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Fatigue on engine pistons – A compendium of case studies

F.S. Silva *

Department of Mechanical Engineering, University of Minho, Azurém, 4800-058 Guimarães, Portugal

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Abstract

Engine pistons are one of the most complex components among all automotive or other industry field components. The engine can be called the heart of a car and the piston may be considered the most important part of an engine. There are lots of research works proposing, for engine pistons, new geometries, materials and manufacturing techniques, and this evolution has undergone with a continuous improvement over the last decades and required thorough examination of the smallest details. Notwithstanding all these studies, there are a huge number of damaged pistons. Damage mechanisms have different origins and are mainly wear, temperature, and fatigue related. Among the fatigue damages, thermal fatigue and mechanical fatigue, either at room or at high temperature, play a prominent role.

This work is concerned only with the analysis of fatigue-damaged pistons. Pistons from petrol and diesel engines, from automobiles, motorcycles and trains will be analyzed. Damages initiated at the crown, ring grooves, pin holes and skirt are assessed. A compendium of case studies of fatigue-damaged pistons is presented. An analysis of both thermal fatigue and mechanical fatigue damages is presented and analyzed in this work.

A linear static stress analysis, using "cosmos works", is used to determine the stress distribution during the combustion. Stresses at the piston crown and pin holes, as well as stresses at the grooves and skirt as a function of land clearances are also presented. A fractographic study is carried out in order to confirm crack initiation sites.

Keywords: Engine pistons; Mechanical fatigue; Thermal fatigue; Compendium

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1. Introduction

Piston materials and designs have evolved over the years and will continue to do so until fuel cells, exotic batteries or something else makes the internal combustion engines obsolete. The main reason of this

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* Tel.: +351 253 510220; fax: +351 253 516007.
E-mail address: fsamuel@dem.uminho.pt.

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continuous effort of evolution is based on the fact that the piston may be considered the 'heart' of an engine. The piston is one of the most stressed components of an entire vehicle – pressures at the combustion chamber may reach about 180–200 bar [1] – a few years ago this value was common only for heavy-duty trucks but nowadays it is usual in HDSI engines. Speeds reach about 25 m/s and temperatures at the piston crown may reach about 400 °C [1]. As one of the major moving parts in the power-transmitting assembly, the piston must be so designed that it can withstand the extreme heat and pressure of combustion. Pistons must also be light enough to keep inertial loads on related parts to a minimum. The piston also aids in sealing the cylinder to prevent the escape of combustion gases. It also transmits heat to the cooling oil and some of the heat through the piston rings to the cylinder wall.

As one of the main components in an engine, pistons technological evolution is expected to continue and they are expected to be more and more stronger, lighter, thinner and durable. The main reason is because the mechanical efficiency of an engine is still low and only about 25% of the original energy is used in brake power [2].

One thing that has not changed is the basic function of the piston. The pistons form the bottom half of the combustion chamber and transmits the force of combustion through the wrist pin and connecting rod to the crankshaft. The basic design of the piston is still pretty much the same. So what has changed? – The operating environment. Today's engines run cleaner, work harder and run hotter than ever before. At the same time they are expected to last longer and with minimal maintenance. Developments have been achieved in different fields: examples may be found on the following papers of piston geometry/combustion flow [3,4]; materials/mechanical and thermal behavior [5–8]; materials/wear and lubrication (coatings) [9–14]; analytical tools – FEA [15,16]; processing technologies [17,18]; etc.

Notwithstanding this technological evolution there are still a significant number of damaged pistons. Damages may have different origins: mechanical stresses; thermal stresses; wear mechanisms; temperature degradation, oxidation mechanisms; etc. In this work only mechanical damages and in particular fatigue damages will be assessed.

Fatigue is a source of piston damages. Although, traditionally, piston damages are attributed to wear and lubrication sources, fatigue is responsible for a significant number of piston damages. And some damages where the main cause is attributed to wear and/or lubrication mechanisms may have in the root cause origin a fatigue crack.

Fatigue exists when cyclic stresses/deformations occur in an area on a component. The cyclic stresses/deformations have mainly two origins: load and temperature. Traditional mechanical fatigue may be the main damaging mechanism in different parts of a piston depending on different factors. High temperature fatigue (which includes creep) is also present in some damaged pistons. Thermal fatigue and thermal–mechanical fatigue are also present in other damaged pistons. In this work, different pistons, from different kinds of engines: train engines; motorcycle engines; and automotive engines will be presented. Different damage mechanisms where fatigue prevails over other damaging mechanisms will be assessed. For a better understanding of the damaging mechanism different analytical tools, such as finite element analysis, fractographic analysis, metallurgical analysis, etc., will be used whenever they are necessary for a clear understanding of the damaging mechanism. A finite element linear static analysis, using "cosmos works", is used for stress and temperature determination.

Only aluminum pistons are assessed in this work because most of the engine pistons are in aluminum.

2. Experimental work

The fatigue-damaged pistons assessed on this work may be divided into two categories: the mechanical and high temperature mechanical damaged pistons and the thermal and thermal–mechanical damaged pistons. The mechanical and high temperature mechanical damaged pistons may be divided according to the damaged area: piston head; piston pin holes; piston compression ring grooves; and piston skirt. The analysis, in this work, will be made according to this classification.

2.1. Mechanical and high temperature mechanical fatigue

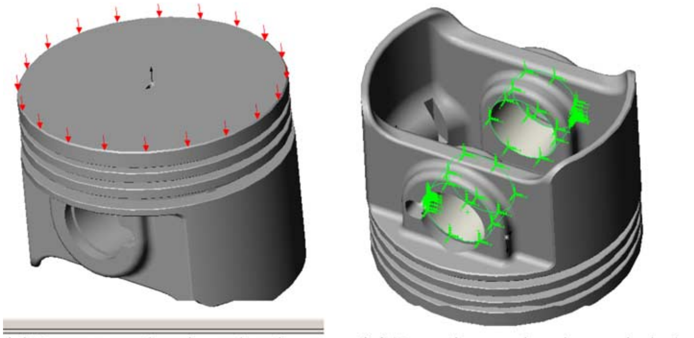
By mechanical fatigue it is meant that in a piston a crack will nucleate and propagate in critical stressed areas. The stresses in this context are due to the loads acting externally on the piston. On point 2.2 stresses induced by thermal gradients will be also assessed.

Although stresses on pistons change with piston geometries and engine pressures, Figs. 1 and 2 show a typical stress distribution on an engine piston. In Figs. 1 and 2 pressures are merely indicative and are used only with the purpose of determination of the most stressed areas. It is not intended to determine the real stresses acting on the piston. The dynamic and thermal stresses are not also included in Figs. 1 and 2.

It is clear that there are mainly two critical areas: the top side of piston pin hole and two areas at the piston head. Stress analyses on diesel pistons show the same critical areas. If holes or grooves are introduced on the pin hole it is possible to introduce critical stressed areas on those discontinuities.

2.1.1. Piston head and piston pin hole

As observed in Figs. 1 and 2, due to the pressure at the piston head, there are mainly two critical areas: piston pin holes and localized areas at the piston head. Subsequently will be presented different engine pistons where the cracks initiated on those areas.



(a) Pressure at the piston head area **(b)** Restraints at the piston pin holes

Fig. 1. Typical engine piston.

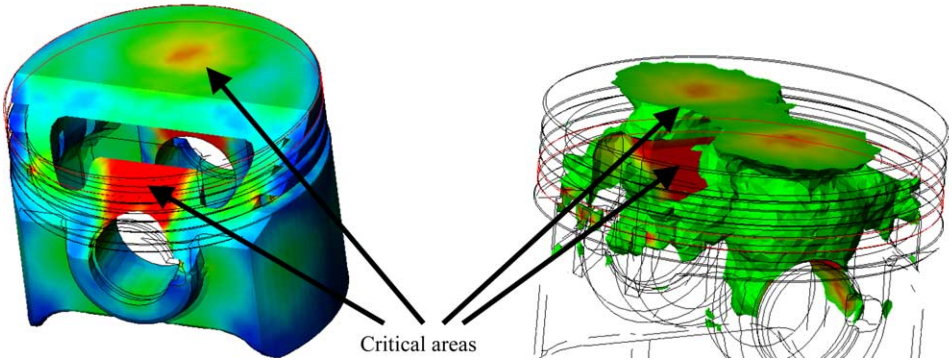


Fig. 2. Typical stress distribution on an engine piston.

On piston in Fig. 3 it seems by fractographic analysis that the crack initiated at the pin-hole. On pistons in Figs. 4 and 5 the crack initiated on the piston head near the combustion chamber.

A FEM analysis, Fig. 6, was made to piston of Fig. 5 and the results show that in pistons with a bowl combustion chamber, besides the pin holes (and in this particular case on the curvature radius on the inner side of the piston top) there are also two regions at the piston head where there exist a stress concentration. These two areas are located on the same vertical plane that contains the pin holes.

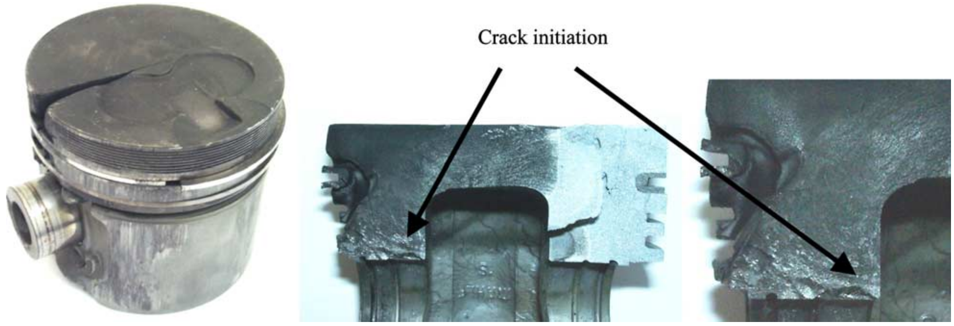


Fig. 3. Petrol engine piston with a crack from one side of the pin hole to the head.

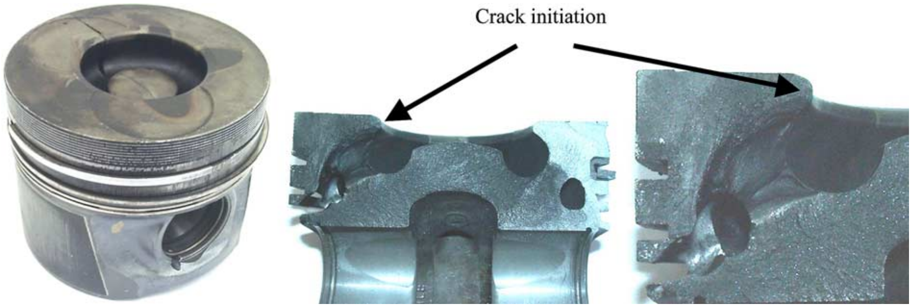


Fig. 4. Diesel engine piston (with cooling gallery) with a crack from one side of the pin hole to the head.

Fig. 5. Diesel engine piston with a crack from one side of the pin hole to the other pin hole going through the head of the piston.

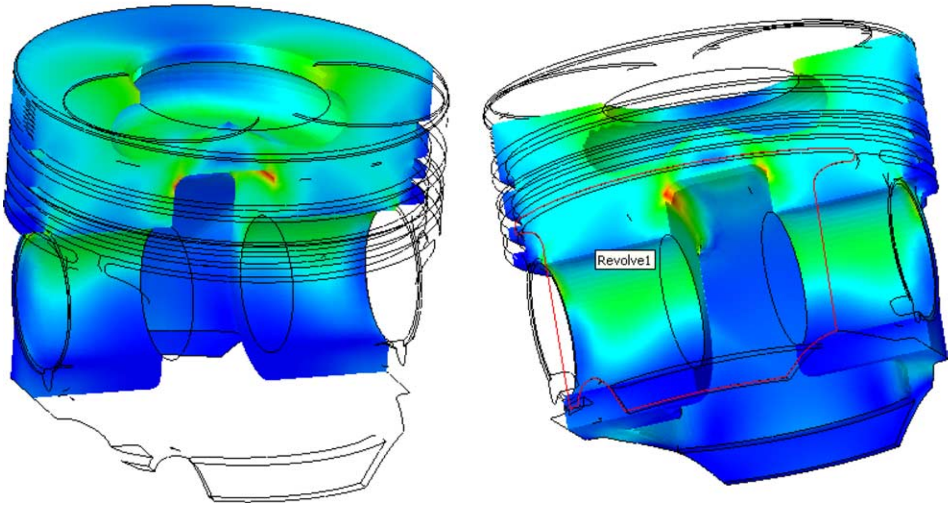


Fig. 6. Linear static stress distribution of piston in Fig. 5.

2.1.2. Piston compression grooves

Another typical fatigue damage occurs on piston compression grooves. Fig. 7 shows one damaged piston.

It is clear by Fig. 7(b) that the mechanism is fatigue. The striations clearly show the propagation of the crack. In Fig. 8 a simulation is made for stress analysis in piston grooves.

It is clear that there is a stress concentration on a stress radius of the groove when the compression ring is not inside the groove – the inner side of the ring is located at mid distance of the groove depth.

For a comparison, a simulation of the maximum Von Mises stress with the ring inside the groove (close to the piston wall) presented a maximum stress of about one third of the one shown in Fig. 8(b), where the inner side of the ring is located at mid distance of the groove depth. Thus there is an exponential growth of the stress when the distance between the ring and the piston wall increases. The same is to say that there is an increase in the stress at the piston groove when the clearance between the piston and the cylinder increases.

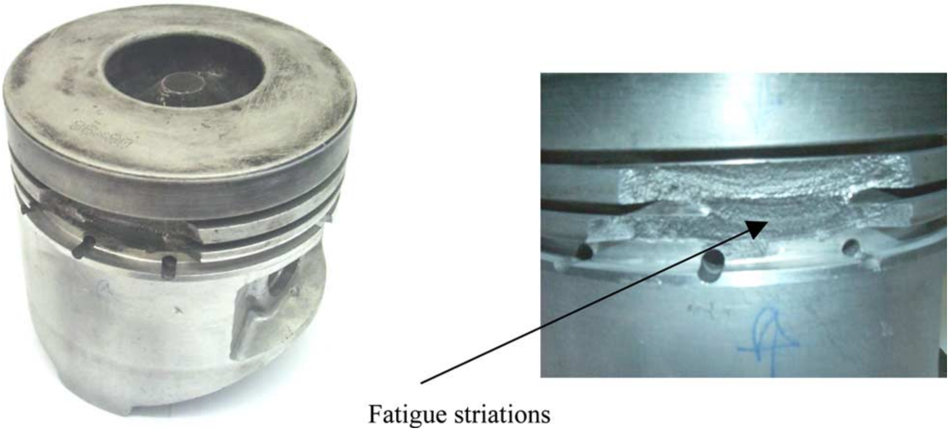


Fig. 7. Engine piston with damaged grooves: (a) piston; (b) detail of damaged grooves.

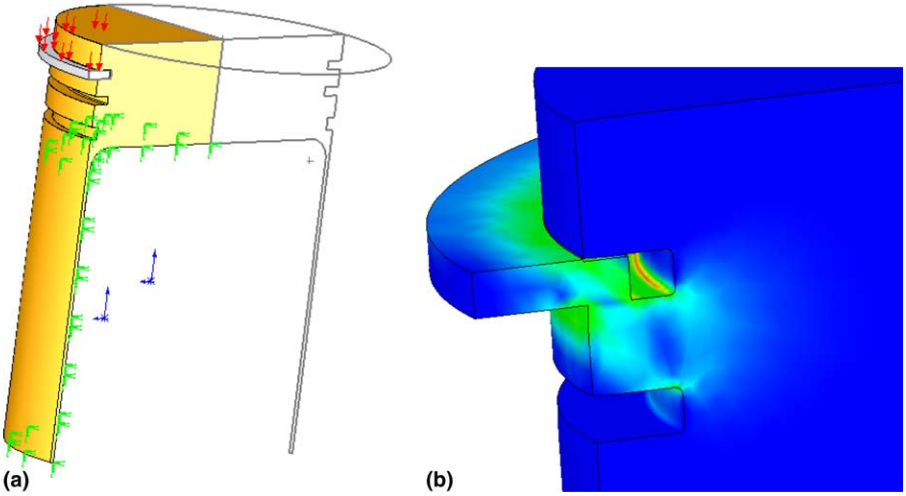


Fig. 8. Typical stress distribution on stress radius on the grooves.

2.1.3. Piston skirt

Another common fatigue damage that occurs in pistons is related to broken skirts, as shown in Fig. 9. In Fig. 9 is clear the crack (on the other side there is another crack) emanating from the curvature radius on the skirt. In Fig. 10 a simulation is made for stress analysis in piston skirt for a specific angle in respect to the vertical axis.

In Fig. 10 it is clear where the stresses are higher when there is an angle of the piston in relation to the vertical position. It is important to consider that there is always a clearance between the piston and the cylinder wall. Because of this clearance the piston never has its upward and downward movements in the vertical position but has always an angle in relation to the cylinder wall. And it is also clear that the contact points of the piston with the cylinder wall are: one side of the bottom part of the piston skirt and the opposite side of the top part of the piston. If we observe in Fig. 9(b) it can be seen the bottom part of the skirt that was in contact with the cylinder wall.

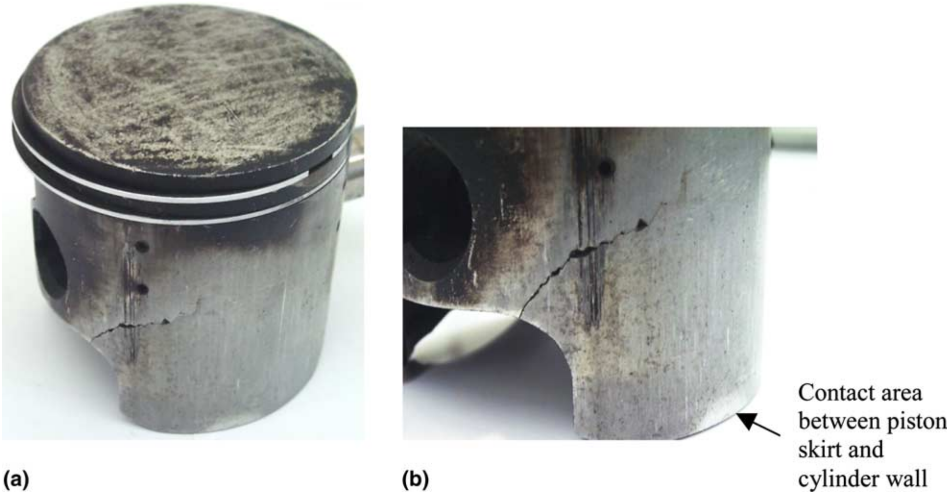


Fig. 9. Engine piston with damaged skirt: (a) piston; (b) detail of damaged skirt.

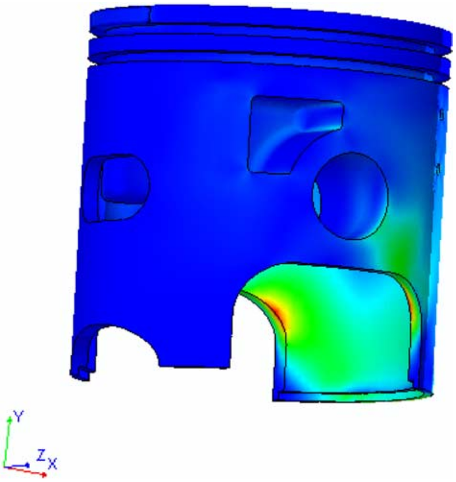


Fig. 10. Typical stress distribution on engine skirt with a big clearance.

If the clearance between piston and cylinder increases the piston rotation angle also increases and the stress at the piston skirt, as shown in Fig. 10, increases substantially.

2.2. Thermal/thermal–mechanical fatigue

Thermal fatigue is related to the stresses in the material induced by thermal gradients in the component. Fig. 11 shows two train pistons with several cracks at the piston head.

Thermal stresses are difficult to simulate because there are, in a piston, two kinds of thermal stresses (see Fig. 12):

(a) Thermal stresses due to the 'vertical' distribution of the temperature along the piston – high temperatures at the top and lower temperatures at the bottom.

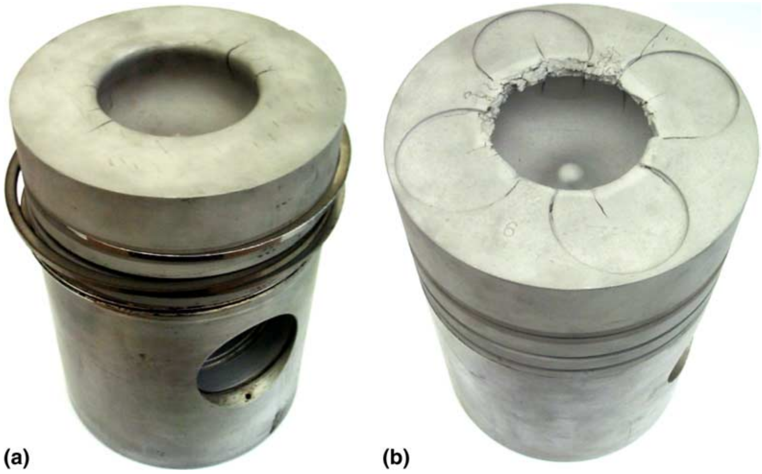


Fig. 11. Train engine pistons with damaged head: (a) piston 1; (b) piston 2.

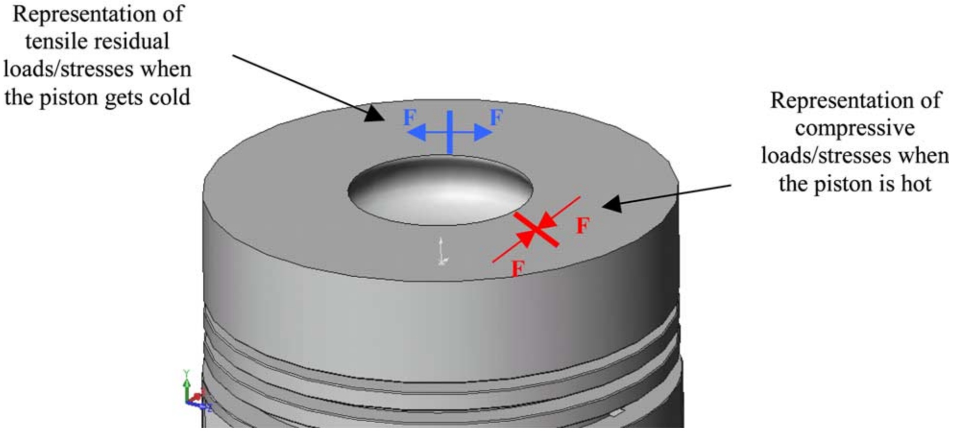


Fig. 12. Sketch of an example of thermal stresses at the top of a piston and forces, F, acting on the material.

(b) Thermal stresses due to the different temperatures at the head of the piston due to the flow of the hot gases or to fuel impingement (related to high-pressure injection).

(a) Thermal stresses due to the 'vertical' distribution are represented in Fig. 13(a)). There is a homogeneous and regular gradient of temperature on the radial direction along the head of the component. It is observed that the bowl rim area is the area where temperatures are higher. Thermal deformations under the operating bowl rim temperature are constrained by the surrounding material. This causes large compressive stresses on the total bowl rim circumference that often exceed the yield strength of the material. After creep relaxation of the high compressive stresses and when the piston gets cold creep effect gives rise to tensile residual stresses on the bowl rim. This cyclic stresses origins cracks distributed all around the rim area.

(b) Thermal stresses due to the different temperatures at the head of the piston are represented in Fig. 13(b)). This distribution causes localized warmer areas. The mechanism under which the thermal

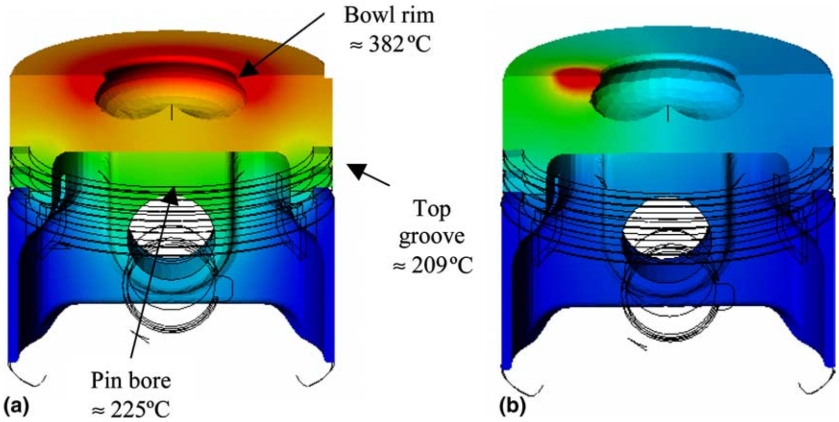


Fig. 13. Schematic thermal distribution at a piston: (a) homogeneous; (b) localized.

cracks form is the same as mentioned in (a) with the exception that in this case these warmer areas will have higher compressive stresses – followed by creep – followed by higher tensile stresses when the piston gets cold. Thus, in this case is most probable that localized areas at the bowl rim will concentrate the thermal fatigue cracks.

In the first case, Fig. 13(a) it would be expected several fatigue radial cracks over the whole piston head. In the second case, Fig. 13(b) it would be expected fatigue cracks in specific areas of the piston head (those where the thermal gradients occur). As a fact the piston in Fig. 11(b) seems to be representative of the first case – cracks all around the piston rim, while Fig. 11(b) seems to be representative of the second case – cracks on localized areas of the rim.

Together with the mechanical load due to peak cylinder pressure, the bowl rim experiences cyclic load in the compressive range. After creep relaxation of the high compressive stresses, alternating fatigue loading, at least along the pin axis, may occur.

3. Examinations and discussion

In this section the different kinds of fatigue damage mechanisms will be analyzed separately.

3.1. Mechanical fatigue

3.1.1. Piston head and piston pin hole

Mechanical fatigue damages at piston head and piston pin holes is the reason of several damaged engine pistons. Static stresses concentrate mainly at pin holes (Figs. 2 and 6) both for petrol and diesel pistons, as well as for automotive, train, and other engine fields. This explains cracks initiated at piston pin holes (Fig. 3). However, if the critical stress is at the piston pin holes why some of the pistons start their cracks at the head, as presented in Figs. 4 and 5? A metallographic study was made in piston of Fig. 5 to see if there was a special reason for that the crack initiated there (such as pores or microstructural defects) and nothing was detected. The reason for the crack to initiate at that point at the piston rim area may be related to two different aspects:

- *Mechanical fatigue*: The crack always initiate at the same points – at the same vertical plane that contains the pin holes (see Figs. 4 and 5). The stresses at the piston head are higher at those areas (Fig. 6). In pistons of Figs. 4 and 5, both broken by the piston head, there is only one visible crack, and this is typical of mechanical fatigue. In Ref. [19] there is a description of a piston with only one crack, similar to those in Figs. 4 and 5, and the crack was attributed to thermal fatigue. Thermal fatigue does not seem to be the reason for these cracks because thermal fatigue produces more then one visible crack and mostly several visible cracks (see Figs. 11(a) and (b)). However, the reason why the crack initiated at the head instead of the pin hole, where the stresses are higher, is not answered yet. The reason may be on temperature.
- *High temperature mechanical fatigue*: There is a temperature distribution along the vertical axis of the piston. The head is always hotter than the bottom and the pin hole area. Thus the fatigue resistance of the material at the head is lower even though the material is the same. In Ref. [20], based on temperatures read with temperature extensometers, is shown that in diesel engine pistons the areas where the temperature is higher is right at the bowl rim of the piston, where the temperature may reach about 382 °C (see Fig. 13(a)). Thus, the edge area at the combustion chamber bowl rim is the less resistant due to the high temperature. If we combine the effect of the temperature with the static stresses, there are two critical areas – those on both sides of the bowl rim area on the same vertical plane that contains the pin holes (this results of a superposition of static stresses (Fig. 2) with temperature distribution (Fig. 13(a)). And the observations show that the pistons broken at the head (Figs. 4 and 5), both initiated the cracks (only one visible crack) in those particular regions.

Thus, depending on the particular geometry of each piston, and taking into account both the static stresses and the temperature influence on the material resistance, either the pin hole area and the bowl rim area may be critical. For a comparison, temperatures on the pin hole may reach about 225 °C at the same piston where temperature at the bowl rim area reaches about 382 °C. At the same time temperature at the top groove is about 209 °C.

This kind of fatigue damage represents, according to our experience on engine pistons, the biggest slice of fatigue-damaged pistons.

3.1.2. *Piston compression grooves*

There is a number of pistons that arrive to our labs broken by the compression ring grooves. The compression ring is the one who has the function of not allowing the pressure to be lost between the piston and the cylinder wall. However, when the clearance between the piston and cylinder wall becomes high (due to wear of the cylinder wall) there is an increase of the pressure acting on the ring (because the ring comes out of the groove – see Fig. 8(b)) and consequently a stress increase on the compression groove. The stresses at that particular curvature radius at the compression ring groove seem to be enough to initiate fatigue cracks on the piston.

Thus the main reason for this damage is related to the clearance between the piston and the cylinder wall.

3.1.3. *Piston skirt*

There are also some pistons with broken skirts. As shown on this work the skirt may break by fatigue (Fig. 9) and the reason are the stresses that act on the curvature radius of some skirt geometries (Fig. 10). As well as on the previous item the main reason for this damage may be related to the clearance between the piston and the cylinder wall. As a fact a big clearance allows the piston to rotate and to contact the cylinder wall mainly in two points: the bottom part of the skirt and the top part of the piston head. If we look carefully at Fig. 9(b) it can be observed that the surface is rough because of the contact with the cylinder wall. These contacts introduce a flexural load on the piston skirt. The consequence will be the stress concentration areas shown in Fig. 10.

The main reason for this damage is also related to the clearance between the piston and the cylinder wall.

3.2. *Thermal/thermal–mechanical fatigue*

Thermal fatigue cracks are easy to identify because they usually show a particular feature. Typically there are some visible fatigue cracks on the areas with cyclic thermal gradients as can be seen on brake disks and other components under thermal fatigue [23]. On mechanical fatigue and high temperature mechanical fatigue there is only one prevailing crack (naked eye visible crack).

As referred before, it may be considered two ways through which thermal gradients act on stresses: thermal stresses due to the vertical distribution of the temperature along the piston – high temperatures at the top and lower temperatures at the bottom (Fig. 13(a)); and thermal stresses due to the different temperatures at the head of the piston due to the flow of the hot air or fuel impingement (Fig. 13(b)). On the first case it would be expected several fatigue radial cracks over the whole piston head. On the second case it would be expected fatigue cracks in specific areas of the piston head (those where the thermal gradients occur). Fig. 11(b) is representative of the first case while Fig. 11(b) seems to be representative of the second case.

It seems that there is no other plausible explanation for cracks shown in Fig. 11.

In Fig. 11(b) there are cracks distributed along the bowl rim and it seems clear that the main mechanism was thermal fatigue due to an homogeneous temperature distribution. In Fig. 11(a) there are several cracks located in opposite sides at the piston crown. If they were high temperature mechanical fatigue cracks it would be only one crack and the crack would be located at the vertical plane that contains the pin holes. That is not the case – cracks are located on a different plane.

4. Proposals and in course solutions

There are a number of in course solutions and some theoretical proposals for the aforementioned fatigue problems. We will mention some of the most promising proposals. In this chapter it is not intended an exhaustive study on this subject. The aim is to point out that the fatigue problem in engine pistons is important and companies take it seriously.

This analysis will be divided into five aspects: materials; local reinforcements; surface coatings; design; and piston cooling.

4.1. Materials

For many years the eutectic Al–Si alloy has been used for pistons (because only aluminum pistons have been assessed in this work only aluminium alloys will be presented). With increased piston temperatures, the need for equal or improved fatigue strength could no longer be satisfied. New alloys with increased Si content and Cu content, and other alloying elements, have been proved be satisfactory to the new requirements [8,21]. Use of metal matrix composites is already in use and also under investigation [4–6]. For the future, additional improvements of the materials properties may be expected. New technologies are also promising such as PM since its components exhibit excellent strength properties. PM has a significant potential for further development. However, these changes must take into account that an efficient heat transport from the piston to the liner and to the oil is needed. Other technologies and die-casting processes are also being developed [16,17].

The development of new materials and processing technologies with improved high temperature mechanical and fatigue performance would help solving the different fatigue damages identified in this work.

4.2. Local reinforcements

The application of inserts or shrink-fitted parts can locally increase the properties of a component beyond the strength of the base alloy. An application that is already in use for years is the austenitic cast ring carrier insert to give improved ring groove wear behavior.

Pin bores is also a potential area where inserts would be useful. Pin bores are highly loaded because they transfer the total cylinder pressure load to the piston pin and in most designs this region of aluminium pistons is loaded very close to the lifetime limit. Other solutions such as geometric measures (see below) are being taken into consideration for these areas. The use of shrink-fitted brass pin bore bushings is also a way of increasing pin bore load carrying capability.

Another area where inserts are applicable is the bowl rim in the piston crown. In this area, normally, yield strength is exceeded. A known solution is to use Al_2O_3 fiber inserts with, for example, 15% of the volume [20,21]. These fiber preforms are infiltrated with the molten aluminium (traditionally by squeeze casting) and create a local reinforcement. This results in higher fatigue strength and increased young modulus (stiffness). Thermal cycle fatigue strength is significantly improved as well as mechanical fatigue.

This solution may be useful either for thermal fatigue damages identified in this work as well as for mechanical and high temperature mechanical fatigue damages, both at the piston head and at the pin holes.

4.3. Surface coatings

All modern aluminum pistons for HDSI engines employ a graphite-modified polymer coating of the skirt [20,21]. Other coatings are also under investigation [8,9]. These coatings optimizes skirt reliability and reduces friction. Another possible future development may include hard anodising of the piston crown, in diesel pistons, to prevent thermal fatigue crack initiation.

This treatments by reducing friction would be useful to reduce wear at the cylinder wall. This means that clearances would resist more time and problems such as broken grooves and broken skirts would be avoided.

4.4. Design

Two specific areas that are under high stresses need an improvement in design: the bowl rim area and the pin bore area.

As mentioned before the highest thermally loaded region is the bowl rim area because of the heat conduction cross section is small in relation to the surface exposed to heat input. Sharp edges or small radii on the bowl rim induce locally steeper temperature gradients and an increased stress of the material. In addition high pressure injection can cause liquid fuel impingement leading to very high frequency local thermal cycles in the surface of the material (Fig. 13(b)). The design of the bowl rim must account for these loading conditions. This implies the need to design smooth transitions and sufficient radii in the bowl rim area. In addition, a larger bowl diameter and reduced bowl depth improve piston strength significantly. Thermal fatigue cracks and high temperature mechanical fatigue cracks may be reduced with design improvement.

The specific pin bore load, for various reasons (weight, using available conrods, etc.), is close to or even exceeds the capability of the cylindrical pin bore at the given operating temperature and can cause pin bore cracks to occur. Current improvements in strength are related to local geometries. A shaped pin bore, side reliefs or an oval pin bore [20,21], change the contact conditions and can help to increase the acceptable specific load. A different assembling geometry, a spherical contact between the rod and the piston, as already proposed and patented by NASA [22] would substantially reduce static stresses. However, these changes result in different deformations and stresses, specially on the bowl rim. Hence, it is necessary to find a compromise between pin bore strength and bowl rim stresses that can give acceptable piston lifetime.

4.5. Piston cooling

The importance of a good piston cooling has been mentioned before. For some applications, spray cooling of the piston is sufficient. However, with increased specific output, there is an increasing amount of cooling gallery pistons. This implies that more heat is transferred to the cooling oil. The temperatures in the first ring groove area are reduced by typically 30–50 °C and at other areas, like the bowl rim area, lower temperatures can be reached. With lower temperatures fatigue resistance increases and fatigue damages would reduce.

5. Conclusions

The first main conclusion that could be drawn from this work is that although fatigue is not the responsible for biggest slice of damaged pistons, it remains a problem on engine pistons and its solution remains a goal for piston manufacturers. And it will last a problem for long because efforts on fuel consumption reduction and power increase will push to the limit weight reduction, that means thinner walls and higher stresses. To satisfy all the requirements with regard to successful application of pistons, in particular mechanical and high temperature mechanical fatigue and thermal/thermal–mechanical fatigue there are several concepts available that can be used to improve its use, such as design, materials, processing technologies, etc.

References

[1] Junker H, Issler W. Pistons for high loaded direct injection diesel engines. MAHLE Technical Information.

[2] Taylo CM. Automobile engine tribology – design considerations for efficiency and durability. Wear 1998;221:1–8.

[3] Kajiwara H, Fujioka Y, Suzuki T, Negishi H. An analytical approach for prediction of piston temperature distribution in diesel engines. JSAE Rev 2002;23(4):429–34.

[4] Payri F, Benajes J, Margot X, Gil A. CFD modeling of the in-cylinder flow in direct-injection diesel engines. Comput Fluids 2004;33(8):995–1021.

[5] Mogilewski R, Brian SR, Wolbach WS, Krucek TW, Maier RD, Shoemaker DL, Chabala JM, Soni KK, Levi-Setti R. Reactions at the matrix-reinforcement interface in aluminum alloy matrix composites. Mater Sci Eng A 1995;191:209–22.

[6] Huang YD, Hort N, Kainer KU. Thermal behavior of short fiber reinforced AlSi12CuMgNi piston alloys. Composites A 2004;35(2):249–63.

[7] Baxter WJ, Alostaz A, Jasiuk I. The effect of shot particles on the fatigue of Kaowool fibre-reinforced 339 Aluminum. Met Mater Trans A 1999;30:95.

[8] Joyce MR, Styles CM, Reed PAS. Elevated temperature short crack fatigue behaviour in near eutectic Al–Si alloys. Int J Fatigue 2003;25:863–9.

[9] Friedrich C, Berg G, Broszeit E, Rick F, Holland J. PVD Cr_xN coatings for tribological application on piston rings. Surf Coat Technol 1997;97(1–3):661–8.

[10] Pinedo CE. The use of selective plasma nitriding on piston rings for performance improvement. Mater Des 2003;24(2):131–5.

[11] Kikuchi T, Ito S, Nakayama Y. Piston friction analysis using a direct-injection single-cylinder gasoline engine. JSAE Rev 2003;24(1):53–8.

[12] Stolarski TA, Zhou Q. Temperature–friction characteristics of used lubricant from two-stroke cross-head marine diesel engines. Wear 2002;252(3–4):300–5.

[13] Priest M, Taylor CM. Automobile engine tribology — approaching the surface. Wear 2000;241(2):193–203.

[14] Takiguchi M, Ando H, Takimoto T, Uratsuka A. Characteristics of friction and lubrication of two-ring piston. JSAE Rev 1996;17(1):11–6.

[15] Cho JR, Joo YS, Jeong HS. The Al-powder forging process: its finite element analysis. J Mater Processing Technol 2001; 111(1–3):204–9.

[16] Vijaya Babu M, Krishna Kumar R, Prabhakar O, Gowri Shankar N. Fracture mechanics approaches to coating strength evaluation. Eng Fract Mech 1996;55(2):235–48.

[17] Nakajima K, Otaka H, Kashimura T, Sakuma S, Tanaka M. Newly developed hollow ring groove insert piston – part 2: producing technology of new piston. JSAE Rev 1996;17(4):448.

[18] Sulaiman S, Hamouda AMS, Gethin DT. Experimental investigation for metal-filling system of pressure diecasting process on a cold chamber machine. J Mater Processing Technol 2001;119(1–3):268–72.

[19] Martin, Gary G. Failure of stationary pump engine piston. J Failure Anal Prevention 2004;4(1):37–9.

[20] MAHLE, Kolben fur Verbrennungsmotoren Die Bibliothek der Technik; 1998. p. 39.

[21] MAHLE, Pistons for high loaded direct injection diesel engines. Technical Information. p. 12.

[22] Valco, Mark J. Spherical joint piston and connecting rod developed. NASA Report 2000;(216):433–3717.

[23] Silva FS. Analysis of a vehicle crankshaft failure. Eng Failure Anal 2003;10(5):605–16.