Thermal and Structural Analysis of Exhaust Manifold of an IC Engine

Mr. IKBAL PATIL[1], Mr. D.S.BHAT[2]

[1]*M.Tech. Student, Dept.Of Mechanical Engineering, SDMCET, Dharwad (K.S), India*
[2]*Dean and Prof. Dept.Of Mechanical Engineering, SDMCET, Dharwad (K.S), India*

Abstract - *The exhaust manifold operates under high temperature and pressure operating conditions. The performance of the engine is directly depends on the ability of the exhaust manifold to push the exhaust gases effectively during exhaust stroke. At the same time high temperature gases exerts a combined thermo-mechanical load on the manifold against the bolt pre-tensioning. The heat transfer analysis is done for manifold of different materials such as Aluminium alloy, Cast iron and mapping of this thermal load is done for structural analysis to check stresses and deformations under safe limit. Results were compared for both the materials. This study deals with carrying out steady state heat transfer analysis for two materials and coupled analysis of thermo-mechanical is done to check maximum deflections of manifold and different stresses on the manifold and bolt. Designing of the exhaust manifold is done using catia V5 software and meshing is done by Hypermesh software and analysis is done by using Abaqus software.*

***Key Words*: Exhaust Manifold, Abaqus, Hypermesh,Stress Deformation, Aluminium, Cast iron, Von-Mises,Tresca.**

1. INTRODUCTION

The exhaust manifold is very essential component of an engine in the field of automobile mounted on the cylinder of internal consumption engine. The gases coming from the cylinder head at different exhaust strokes are collected with minimum back pressure for smooth exhaust. The gases coming from one cylinder at a particular stroke need to discharge smoothly before the gases from other strokes. From multiple pipes gases were supplied into a common pipe before entering into the muffler. The performance of an IC engine depends upon the design of the manifold and effective emission of combustion products. The exhaust gases coming out of the engine cylinder has a temperature in the range of 800°C with pressure range from 100kPa to 500kPa and manifold surface experiences 250°C-300°C temperature. Therefore the manifold due to temperature gradients exerts thermal load on the material and causes displacement of the material from the mounted position with the cylinder head. When this thermal load is mapped along with the structural load due to bolt pretension the stresses will be results both on the manifold as well as bolt materials. These stresses should be within the limit for safe design. There it is necessary to do the thermo-mechanical analysis during initial stage of the design.

1) Thermal analysis of manifold is required to get the nodal temperature as thermal load.
2) Mapping of the thermal load against bolt pre tension for thermo-mechanical analysis to obtain deformation and stress.

2. PROBLEM FORMULATION

It is observed that manifold material requires high strength at high temperature applications. Most commonly used materials are cast iron, stainless steel and carbon steel. The manifold material undergoes thermal fatigue cycle from no load to full load during engine operation. A manifold made of these materials undergoes more deformations and stresses with respect to fixed positions due their more weight under high temperature applications. There is scope of analyzing the manifold under temperature gradient. Mapping of these thermal load in structural analysis to get deformations and d stresses against the bolt pretention. The induced deformations and stresses in aluminium alloy manifold are compared with cast iron manifold to check the feasibility of aluminium alloy material with cast iron to achieve high strength to weight ratio for the same boundary conditions. Based on these induced stresses a better aluminum alloy can be preferred in the initial stage of the design for safe operations.

3. METHODOLOGY

The geometry of exhaust manifold is created using CatiaV5 R20 software. The exhaust manifold dimensions and geometry is taken from the study reference model. The neutral step file of the exhaust manifold is imported into the commercial preprocessing tool called as Hypermesh. The imported design of the manifold model geometry is done cleanup process. Meshing is carried out on the simplified cleaned up geometry. Solid section parameter is selected and material properties are created and assigned to the model. Loads and boundary conditions are applied on the model. The input file generated in the hypermesh software is imported and executed in command prompt of abaqus software to generate odb file for two different materials. The results generated in odb file are compared and conclusion is made.

4. MATERIAL PROPERTIES

The Table1 shows the material properties of Aluminium alloy and Cast iron used for analysis of manifold.

Table1 Material properties of manifold

Sl.No	Properties	Material	
		Aluminium alloy	Cast Iron
1	Young's modulus	0.7 Mpa	1.38 Mpa
2	Poisons ratio	0.28	0.28
3	Density	2850 kg/m^3	7200 kg/m^3
4	Thermal Conductivity	190 W/m-^{0}C	45 W/m-^{0}C
5	Specific Heat	1050 J/kg^{0}C	450 J/kg^{0}C

5. LOADS AND BOUNDARY CONDITIONS

The exhaust manifold is mounted on engine cylinder head is fixed with bolts. Here in the current work the engine head is modeled as a rigid plate which will never deform. This reference plate is arrested with all 6DOF. And load transfer will takes place from exhaust manifold to the rigid plate through the bolts as shown in below Figure 1.

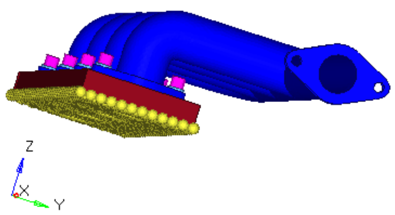

Figure 1 Exhaust manifold fixed to the plate

From the available experimental data head side is subjected to thermal load of 115^{0}C and exhaust pipe side is subjected to thermal load of 90^{0}C is applied as shown below Figure 2

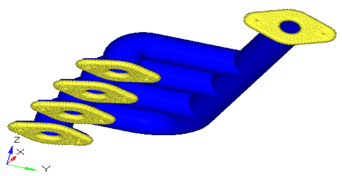

Figure 2 Thermal load on exhaust manifold

Bolt Preload Calculation

Bolt pretension, also called preload or prestress used as structural load, comes from the installation torque T you applies when you install the bolt. The inclined plane of the bolt thread helix converts torque to bolt pretension.

Bolt preload is computed as follows.

Pi = T/ (K D)

where

Pi = bolt preload
T = bolt installation torque.
K = torque coefficient.
D = bolt nominal diameter (i.e., bolt nominal size).
Avg. torque T= (55+75)/2
(From metric bolt chart for M10)
=65 NM
=65000N-mm
Diameter D=10mm
K=0.32 (from specific thread chart data)

Pre-tension force
P= T/ (K*D) = 65000 / (0.32*10)
= 20312 N
P=20kN is taken as bolt pre load.

6. RESULTS AND DISCUSSIONS

1. Thermal analysis

Figure 3 shows the temperature distribution of aluminium alloy manifold. The maximum surface temperature of convective film is taken as 300^{0}C is input for manifold. The result shows the temperature gradient with maximum temperature of 292.8^{0}C and minimum temperature is 90^{0}C on the manifold as shown.

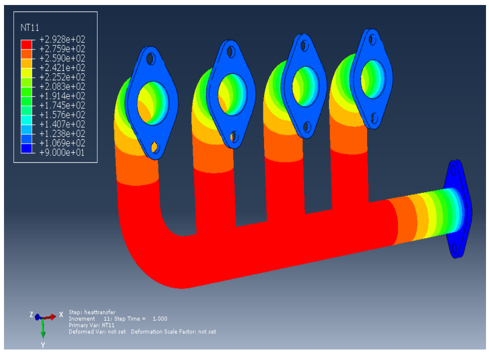

Figure 3 Temperature distributions on Al alloy manifold

Figure 4 shows the temperature distribution of cast iron manifold. The maximum surface temperature of convective film is taken as 300^{0}C is input for manifold. The result shows the temperature gradient with maximum temperature of 295.8^{0}C and minimum temperature is 90^{0}C on the manifold as shown.

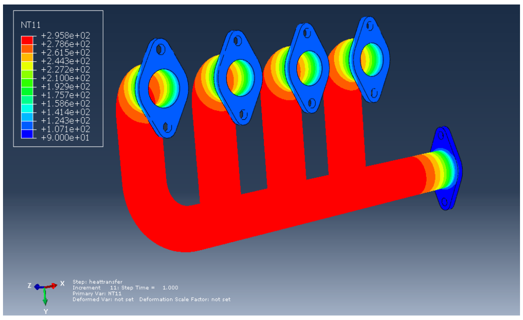

Figure 4 Temperature distributions on Cast iron manifold

2. Thermo-Mechanical analysis

a. Deformation analysis

The manifold experiences a small deformation in X, Y, Z direction under the influence of thermo-mechanical loading. The figure 5 shows the magnitude deformation of aluminum alloy manifold. From the figure it is clear that maximum deformation is 0.246mm occurs at exhaust side.

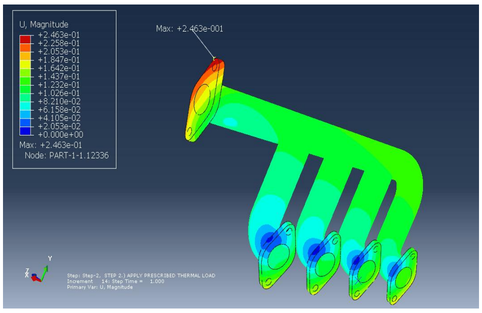

Figure 5 Aluminium alloy manifold

The figure 6 shows the magnitude deformation of cast iron manifold. From the figure it is clear that maximum deformation is 0.19mm occurs at exhaust side.

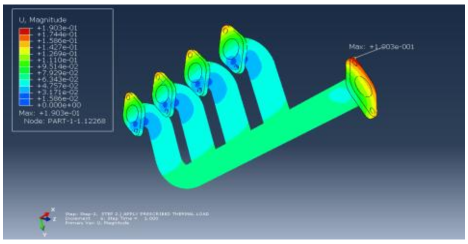

Figure 6 Cast iron manifold

Table 2 shows the deformation of manifold in X, Y, Z direction for aluminium alloy and cast iron materials.

Table 2 deformation of manifold

Material	Deformation(in mm)			
	X-direction	Y - direction	Z-direction	Magnitude
Al-alloy	0.17	0.16	0.027	**0.246**
Cast iron	0.0735	0.1749	0.0313	**0.19**

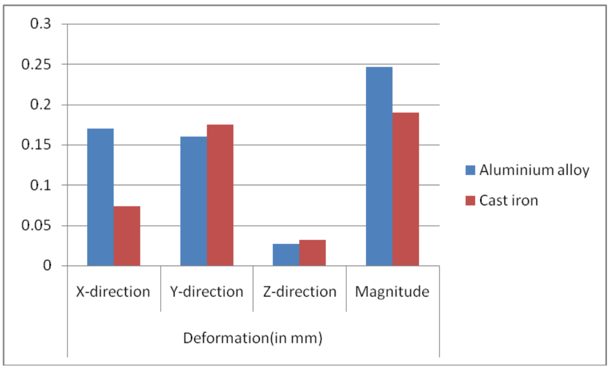

Chart 1: Graphical representation of deformation.

The above chart 1 shows the deformation of manifold in all – directions under thermo-mechanical loading for aluminium alloy and cast iron manifold material.

b. Stress analysis

Case1: Load step1 (Pre-tensioning load)

Under pre-tensioning load manifold undergoes stress called pre-tensioning stress. The figure 7 and figure 8 shows the max.stress occurs is Tresca stress for both aluminium alloy and cast iron manifold as shown below.

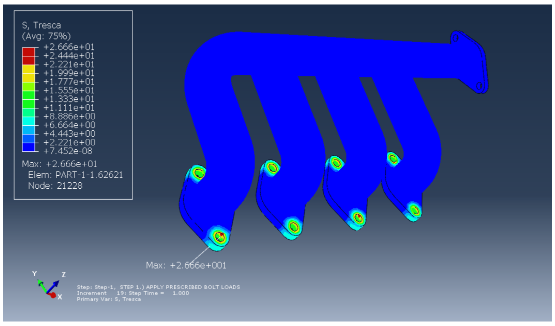

Figure 7 Tresca : 26.66MPa for aluminium alloy manifold

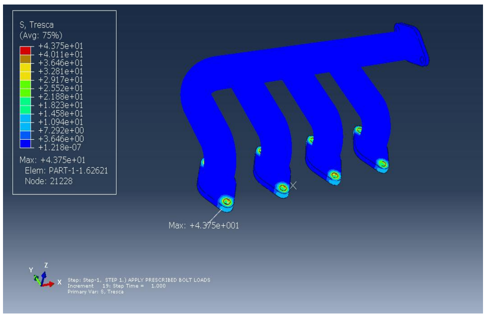

Figure 8 Tresca: 43.75MPa for Cast iron alloy manifold

Table 3 shows the induced stresses under load stpe1 for aluminium alloy and cast iron manifold.

Table 3 stresses induced under load step1

Mat.	Working stress(in MPa)				Yield Strn.th @25⁰C	F.O.S
	Von - Mises	Tres- ca	Max- Prin	Min- Prin		
Aluminium alloy	23.14	**26.66**	8.69	0.04	400MPa	**15**
Cast iron	37.94	**43.75**	16.57	0.05	400MPa	**9.14**

Case2: Load step2 (Thermo-Mechanical loading)

Under thermo-mechanical loading manifold undergoes couple field stress. The figure 9 and figure 10 shows the max.stress occurs is Tresca stress for both aluminium alloy and cast iron manifold as shown below.

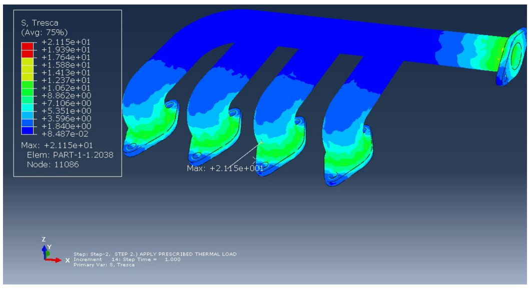

Figure 9 Tresca: 21.15MPa for aluminium alloy manifold

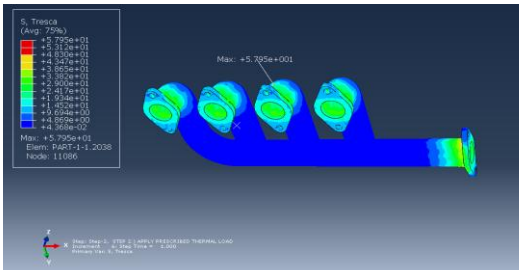

Figure 10 Tresca: 57.95MPa for Cast iron alloy manifold

Table 4 shows the induced stresses under load stpe2 for aluminium alloy and cast iron manifold.

Mat.	Working stress(in MPa)				Yield Strn.th @300⁰C	F.O.S
	Von - Mises	Tres- ca	Max- Prin	Min- Prin		
Aluminium alloy	18.36	**21.15**	16.11	2.65	160MPa	**7.56**
Cast iron	50.38	**57.95**	35.81	8.38	380MPa	**6.55**

From above Table 4 it is clear that at temperature 300⁰C aluminium alloy manifold undergoes less stress and better factor of safety than cast iron manifold.

Case3: Load step3 (Ambient Temperature)

At the ambient temperature (@25⁰C) the manifold undergoes maximum Tresca stress and occurs at bolt hole for both the materials as shown below figure 11 and figure 12.

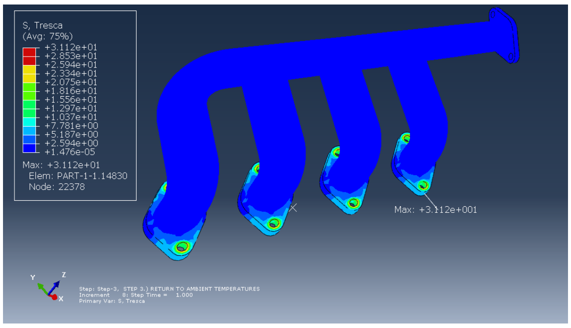

Figure 11 Tresca: 31.12MPa for aluminium alloy manifold

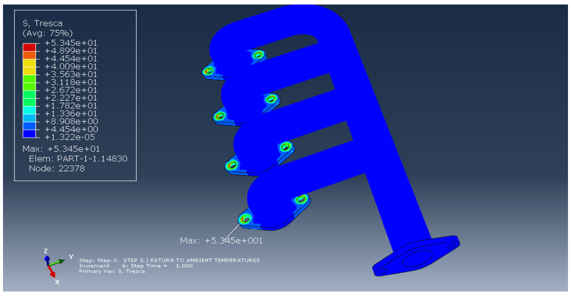

Figure 12 Tresca: 53.45MPa for Cast iron alloy manifold

From the above figure 11 and figure 12 it is clear that maximum stress will be tresca. These stresses are larger than stress at room temp for step1 because some residual stresses will added to the pre-tension stresses due to thermal effect. The below Table 5 shows the different stresses induced in manifold for both materials at ambient temperature.

Table 5 shows the induced stresses under load stpe3 for aluminium alloy and cast iron manifold.

Mat.	Working stress(in MPa)				Yield Strenth @25⁰C	F.O.S
	Von - Mises	Tres-ca	Max-Prin	Min-Prin		
Aluminium alloy	27.16	**31.12**	11.93	0.16	400	**12.82**
Cast iron	46.48	**53.45**	20.54	0.21	400	**7.48**

Results summary of manifold under Load Step1, 2, 3

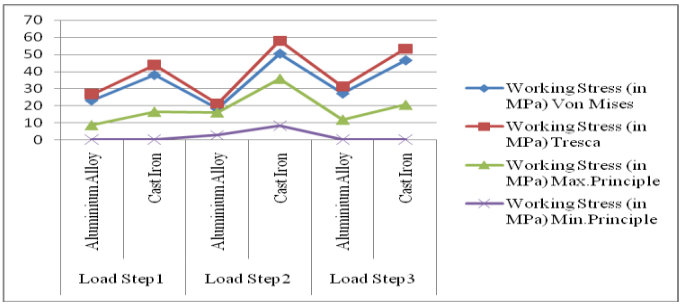

Chart 2: Working stresses for load step1, step2 and step3

The above chart 2 shows the graphical representation of the working stresses for all load steps for both aluminium alloy and cast iron manifold material. It is clear that tresca stress in cast iron material manifold is more in all three load step compared to aluminium alloy manifold material.

7. CONCLUSIONS

- Good dynamic stability and less vibration due to less weight suitable for comfort applications.
- In the application where the manifold maximum temperature will be up to 300⁰C the aluminium manifold material can be used in place of cast iron material with better factor of safety.
- Magnitude of deformation induced in the manifold for both the materials are very small.
- Working stresses induced up to 300⁰C temperature in the aluminium alloy are less than the cast iron materials due to low stiffness.
- High strength to weight ration can be achieved i.e. for the same volume of aluminium alloy manifold component weight will be 2.75 times less weight than the manifold made of cast iron material.
- Due to good thermal conductivity property of aluminum alloy better heat dissipation can be achieved.
- Good castability and complicated shapes can be casted because of good flow of material in the mould due to its low density.

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