Design considerations and overview of an engine exhaust manifold gasket

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ABSTRACT

The design of an exhaust manifold plays a key role in the performance of an engine because a back pressure is induced into the cylinders which lead to reduction in performance. The major design objective for any type of gasket is to possess compressibility, recovery and resistance to degradation subject to: flange, fluid to seal and atmospheric interaction. This paper describes the mechanics and failures of an exhaust gasket in an internal combustion engine. The mechanics of an exhaust manifold gasket is explicated by enlightening on compressive bolt, vibration and thermal loads; and failures are by thermo-mechanical influences, insufficient sealing and spot weld joint failure. A reliable approach is followed for developing the design considerations of an exhaust gasket by understanding the mechanics and overcoming the failures suffered. Hence, an adequate sealing stress and pressure distribution can be obtained ensuing to a mechanically efficient, low emission, highly durable and economic sealing joint.

KEY WORDS: Mechanics, exhaust gasket failure, design considerations.

1. INTRODUCTION

In an automotive engine, an exhaust manifold collects the exhaust gases from multiple cylinders and drains it through the outlet port. It is not only helps to carry away the exhaust gases but also plays a key role in increasing the performance of the engine. The design of an exhaust manifold system is very important, due to the exhaust back pressure would lead to drop the engine output power output. The exhaust manifold gasket is placed in between the exhaust manifold and cylinder head. Exhaust gaskets are generally designed in the form of composite graphite -cemjo, crush ring, spiral wound gasket, wire mesh gasket and steel embossed gaskets. These gaskets are used in tractor, agriculture engine/pump, two wheelers and car engines, heavy duty engines and commercial vehicles and industrial applications. Composite gasket has high resilience and compressibility, in which a perforated metal core is placed between heat resistant materials facing on each side (the construction can go vice versa as well. The crush ring gasket is pasted with metal sheet along with graphite material thus formed to a ring shape. The spiral wound gasket has v- preformed hoops and filler that are spirally wound together and then spot welded at ends. According to the need of mating flanges, an outer ring or inner ring or both types of rings might be attached to the gasket. Wire mesh gaskets are joint - less with either round or rectangular cross sections and are made by die-compressing knitted wire mesh into a wide range of shapes and resiliencies. Steel embossment gaskets: sheet metal embossed over bore for sealing operation using half and full type of beads which acts as a spring. The present study outlines the various design aspects of an exhaust manifold gasket in terms of gasket design mechanisms, gasket failures and solutions for gasket failures in order to achieve an efficient and economic sealing at the flanges. The exhaust manifold gasket mechanisms and it's possible failure routes and the possible solutions for minimizing the failures are properly studied and investigated. The design aspects of exhaust manifold gasket are shown in Fig.1.

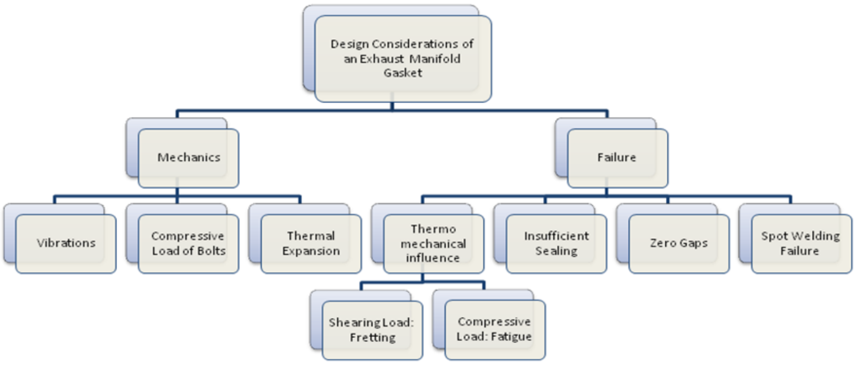

Fig.1. Flow chart of exhaust manifold gasket design aspects

Mechanics of an Exhaust Manifold Gasket Design: The mechanisms of gasket design formation is mainly depends on the sealing stress is generated at a sealing joint. The required pressure and load must be generated at contact place by the bolts thus provide the adequate sealing, for withstand the other loads too-vibrations and thermal expansions. The exhaust manifold behaviour could be understanding through vibration, compressive load of bolt and thermal expansion mechanisms.

Vibrations: Exhaust manifold is subjected to vibrations because of the inertial reciprocating and rotary motion of components present in an engine assembly. The exhaust manifold has its own natural frequency which resulted in vibrations. This natural vibration produces deflection in the exhaust manifold which will appear as bulging of headers at high temperatures. The fluctuating thermal mass across the manifold leads to vibrations as well. Thus the gasket design has to be made in order to check the resilience of sealing. The vibration mechanics are considered by studying natural frequency and vibration fatigue mechanisms.

Natural Frequency Study: The weight loss in gasket produces high natural vibration frequency. In finite element analysis, the engine is represented by a rigid body mass, the power train is given with an inertial representation and the engine mounts is also to be defined (usually defined as grounded). The engine assembly is further bolted to gasket and headers with the defined tightening torque. Structural resonance occurs when the forced excitation is same as to the natural frequency**.** If the natural vibration frequencies of exhaust manifold gasket and the engine assembly became equal this may cause crack in material or material removal. Resonance has to be avoided since it leads to vibration and noise related problems. Eigen value problem concept has been used generally for vibration related studies of gasket without considering the natural frequency.

Vibration Fatigue Study: The vibration fatigue study in exhaust gasket design can be conducted in early stage development in terms of dynamic loads. The road load data of road time history and the structure's response are acquired by various track tests .The road load is transferred to exhaust through chassis suspension rubber and engine through direct connection. The designer must aim on achieving the least dispersions through simulations during analysis through Dynamic Modal Analysis (DCM In addition, vibration fatigue study can be concluded by calculating the damage and the time cycle for damage during analysis.

Study of Compressive Load of Bolt: Bolts are required to connect the exhaust manifold and the head of the engine and a gasket is placed in between for sealing mechanism. Gasket not only acts as a sealing system but also plays a role to transfer the load. The load have to be uniformly distributed by the bolts and have to be tightened in a sequence with a calculated torque, otherwise the gasket won't be able to seal at the weakly clamped point. The gasket must retain the torque after engine is switched off in accordance to get a sufficient cold sealing which is also depending on material, number of bolts and their positioning across the flange, design of gasket and clamping force applied. The load from bolts is a critical parameter for gasket performance for maintaining the rigidity of the flange. The load from bolts is in highly dynamic condition due to thermal expansion and vibration. It is also important to estimate the stress concentration around the flange for proper sealing arrangement.

Effect of Various Factors on Exhaust Manifold Gasket Failure: The engine exhaust manifold gasket life could affect by various factors. The possible failure aspects of exhaust manifold gasket are explained in this section.

Failure Due to Shearing Load: Fretting: Fretting is the thermo- mechanical failure of manifold gasket due to the variation of thermal expansion of flanges on contact surfaces of cylinder head, manifold and gasket under high temperature operating condition. In addition, fretting also occurs due to micro relative movements of mechanically compressed contact surfaces which cause thermal expansion and vibrations. Thomas (2011); and Sangwoo (2011), investigated the fretting fatigue failure and its effect automotive engine gasket life. It is the repeated cyclical rubbing between two surfaces, over a period of time which removes material from one or both surfaces in contact. Fretting could cause due to wear, fatigue and corrosion. Fretting begins with crack initiation due to wear is considered as wear fretting. In case of fretting corrosion, the uneven surface under load and relative motion gets ruptured with small amount of metal being removed; this metal easily gets oxidized and further repetition of this process leads to formation of high oxide debris. It can be also due to oxidized layer already present on the contact surface.

Failure Due to Compressive Load Effect on Fatigue: The fatigue can be generated at the flange due to repeated cyclic loading and unloading which resulted thermal expansions and vibrations known as thermo-mechanical fatigue cracks. This may create insufficient sealing at the joint. In addition, this kind of repeated cyclic loading could increase resilience loss for the embossment. If the loads are above a certain threshold, microscopic cracks will begin to form at the stress concentrators such as the surface. Eventually a crack will reach a critical size, the crack will propagate suddenly, and the structure will fracture. Stressed areas decrease in size and therefore the true stress increases. Finally the remaining area is unstable to sustain the load.

Failure Due to Thermal Expansion on Fatigue: The engine's ambient temperature varies because of various climates in different geographical regions, could be as cold as -20^0C somewhere in Europe or 50^0C in Asia. Engine runs at high temperature mode during idling due to lesser cooling from air drag, or longer running periods, or air fuel mixture being lean. During climbing on mountain ranges temperature will be lower. The thermostat valve opens after a certain temperature which controls the operation of radiator so as to maintain the engine operation in an optimum range. Due to such variation in temperature, a variable thermal cyclic load is applied to exhaust gasket.

Failure due to Insufficient Sealing: If exhaust gas gets leaked through the sealed gasket joint would resulted in the turbocharger efficiency, which leads to inadequate supply of air to the cylinders during the induction stroke of IC engines. This failure also leads to reduced fuel efficiency. The insufficient sealing arrangement of gasket might also disturb the function of engine management system and sound characteristics.

Failure due to Zero gap in Gasket Mounting: The exhaust manifold gasket usually mounted on an exhaust manifold with the help of bolt or stud with small clearance for bolt movement. This clearance allows the bolt to push itself in the direction of vibration occurrence, which tends to tear away the exhaust manifold gasket. A failed exhaust manifold gasket because of zero gaps between the bolt and gasket leading to total wear at one end of the exhaust gasket is shown in Fig.2.

Fig.2. Evidence of no gap failure in an exhaust manifold gasket leading to wear at one end

Gasket Failure Due to Spot Welding: In case of multi-layer steel gasket (MLS), the joints are made using spot welding technique because of its cost effectiveness and also to prevent lateral movement in a spot. The motion is constrained at this point, but elsewhere loads will act. The thermal expansion along with high temperature oxidation takes place leading to breaking apart of joint at the spot welded region. This can be avoided by providing an extra area and folding it at the joining point in a double-fold manner which will enhance the strength.

Design Considerations for an Exhaust Manifold Gasket: The various design parameters of an exhaust manifold gasket design for different applications are clearly discussed in details in this section.

Bolt Size and Grade/Number of Bolts: Bolt grade defines the ultimate and yield strength of a bolt. The number of bolts varies the distribution of load across the flanges. If bolts are connected near to each other, then the gasket and flanges shows low secondary bending characteristics. At the same time fewer bolts (of higher tensile strength) should be brought into application in order to reduce the cost of manufacturing of both flanges and gasket.

$$\text{Number of bolts: } \frac{total\ preload\ required}{safe\ preload\ for\ type\ of\ bolt\ selected}$$

Bolt Tightening Torque/Load: This is required to know the amount of load to be applied on the flanges in order to get proper sealing stresses as well as to overcome the failures.

Total preload required = factor of safety* load applied

Material Property: The material properties of exhaust manifold like thermal expansion coefficient, young's modulus, Poisson's ratio, mass density, thermal conductivity, specific heat of cylinder head and exhaust manifold also to be known for determination and calculation of the thermo-mechanical Characteristics.

Pressure Due to Gases from Bore: For designing the exhaust gasket, the pressure exerted by the gases on head has to be estimated, so as to design a safe sealing stress and its distribution over the gasket.

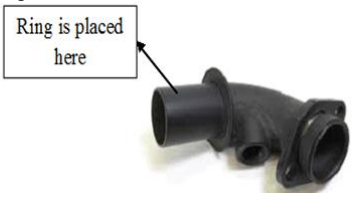

Fig.3. Application of ring type gaskets-crush ring, spiral wound, wire mesh

Design of the Header and Type of Gasket: The construction, forming process and manifold's material are to be understood while designing the exhaust manifold. According to the thermo mechanical analysis of flange, the desired behavior for the gasket needs to be estimated in terms of recovery and compression. A ring type exhaust manifold - crush Ring, spiral wound, and wire mesh gasket; is used at locations where header is directly fitted into the engine head exhaust manifold as shown in Fig. 3. Ring type gaskets have different constructions which vary in density and sealing properties and used as per the requirement. Ring type gaskets are easy to align. The spiral wound gasket uses the resiliency of the metal foil to hold the soft filler material against the flanges, forming a leakage barrier. A Multi-Layer Steel (MLS) gasket has a three or more layer construction as shown in Fig.4 comprises of an upper embossed layer, a stopper/spacer/embossed layer in between and a lower embossed layer. Consider two types of gaskets: single layered embossed gasket and a multi-layer embossed gasket.

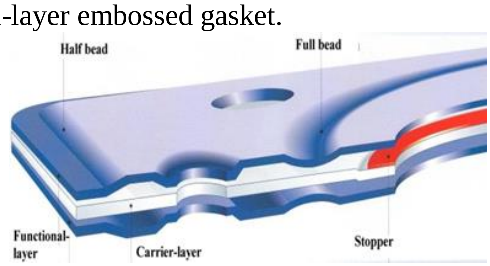

Fig.4. Construction of a MLS gasket

Cover Factor/Factor of Safety: The cover factor is equal to the applied bolt load divided by the gas/fluid pressure (Fig.5)

Load exerted by gas = Pressure in bore*Area of the Bore
Load exerted by the bolts = Number of bolts*Force exerted by the bolts
This factor of safety should be more than 1 otherwise the assembly will fail which may lead to tearing away of Gasket.

$$\text{Cover Factor/Factor of safety} = n * \frac{F}{PA}$$

Where n is the number of bolts. The cover factor is taken around 10 for engine application purpose. The bolt load is to keep the flanges together, carry the weight of the assembly, and resist to vibrations and to bears other stresses as well. Therefore, the stresses applied through the bolt are very much high compared to the pressure exerted by the gas. Hence, the pressure distribution over the gasket is to be managed and designed in such a manner that, the sealing stresses are distributed all throughout it, maintaining the required contact.

The Flatness of the Flanges for designing a Gasket: As castings have become lighter and less rigid, the need for smoother, flatter surfaces are more important. Some aftermarket gasket manufacturers now recommend a surface finish of 30 to 110 RA (Roughness Average) for cast iron head and block combinations, with a preferred range of 60 to 100 RA for best results. For aluminum heads, the numbers are even lower. The typical recommendation today for an aluminum head on a bimetal engine is a surface finish of 30 to 60 RA, with the preferred range being from 50 to 60 RA. It is not difficult to achieve mirror-like finish when they manufacture a brand new engine on an assembly line. If the surface is too rough (more than 113 RA), it may be too rough to seal properly and the head gasket will leak. If the surface is too smooth (less than 54 RA), it may not provide enough "grip" to prevent the gasket from flowing or scrubbing.

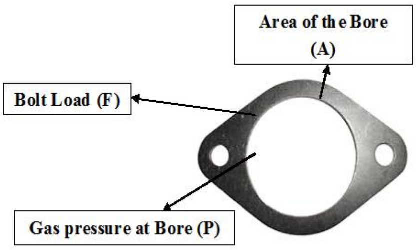

Fig.5. Loads applied on a gasket

Compression and Permeability: After the engine works for long cycles, all the properties and components go under some deformation. There is a permanent set in the geometry of the flanges leading to a significant change in pressure distribution. The gasket material now requires an additional load to block the permeability through the flanges and gasket. Permeability through gaskets varies greatly for different types of material, but in almost all cases, leak rates decrease as the compressive load increases. The material should be designed in a manner to provide the desired compressible and permeable behavior.

Surface Roughness and Flatness: Surface roughness is required in order to deal with the sealing characteristic of material, how it behaves with the fluid. Flatness is required in a surface area to keep it air or liquid tight throughout the span. This is usually required where the deflection is comparable to the flatness values of both the flanges and gasket.

Zero Gap: At top end along bolts in a gasket leading to wearing of an end of gasket, it can be resolved by making a cut out along the mounting bolt hole on gasket either on all the bolt holes or few of them, so as to fit the gasket and prevent gasket wear along the bolts in an exhaust manifold gasket as shown in Fig.6.

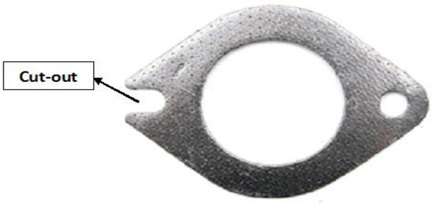

Fig.6. Exhaust manifold gasket with a cutout on one end

Fig.7. Star design to overcome vibrations i.e. constrain motion

Star Design: A star type of design can be made at the bolt as presented in Fig.7. It facilitates the bolt and flange movement due to thermal expansion and vibrations keeping intact the priming sealing feature of gasket.

Spot Welding: Spot welding is done to keep the gasket assembly intact for multilayer gaskets. The joint being cost more cost efficient than other methods; though it is not 100% efficient. At high temperature rapid oxidation, thermal expansion takes place in material, for instance SS 301 loses its plastic behavior which was applied to it through forming methods and starts becoming less rigid. This failure of breaking up of spot welded joint can be dealt by clinching the joint or using high temperature and corrosion resistant steel alloy: Inconel type of steels shows a brilliant characteristic for this application. This type of steels is passivative to high temperature, hence are more corrosion and temperature resistant but their usage is still limited because of high costs.

2. CONCLUSION

The mechanics and failures of an exhaust manifold gasket are discussed and then applied in determining the design consideration for an exhaust manifold gasket. An exhaust manifold gasket faces torque loses while setting of gasket and due to corrosion in engaged bolt threads. Mechanics of an exhaust gasket includes the thermal expansion, vibration loads and bolt compressive loads taken by it. Thermal expansion leads to fretting: thermo-mechanical failure and cyclic thermal loads lead to fatigue failure. Inefficient sealing at joint leads to leakage of harmful gases, resulting to disturbance in estimation of parameters by engine management systems and various components efficiency. Behavior of flange bolts is derived with respect to the flanges: the sealing load at intake manifold reduces and at exhaust manifold increases when engine gets hotter. The manifold's configuration, material and forming process need to be understood as per the gaskets application requirement. Multi-layer Steel (MLS) gaskets offer high recovery, compressibility and working life in steel embossment gaskets. The thickness of gasket is to be determined by considering the factors: flatness of flanges, permeability and compressibility characteristic of material, Tribology, working fluid and applied load and stress values. The failure of zero gaps can be resolved by making a cut out at mounting hole of the gasket. A star type of design is made to constrain the motion so as to eliminate the wear at one end of an exhaust manifold gasket. Inconel type of super alloy can be used as an exhaust manifold gasket material since it's highly temperature and corrosion resistant and can also eliminates the failure of breaking of spot welded joint.

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