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Analytical Study of Fatigue Failure of Aluminium Alloy Piston in IC Engines

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Abstract - *An analytical study was performed about piston failure by fatigue. Fatigue cracks are initiated and propagated by the action of mechanical and high temperature loading conditions which induces cyclic stresses in the piston material. The areas of combustion bowl, piston pin bore, skirt parts are the stress critical points at which cracks so developed grow into fracture. The metallurgical composition and presence of alloying elements and intermetallics also aided the crack propagation. Various proposals and solutions are presented so that necessary care can be taken to prevent piston failure in future.*

Key Words: **Piston, Fatigue, Fracture, Aluminium, Intermetallics.**

1. INTRODUCTION

The automotive piston is indeed a highly thermo-mechanically loaded part that sometimes requires specific features and characteristics in order to improve its performance and thereby to reduce the polluting emissions. From a thermal cycle point of view, during normal engine operation, a piston first gets heated by the combustion process and is cooled thereafter by engine oil, rings and cylinder block. These simultaneous heat exchanges generate unsteady loading cycles in the component [2)] [4)]. When these thermal loading couples with the external mechanical loads, the combination will induce transient thermal–mechanical loadings which are more severe [1)] [2)] [4)].

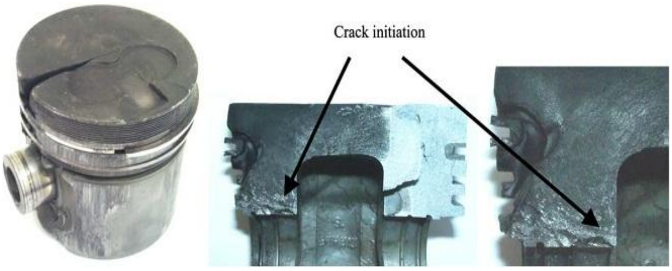
The repetition of such a process gives rise to development of cyclic stresses and subsequent deformations within the components. With the resulting gradual reduction of piston material strength, cracks nucleate and propagate up to fracture by fatigue [1)] [2)].

Under fatigue damages, thermal fatigue and mechanical fatigue play prominent roles. Heat load is the major factor to cause cracking and erosion of piston head, whereas mechanical load develop cracks at piston pin seat [1)] [13)].

2. LITERATURE REVIEW

2.1 Fatigue fracture mechanism

By mechanical fatigue it is meant that the piston is subjected to external loading. The resulting stress causes cracks to nucleate and propagate in critical stressed areas. As shown in **Fig -1**, there are mainly two stress critical areas where crack initiates: piston pin holes and those regions on both sides of the bowl rim area which are located on the same vertical plane that contains the pin holes. Also, it is observed that there is only one visible crack for mechanical fatigue [1)] [3)]. Also, exposure to high temperature combined with the static stresses will



results in a gradual loss of fatigue strength at head, thereby cracking the material [1)].

Fig -1: Petrol engine piston with a crack from one side of the pin hole to the head [1)].

Under thermal fatigue, thermal gradients develop stress in two ways. Thermal stresses due to the distribution of the temperature along the vertical axis of piston – high temperatures at the top and lower temperatures at the bottom – and that due to the different

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temperatures on the piston head due to the flow of the hot air or fuel impingement. On the first case several fatigue radial cracks over the whole piston head can be observed.

On the second case, the fatigue cracks would be in specific areas of the piston head where the thermal gradients occur [1)] [3)] [4)].

The cracks so formed gradually grow under the fatigue conditions until it develops into a fracture on the crown. If severe enough, fracture continues across the crown surface to have the piston sliced to parts [1)] [3)].

As shown in **Fig -2**, the finite element analysis performed on the piston indicates that the piston bowl lip and crown area are clearly critical areas of fatigue [3)]. Stresses up to 40 MPa and temperatures up to 341^{o}C are obtained on the top surface of the piston at rated power output conditions [3)].

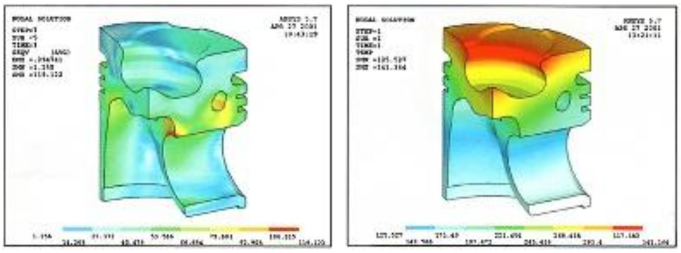

Fig -2: Contour plot depicting the distribution of stress (left) and temperature (right) due to the combined thermal and pressure loads experienced in an engine [3)].

2.2 Failure Causes

The fatigue failure is caused by the initiation and propagation of cracks developed in the piston as a result of undesirable operating conditions and many material defects.

Fig -3 describes the crack initiation and development process. During normal engine operation, the piston crown and combustion bowl lip surface experiences large thermal stress cycles for every significant change in engine load. These continuous thermal cycling leads to expansion mismatch between the aluminium matrix and silicon grains on the combustion bowl lip and piston crown. This will leads to localized micro-plasticity and the initiation of micro-cracks due to reduced fatigue strength [3)].

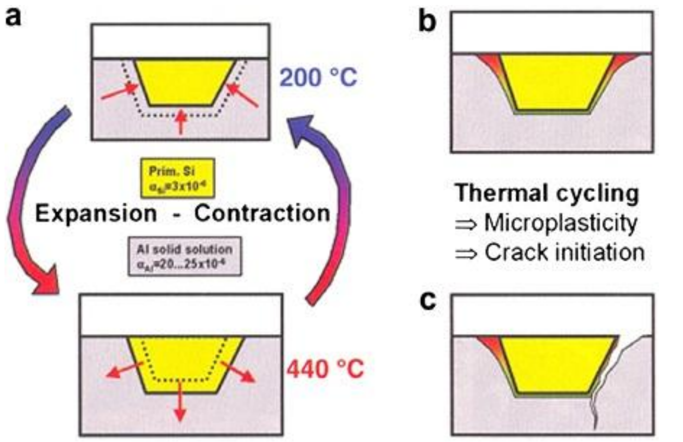

Fig -3: Sketch depicting the mechanism of crack initiation due to expansion mismatch of aluminium matrix and primary silicon phase [3)].

The thermal fatigue strength degradation would give rise to the formation of network of micro-cracks, which when exceeds the threshold flaw size, results in fatigue crack propagation and subsequent failure. Also, the elevated temperature and associated stresses reduce the threshold flaw size required for crack propagation [3)].

Usually, near eutectic Al–Si alloys are employed for casting pistons due to their good wear resistance, higher strength to weight ratio, high stiffness, and a low thermal expansion coefficient [9)] [10)]. Especially, the alloys contain several major alloying elements that may form complex multi- phase microstructures which comprises of eutectic Al–Si composition, various intermetallic particles and numerous precipitates. Large primary Si particles are also present that may act as preferential cracking initiation sites [3)] [9)] [10)].

In simple Al–Si binary eutectic alloys without casting defects, cracks initiate at the Al–Si interface. The crack nucleated from a large intermetallic colony close to the specimen surface and propagates along the boundaries between the intermetallics and Al–Si eutectics, which is caused by the debonding or fracture of intermetallics and Si particles [4)] [8)-11)]. This happens due to the weak interfacial strength between the Si particles and the Al matrix and also due to the brittleness of the Si particles [10)].

A better fatigue performance is obtained by optimizing the microstructure and for that, it appears necessary to reduce the presence of large intermetallic colony. Tiny intermetallics that are dispersively distributed within the composition help to improve the fatigue property of the Al–Si piston alloys [10)].

It was observed that in an Cu-Ni piston alloy with low Cu (0.94 wt %) and Ni (0.96 wt %) contents, crack initiation occurs exclusively at fractured Si particles, whereas in alloys with high Cu (3.9 wt %) and Ni (2.8 wt %) levels, initiation occurs on both Si particles and intermetallic particles such as Al_9FeNi and $Al_3(Cu\ Ni)_2$ [8)] [10)].

It was also observed that intermetallic particles may dominate the fatigue process when the Si particles are less in number or are absent [8)] [12)], i.e. lowering the Si levels reduces the role of Si particles in fatigue crack initiation. However, this is followed by increased porosity, which then dominates fatigue behavior especially for the low Si alloy. For low Si alloys, cracks were observed exclusively on pores [3)] [8)] [12)].

The use of neutral injector codes in the engine ECUs deactivates the ECU's function of automatic recalibration of the fuel injector flow rates. This results in minor over-fuelling and subsequent thermo-mechanical overload of pistons [3)].

A poorly controlled post intercooler air temperature and an elevated set point could results in the overheating of piston and other combustion chamber. During the engine testing, high engine oil temperature has been observed due to which the engine coolant temperature set point would be required to be reduced. This could increase the thermal gradients in the combustion chamber, thereby increasing their thermally induced stress levels [3)].

2.3 Fatigue Damages to Piston

Apart from piston crown, fatigue cracks are developed in other parts of piston as well and it includes piston rings, skirt, piston pin and pin bore.

2.3.1 Piston ring

As the wear on cylinder walls increases, clearance between the piston and cylinder wall becomes high. Eventually, pressure acting on the ring increases (because the ring comes out of the groove) and consequently stress increase on the groove. The stresses at those fillet portions in the ring groove seem to be enough to initiate fatigue cracks on the piston [1)].

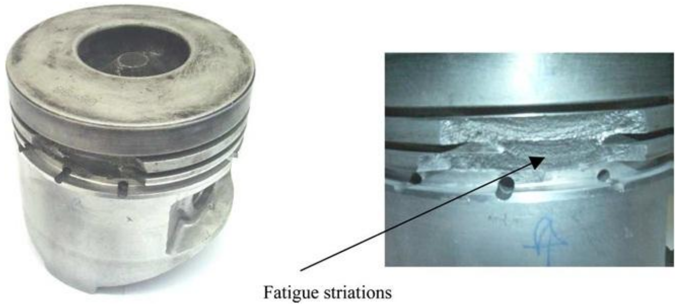

Fig -4: Engine piston with damaged grooves [1)

In case the rings are not fitted correctly in the grooves, the resulting misalignment stresses the ring material by the continuous reciprocating motion. This will accelerates the fatigue crack propagation which in turn stresses the ring lands and cause material to fracture away from the ring land areas, as depicted in **Fig -4**. Such a condition causes the ring to flutter within groove which increases the clearance further by wear of ring. Under such a circumstance severe blow by and power loss occurs [14)].

2.3.2 Piston pin failure

Piston-pin transmits compressive force produced from combustion into the crankshaft through small end of connecting rod to make the engine turn. If the piston is misaligned with cylinder during installation, the unbalanced dynamic forces developed during running act on the piston pin. The non-metallic inclusions present on the pin decrease the fatigue strength and aids in crack formation on ends. Cracks so formed propagate into the point where connecting rod connects with pin at which shear stress develops. With further fatigue loading, these cracks lead to fracture [5)] [6)]. **Fig -5** indicates the longitudinal crack initiation and subsequent propagation in transverse direction.

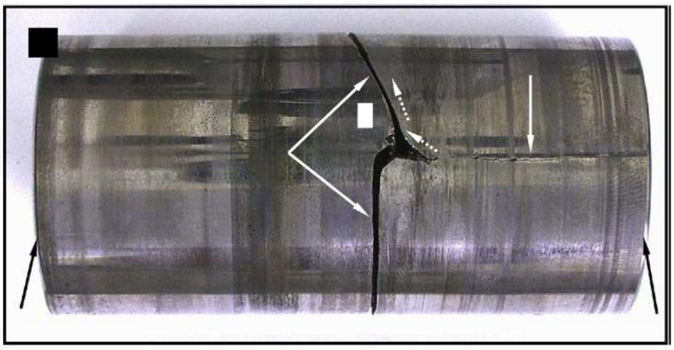

Fig -5: Failed piston-pin showing crack morphology [5)

A defective carburization technology can results in insufficient depth of carburized layer. This will reduce the fatigue strength of the piston pin [6)].

From the mechanical fatigue experiments and finite element static and dynamic analysis, it is found that the maximum stress generates at the upper end of the piston pin boss inner hole [7)] [13)]. It shows that initially crack originates at the piston pin seat and is called the horny crack. As the loading prevails, the crack extends farther on the lumen and is considered as the surface crack [7)].

2.3.3 Skirt fracture

If the clearance between piston and cylinder becomes too large, piston will be misaligned with cylinder, i.e., piston will be always at an angle with the cylinder walls. This causes the piston to flutter within the bore during the engine running. With larger clearances, the piston rotation angle also increases and makes contact with cylinder walls at two points; the bottom part of the skirt and the top part of the piston head. These contacts introduce a flexural load on the piston skirt. The consequence will be the formation of stress concentration areas where cracks initiate and propagate onto fracture [1)], which is explained by **Fig -6**.

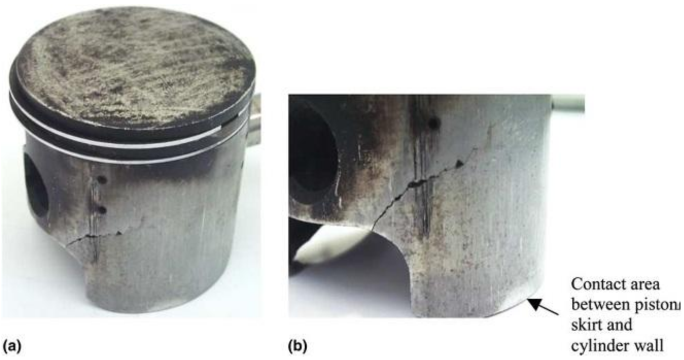

Fig -6: Engine piston with damaged skirt [1)]

2.4 Solutions and Preventive measures

There are some solutions for the aforementioned fatigue problems which are discussed hereby.

1. New materials that can provide improved fatigue performance needs to be developed. It includes new alloys with increased amounts of Si, Cu and other alloying elements, metal matrix composites etc. [1)]

2. The use of inserts or shrink-fitted parts in various parts of piston improves the material properties. This includes the following methods:
   - Austenitic cast ring carrier inserts which improves the ring groove wear behavior [1)].
   - Shrink-fitted brass pin bore bushings increases the pin bore load carrying capability [1)].
   - Al2O3 fiber preforms are infiltrated with the molten aluminium (normally by squeeze casting) creates a local reinforcement in the bowl rim area. This results in higher fatigue strength and increased young modulus (stiffness) [1)].

3. Employing graphite-modified polymer coating optimizes the skirt reliability and reduces friction and subsequent wear at the cylinder wall. Another method is the hard anodizing of the piston crown in diesel pistons which prevents thermal fatigue crack initiation [1)].

4. An efficient heat transport from piston to liner and oil is needed by which lower temperatures can be reached in the grooves and bowl rim [1)]. This can also be achieved by lowering the coolant temperature setpoint which reduces the oil temperature and hence the thermal loading [3)].

5. Improved fatigue strength can be achieved by having a smaller grain composition through utilization of modern technologies which include improved casting processes, use of improved hyper-eutectic alloy materials and a new patented heat treatment technology whereby the rim of the piston bowl is remelted using a computer controlled welding machine prior to final machining [3)].

6. Modifications in the design and geometry provide smooth transitions and sufficient radii in the bowl rim area. Increased bowl diameter and reduced bowl depth can improve the piston strength significantly. Also, a properly shaped pin bore and side reliefs change the contact conditions and help to increase the load carrying strength. However, care should be taken that these changes will not cause any deformations and stresses in the bowl rim at the expense of pin bore strength. This will ensure an acceptable piston lifetime [1)].

3. CONCLUSIONS

The study performed so far indicates that an IC engine piston is heavily subjected to fatigue loading in an unsteady manner throughout during its normal operation period. Resulting from mechanical and thermal loadings, stress gradients are developed along the piston. This will subsequently lead to crack initiation and propagation in various piston parts such as combustion bowl, crown surface, skirt, piston pin and pin seat. Aided by the characteristics of metallurgical structure and alloying elements present in it, crack develops into fracture away of material. Such a situation is avoided by ensuring proper preventing measures which includes design changes, new materials, fittings etc.

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