Piston Analysis of IC Engine

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ABSTRACT

Engine pistons are one of the most complex components among all automotive or other industry field components. 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. 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.

Keyword: - *Piston, Analysis, Evolution, Fatigue*

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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 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. A few years ago this value was common only for heavy-duty trucks but now a days it is usual in SI engines. Speeds reach about 25 m/s and temperatures at the piston crown may reach about 400^0C [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 andthey 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 materials/mechanical and thermal behavior; materials/wear and lubrication (coatings); analytical tools – FEA; processing technologies 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

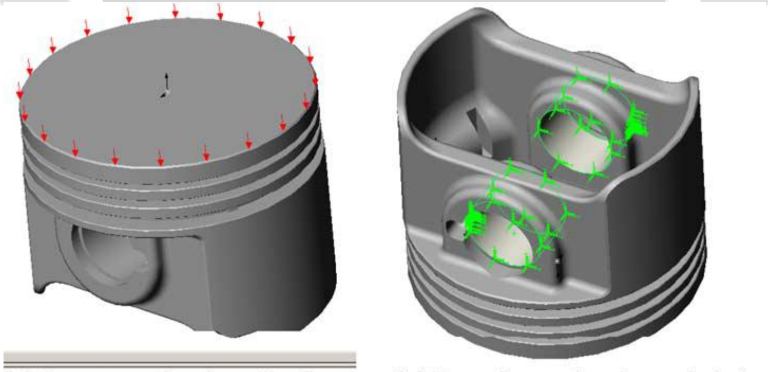
The fatigue-damaged pistons assessed on this work may be divided into two categories: the mechanical and high temperature mechanical damaged pistons and the thermal and thermal–mechanical damaged pistons. The mechanical and high temperature mechanical damaged pistons may be divided according to the damaged 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. 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.

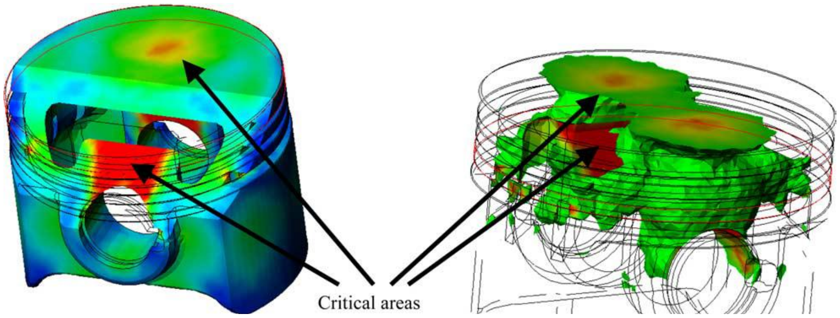


Fig.2- Typical stress distribution on an engine piston

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.

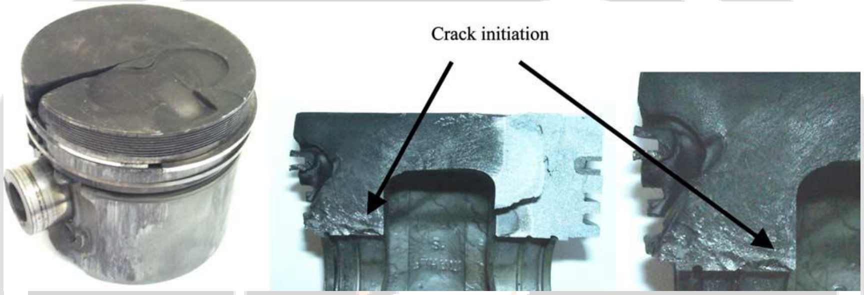


Fig.3- Petrol Engine Piston With A Crack From One Side of The Pin Hole To The Head.

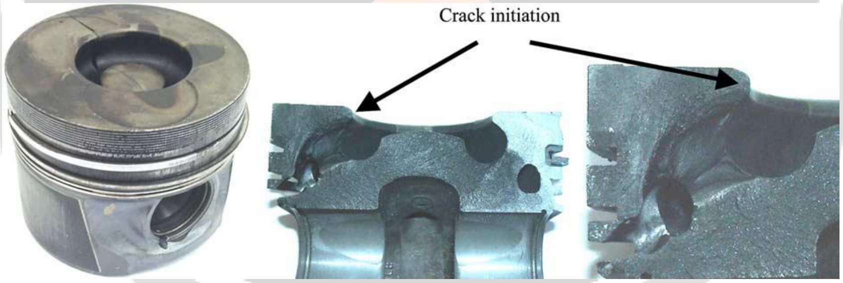


Fig.4- Diesel Engine Piston (With Cooling Gallery) With A Crack From One Side Of The Pin Hole To The Head

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

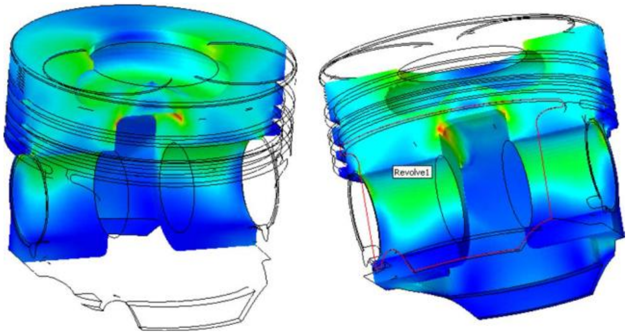


Fig.6- Linear static stress distribution of piston in Fig.5

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.

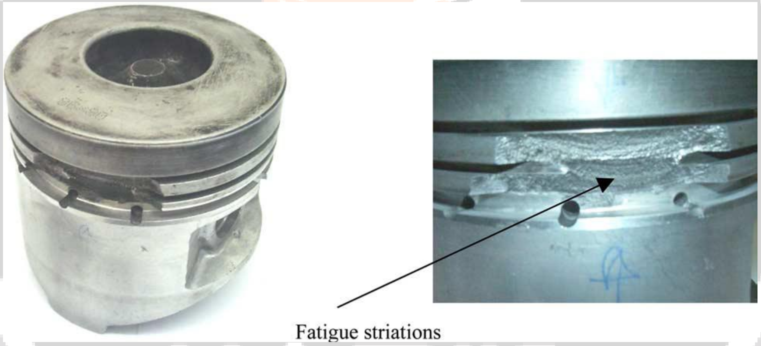


Fig. 7- Engine piston with damaged grooves: (a) piston; (b) detail of damaged grooves.

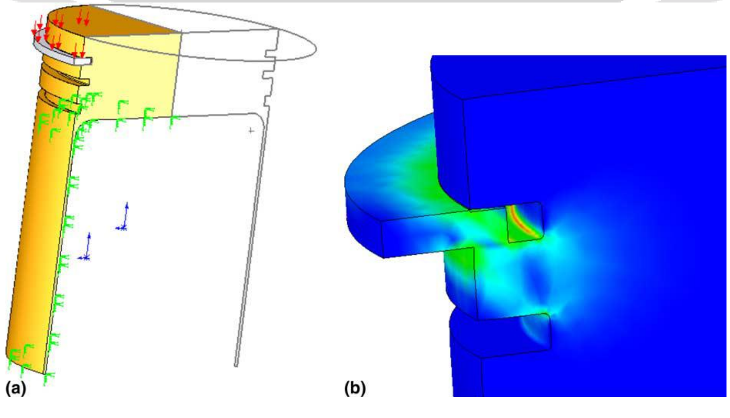


Fig.8-. Typical Stress Distribution on Stress Radius On The Grooves.

2.1.3 Piston Skirt

Another common fatigue damage that occurs in pistons is related to broken skirts, as shown in Fig. 9.Itis 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.

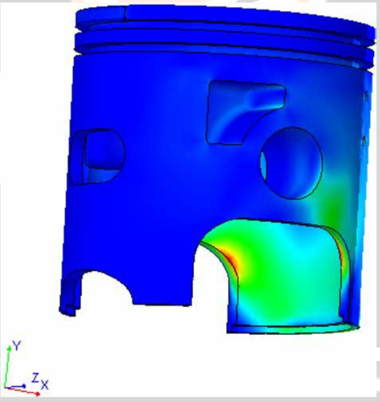


Fig.10- Typical stress distribution on engine skirt with a big clearance

If the clearance between piston and cylinder increases the piston rotation angle also increases and thestress 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 (seeFig. 12):(a) Thermal stresses due to the vertical distribution of the temperature along the piston – high temperature sat the top and lower temperatures at the bottom.

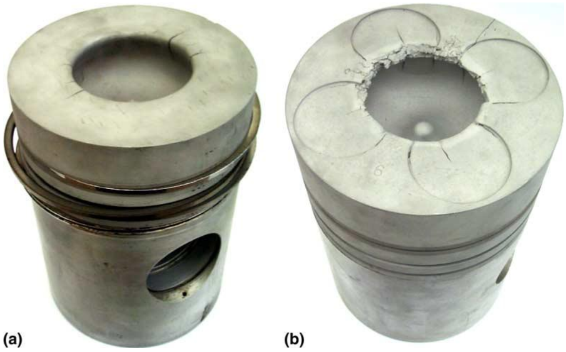


Fig.11- Train Engine Pistons With Damaged Head: (A) Piston 1; (B) Piston 2.

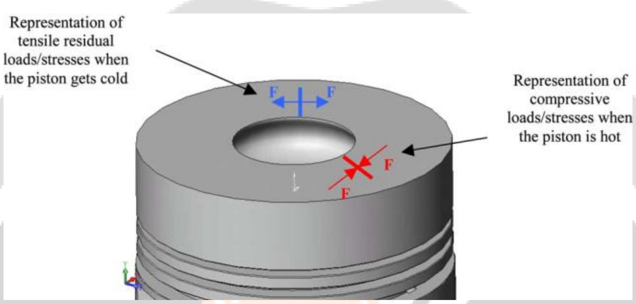


Fig.12- Sketch of an example of thermal stresses at the top of a piston and forces, F, acting on the material

(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 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

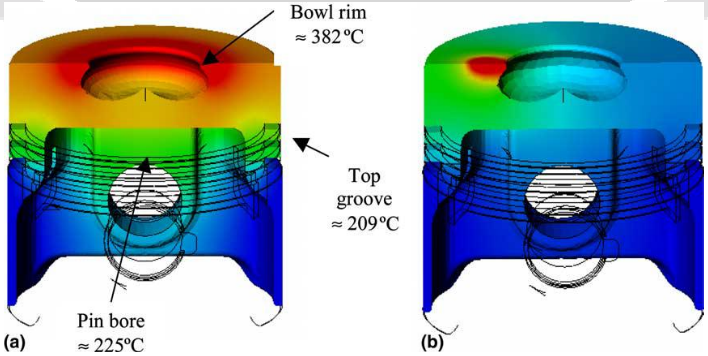


Fig.13- Schematic thermal distribution at a piston: (a) homogeneous; (b) localized.

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.

2.3 Macromorphology of The Composite Pistons

Fig. 14shows as cast pistons directly taken from the mold. Only the upper and lower pistons were used for material characterization. In Fig. 15is shown the clean piston. The piston has clear outlines and a smooth surface and was obtained with the requireddimensions. The clean piston was machined to create a piston with grooves, shown in Fig. 16. The piston with grooves was then cut along the axis by EDM, and the cross-section morphology, as shown in Fig. 17, revealed many SiC particles gathered in the piston head. In contrast, there are no SiC particles in the piston skirt. This observation indicates that the SiC particle segregation was achieved under a centrifugal force, and eventually Al alloy-based composite pistonswith partial SiC particle segregation were manufactured by centrifugalcasting.

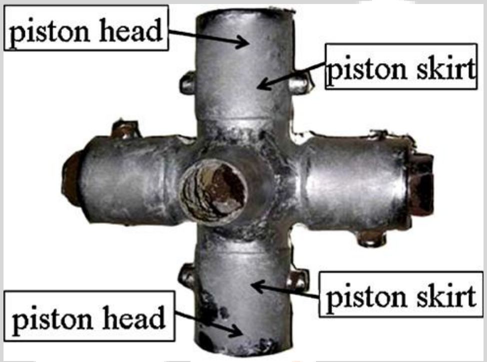


Fig. 14. As-cast pistons fabricated by centrifugal casting.

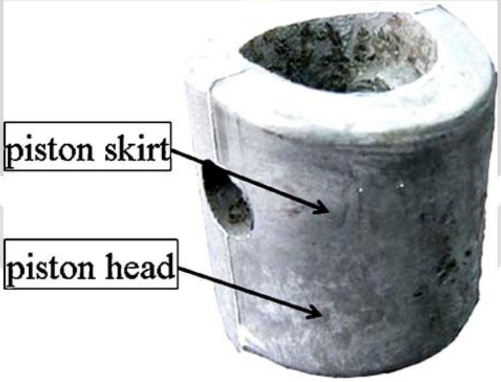


Fig.15-The clean piston

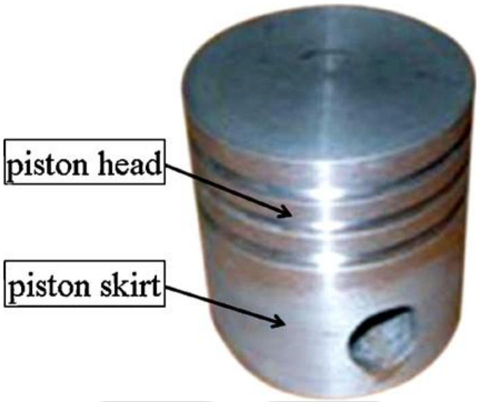


Fig.16. Piston with grooves after machining

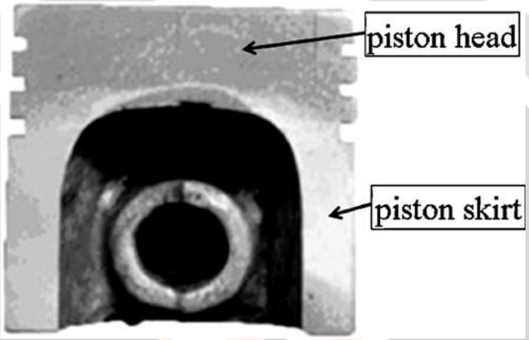


Fig.17-Cross-section morphology of the piston.

Fig. 18shows the transverse cut of the samples, along the axes of pistons obtained using the processing conditions. As can be seen, the pistons with processing (1), (2), (3) can be divided into three zones from the piston skirt to the piston head, i.e., the defects gathering zone containing a large number of pores and oxide inclusions, the metal matrix zone free from SiC particles and impurities, and the SiC particle segregation zone. However, there is no evidence of divided zones in pistons with processing (4). And it is seen that as the temperatures of pouring slurry and preheatedmold decrease, the area of the segregation zone in the piston head becomes gradually big.

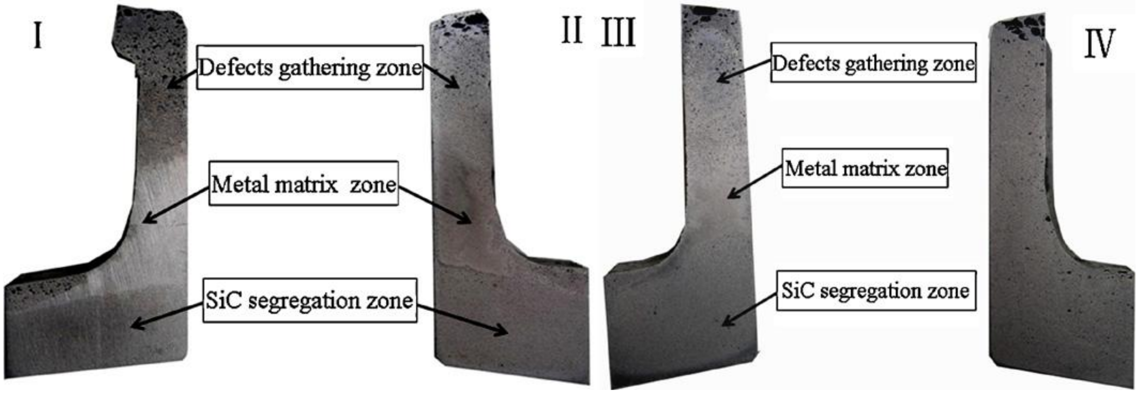


Fig.18-Macromorphology of samples with various processing parameters

3. MATERIAL

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. CONCLUSION

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 agoal 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 areseveral concepts available that can be used to improve its use, such as design, materials, processing technologies,etc

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