it. So that the thermodynamic analysis done on both the closed and the open parts. After the applying the state equations and the energy with appropriate gas heat transfer and mass exchange with the atmosphere sub-models. After that the gas temperature variation throughout the engine cycle analyzed by using fourier analysis techniques. Here the theoretical analysis results compare well with the corresponding experimental ones at the load and speed conditions examined for the high wall thermal fatigue study on the cylinder walls of a diesel engine.

Jun Hong et al.**[9]** studied about the optimal design of the engine cylinder head in which a simplified topological model composed of beam, shell and membrane elements is developed to simulate the metal cylinder head. Here finite element method is used for the study of load-bearing mechanism of cylinder head during running condition of an engine. The behavior of all key components studied under stress and strain effect by parametric analysis. And the new optimization criterion is developed based on the Lagrange conditions which gives the ideal 'balanced point' among the main design parameters in terms of weight distribution of the key components the cylinder head. Finally in this way the optimization of cylinder head structure is implemented successfully.

Pradeep Mani Tripathi et al. **[15]** performed the thermal analysis on cylinder head. In which they had created model in Solid Works v12 and also they performed the two kinds of analysis like a steady-state thermal analysis and a transient thermal analysis. Also they used the FEM program for find out the temperature distribution on the parts of cylinder head. And they had changed the metal matrix composites in place of cast iron for reducing the weight and the analysis mentioned in this paper is handy in automotive applications.

Thermal analysis and surface temperature prediction was studied by **Amit V. Paratwar** and **D.B. Hulwan**. **[1]** They had developed the heat transfer model for analyzing the thermal behavior of diesel engine cylinder. In this paper the steady state heat transfer analysis of cylinder liner and cylinder head was done using CFD analysis. And they marked that the theoretical values of the gas side heat transfer co-efficient with crank angle reaches peak value of 3000 W/m^{2}k at 15˚ after TDC. After that they performed the thermal simulations and found that the maximum temperature present in the region of exhaust port and also at near the exhaust bridge. Finally by help of CFD analysis and by help of thermal simulations they obtained temperature drop by 7-10K in the critical zones as simulation result.

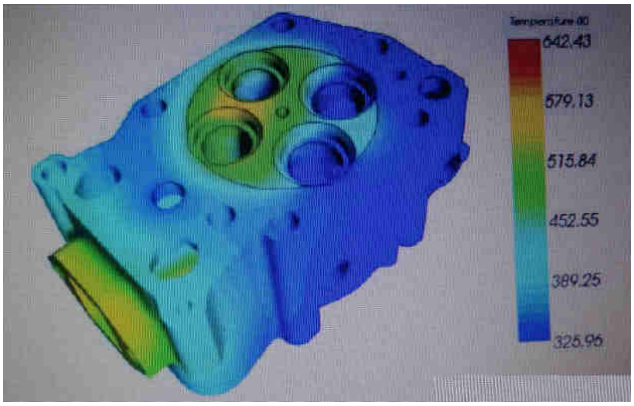
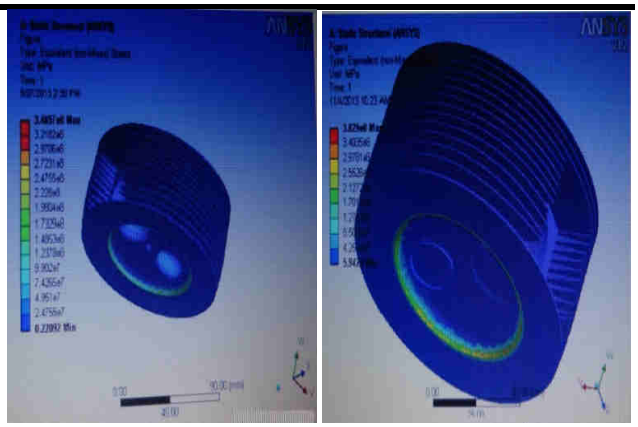


Fig.8: Temperature distribution across head [1]

The static stress analysis of cylinder head investigated by **Sreeraj Nair K.** et al.**[18]** In this paper they had completed model in Solid Works and the analysis was done by using FEA software package in ANSYS v12. In this investigation the maximum stress is detected not more than the material strength of the cylinder head. Here the main role of FEA is to predict and simulate the Von-Mises stress and strain pattern and thermal load distribution of the cylinder head which provide the rapid prototyping of the cylinder head.



(a) (b)

Figure 9: (a) Results for Aluminum LM13, (b) Results for Aluminum A356 [18]

Shiang et al.**[16]** investigated that the assembly load and firing load acting on a new twin-cam 16-valve cylinder head and block structure by using the finite element method. The small bridge of metal between two ports was found to be more highly loaded due to assembly and gas combined loads and after that the surface finish should be investigated and monitored using Non Destructive Test (NTD) during quality checks and development to predict a small initial crack. In this way after performing analysis process the maximum principle stress of static analysis under firing load is 6.25 KgF/mm^2 and maximum equivalent stress is 12.50 KgF/mm^2 obtained and which is not exceed the allowable strength of cylinder head design material 32.5 KgF/mm^2 , the cylinder head with no yielding and structural failure under firing load case can be satisfied.

Nitin Kumar Sharma et al.**[13]** optimized the fins of the four stroke single cylinder petrol engine. They had observed that the maximum heat dissipation possible by providing the appropriate length with minimum thickness of fins and the maximum number of fins mounted on the cylinder. So by help of these all phenomenon they had obtained maximum possible cooling and better reliability of an engine at the maximum temperature.

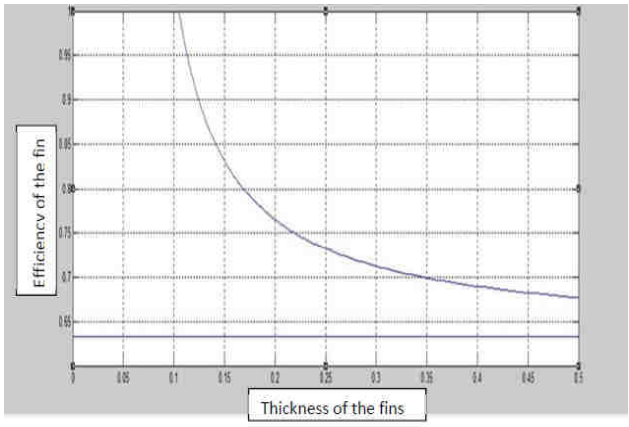


Fig. 10: Thickness of the fins / Efficiency of the fins [13]

F Zieher et al.**[6]** observed in current engine development program is that the design iterations resulting from durability testing for prediction of thermal mechanical fatigue (TMF) failure is necessary. At here complete life time simulation process is presented with emphasis on a newly developed material model for describing the constitutive behaviour of gray cast iron and compacted graphite iron under thermal cycling. The formulation of material model is based on a continuum-damage-mechanics (CDM) approch in order to findout the tension or compression anomaly of cast iron. Thermal mechanical fatigue simulation of cylinder predicts the fatigue life and also predicts the stabilized stress/strain response at the valve bridge center.

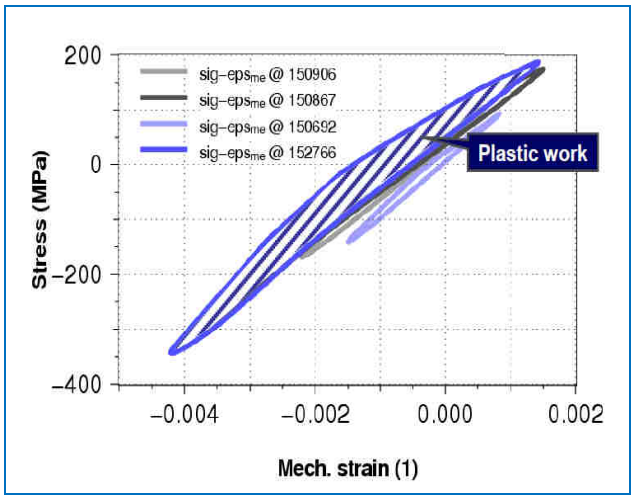


Fig.11: Stabilized stress/strain response at the valve bridge center[6]

V. CONCLUSION

The following conclusions derived from the literature survey:

The study of cylinder and cylinder head indicates that the use of Aluminum alloy, Al-Si alloy and Beryllium metal in place of Cast iron and Cast steel as a material gives better performance and also gives optimum weight reduction.

The APS coating and Ceramic material coating mainly used to reduce the friction loss and wear loss with improve the overall life of the cylinder and cylinder head of an engine.

The FEA tool plays a vital role because it reduces the maximum Mathematical calculations and working time.

The thermo-mechanical and CFD analysis mostly helpful for the screening test of the temperature distribution, fatigue stress distribution and fluid flow analysis of the cylinder and cylinder head respectively.

So; Finally as per the all above considerations, It can be possible to improve overall proficiency and efficiency of the cylinder and cylinder head by using MMC in place of Cast iron and other metal alloys and also by providing appropriate structure of Fins on the surfaces of the cylinder and cylinder head for better air cooling of an engine and these all parameters finally improve the overall life and structural strength of the cylinder and cylinder head of an any engine.

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ABBREVIATIONS

HP - Horse Power
DI - Direct Injection
TDC - Top Dead Center
APS - Air Plasma Spray
NTD - Non Destructive Test
FEM - Finite Element Method
FEA - Finite Element Analysis
cc - Cubic Centimeter Capacity
MMC - Metal Matrix Composite
HTC - Heat Transfer Coefficient
TMF - Thermal Mechanical Fatigue
CFD - Computational Fluid Dynamics
CDM - Continuum-Damage-Mechanics
OEM-Original Equipment Manufacturer