

Exhaust Manifold Durability Subject to Splash Quenching

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ABSTRACT

Exhaust manifold design is one of the more challenging tasks for the engine engineer due to the harsh thermal and severe vibration environment. Extremely high exhaust gas temperatures and dynamic loading combine to subject the manifold to high cyclic stress when the material has reduced fatigue strength due to the high temperature. A long service life before a fatigue failure is the objective in exhaust manifold design. Accumulation of fatigue damage can occur from dynamic loading and thermal loading combined. Thermal mechanical fatigue (TMF) is a primary mechanism for accumulating fatigue damage. TMF typically occurs when a vehicle driving cycle has operating conditions that repeatedly change the exhaust gas temperature between hot and cold. Another way to experience temperature cycling is through splash quenching. Splash quenching was analyzed and found to rapidly accumulate fatigue damage. An experimental and analytical method is presented that quantified splash quenching and the impact on exhaust manifold durability. The number of quenches in the life of a vehicle is uncertain. It is therefore recommended that vehicle packages are designed in such a way that splash quenching of the exhaust manifold is avoided. This will maximize the durability of the hot exhaust components.

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INTRODUCTION

Modern engines adhere to several trends in engine design. This includes downsizing displacement while achieving higher specific output and high power levels. To achieve this high performance level it is desirable to be robust to high exhaust gas temperatures. The higher the exhaust gas temperature, the more power an engine can produce. Exhaust temperature is typically limited by material capability. Engine exhaust valves, cylinder heads, exhaust manifolds, and after treatment systems all limit engine exhaust gas temperature. The focus of this work is the exhaust manifold.

The exhaust purpose of an exhaust manifold is to route exhaust gas from a cylinder head to the after treatment system. While doing this it must minimize flow losses and be durable in the hands of the customer over the intended useful life of the vehicle. A material must be selected that can withstand the heat delivered in the exhaust gasses. The geometry must be one that is optimized for low flow restriction since flow losses hurt volumetric efficiency and therefore reduce engine specific power. The attachment method must be designed to be easy for manufacturing plant production and insure sealing over the full design life of the vehicle.

HOW EXHAUST MANIFOLDS FAIL

Perhaps the biggest challenge in exhaust manifold design is achieving the desired durability. The heating and cooling cycles at elevated temperatures cause the manifold to accumulate fatigue damage. As damage occurs, manifolds can warp and loose clamp load on the gaskets resulting in an exhaust leak. Customers may become

dissatisfied with a loud exhaust leak and low leak attestation is required for government certification. As thermal cycling continues, the warp can lead to initiation and propagation of a crack. [Figure 1](#) shows an example of a cracked exhaust manifold that was subject to thermal mechanical fatigue damage.

There are several forces that drive fatigue damage. The manifold and down pipe are subject to vehicle vibration generated from road inputs and engine inputs. These dynamic loads impart a stress in the manifold at critical locations.

The manifold is also exposed to thermal mechanical fatigue (TMF). This is a condition where the heating cycle causes the exhaust manifold to grow. This growth is typically characterized the following relation:

$$\Delta L = \alpha L \Delta T$$

In this case the change in length, ΔL , is proportional to a thermal expansion coefficient, α , the initial length of the part, L , and the change in temperature, ΔT . When a manifold is heated, it will expand.

If a theoretical sphere in free space was heated and it expanded, there would be no stress imparted. However, when there is a constrained condition, the part will want to expand but the constraints resist expansion thus creating stress in the part. In the case of an exhaust manifold, it is bolted to a cylinder head which acts as the constraint. When heated, the material expands. Since it is constrained, the stress increases rapidly and local high stress region will yield. The yielded part is really a new geometry at the elevated temperature.

When the manifold is then cooled, the temperature changes and the manifold wants to contract. Since it is still constrained, this contraction will result in another high stress event. The stress when cooling from hot temperatures is again enough to yield the part.

Repeated cycles of heating and cooling across the stress-strain domain cause mechanical fatigue induced by the thermal cycles in the part, and hence the name thermal mechanical fatigue. An analytical example of a manifold subject to repeated temperature cycles is shown in Figure 2. The resulting yield and distortion is apparent after repeated thermal cycles.

The primary way to induce thermal mechanical fatigue is normal driving cycles. The manifold initial condition is when the vehicle components settle to a uniform ambient temperature throughout. Starting the vehicle and driving away begins to heat the manifold. Strenuous driving can result in even higher temperatures and eventually the manifold is completely warm. Upon changing to a more mild driving cycle or switching off the vehicle can results in cooling. When fully cool, one thermal mechanical fatigue cycle has been completed.

The repetition of thermal cycles can accumulate fatigue damage in the manifold. Techniques like rain flow counting can be used to estimate the cumulative damage resulting from the heating cycles. The strain life curve is used to characterize the number of cycles which can be accumulated before the part fails when it is subject to plastic deformation. Figure 3 shows a sample strain life curve where a strain of 0.01 would result in just over 100 cycles to failure.

An additional design challenge for exhaust manifolds is that material properties plummet with rising temperature. When exhaust manifolds are operating hot, the tensile strength might only be 10% of the cooler tensile strength.

Several TMF damage prediction models have been published, such as TMF linear accumulated damage model by Sehotoglu [1], strain range partitioning method by Masson, Halford, and Hirschberg, [2] and some non-linear continuous fatigue damage models. These models can be applied analytically to predict the exhaust manifold life.

FIELD EXPERIENCE

In the course of engineering exhaust manifolds, some instances occurred where a particular vehicle line had an unusually high number of exhaust manifold repairs. These repairs tended to have higher numbers in areas of the world where corrosion is the most severe.

Corrosion can increase fatigue damage on exhaust manifolds. When a manifold is heated, it slides under the head of the fasteners. This sliding has friction and corrosion increases the amount of sliding friction. When corroded, each thermal cycle or TMF event actually causes higher stress and increases the amount of fatigue damage for each thermal cycle. In addition, the corroded surface may accelerate the initiation of cracks and reduce the fatigue life further.

An interesting observation from field returns were that V-engine equipped vehicles often had a much more significant number of repairs on only one bank of the engine. The number of thermal events caused by engine power and vehicle driving would be common between the manifolds on both banks. CAE analysis did not indicate that the geometry of one manifold was prone to higher stress than the other. And, the corrosion patterns on both sides of high mileage vehicles were similar.

It was also observed that the number of repairs increased with time. This is indicative of a fatigue related issue. In all engine families the numbers of exhaust manifold failures increases with time due to fatigue damage. In many cases the failure was well outside the typical warranty period.

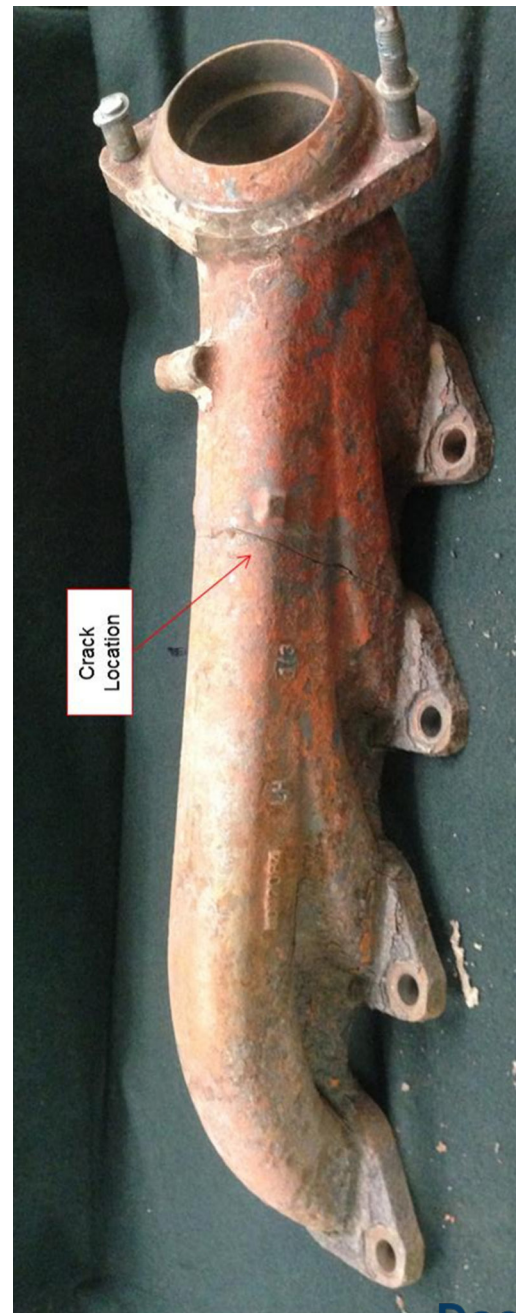


Figure 1. An exhaust manifold that has cracked.

One of the hypotheses for the increased failures on one bank was an increase in TMF resulting from additional thermal cycles. Water splash from water or slush on the roads can also cause a temperature change in the exhaust manifold. This temperature change can drive additional fatigue damage. Each bank of an engine experiences different exposure to water. In a North-South oriented engine the differences may be due to the vehicle body structure. In an East-West engine orientation, the front manifold stays quite dry while the rear manifold can be repeatedly splashed by adjacent wheels.

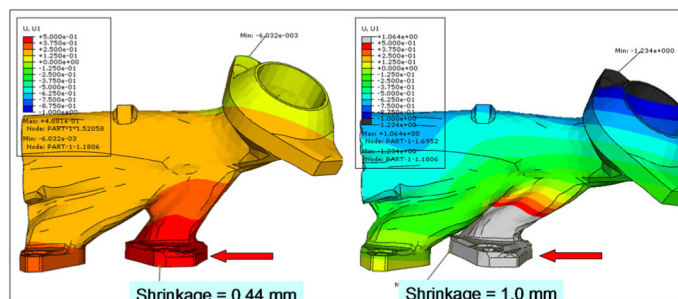


Figure 2. CAE showing how one exhaust port can deform from TMF during repeated heating and cooling cycles.

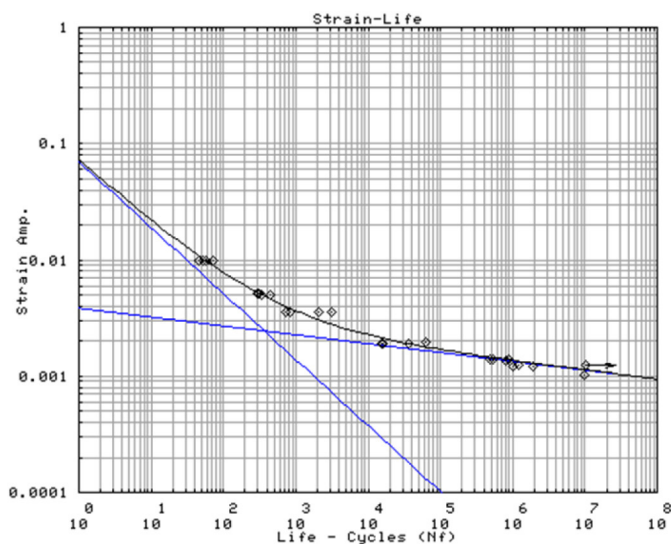


Figure 3. Sample strain life curve.

EXPERIMENTAL METHOD

To further investigate the condition of splash affecting the exhaust manifolds an experimental technique was developed. Thermocouples were placed in a hot location on the surface of the exhaust manifold and the vehicle was driven through a water trough at a proving ground. Figure 4 shows a red dot representing a thermocouple location on a hot spot on the surface of the manifold near the outside edge.

Once the hot spot was identified, the vehicle was driven through a water trough at various speeds and depths. Figure 5 shows the thermocouple response when driving through 5 cm of water at 32 kph. The manifold temperature was unaffected by the water. When the speed was increased to 64 kph there was a thermocouple

response. The right hand thermocouple showed significant cooling while the left side did not. This indicates that the right hand thermocouple was being splashed. The splash was such that water boils on the surface and the thermocouple of the manifold skin surface remains at 100 °C. When more water was added to the trough, both banks experienced splash cooling of the exhaust manifold as shown in Figure 7. The left hand side cooled to 100 °C while the right hand side cooled below 50 °C. This indicated that the manifold had received so much water that it had cooled deep into the material and the manifold surface was approaching the water temperature. There is not enough energy in the manifold to continue to boil the amount of water supplied by the splash.

Recall that some of the exhaust manifold failures occurred only on one bank of a V-engine. To determine the speed and depth of water appropriate as a performance criterion, a road driving test was performed. Figure 8 shows the thermocouple results from driving for three hours on a day where 25 cm of snow accumulated. There was salting of the roads and much slush existed. In this case, the right hand manifold experienced 19 splash cooling events where the temperature dropped to 100 °C while the left hand manifold experienced none. This proved that the right hand manifold could fail sooner from TMF due to splash and explained the preferential side for the vehicle concerns.

The correlation between the road data and the splash test in a trough brought a consensus that 5 cm at 64 kph was correlated to road driving and that it should be used as the criterion to validate vehicles for splash performance. A variety of other vehicle programs were evaluated with the same criterion and it has become a standard test for evaluating the influence of water splash on manifold temperature.

The splash phenomenon is also a problem for exhaust manifold designers. It is difficult to know how many splash cooling events a manifold will experience in use as it is difficult to know how many natural thermal cycles a manifold will experience. Fortunately, most vehicles have a typical drive cycle defined for the life of the vehicle and corporate standards are established for the most severe vehicle usage. Minimal information exists to quantify the number of splash cooling events over the useful life of a vehicle. For this reason a detailed understanding of the stress created by the splash is required. If the stress was small, then many events could be accommodated, perhaps even achieving infinite life against splash. If the stress is large, then it could be a significant contributor to the fatigue damage of the manifold.

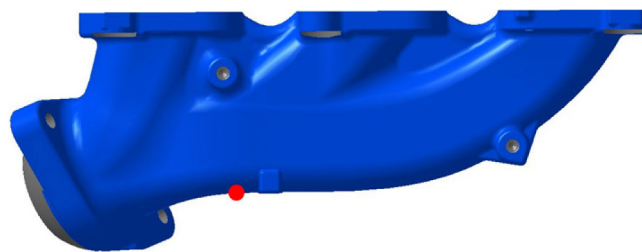


Figure 4. An exhaust manifold with a skin mounted thermocouple on