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Failure of Piston in IC Engines: A Review

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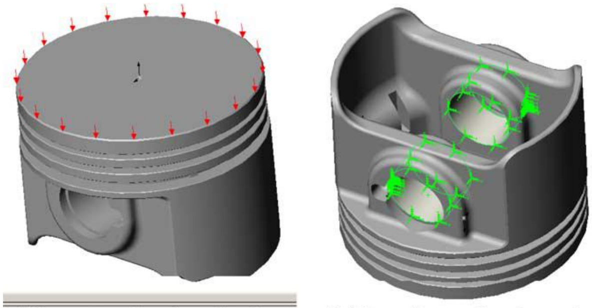
Abstract: *Piston in the internal combustion (IC) engine is robust, dynamically loaded tribo-pair that reciprocates continuously at varying temperature. Study has been made by various researchers on piston design, dynamics, fatigue and wear at the interface with other element in contact along with their effects on IC engines. It was found that the friction coefficient increases with increasing surface roughness of liner surface and thermal performance of the piston increases with increased coating thickness. The free material liberated due to deep scoring between the piston and liner snowballs, leads to seizure failure.*
Keywords: *Piston, Tribo-pair, IC Engines, Fatigue, Wear.*

I. INTRODUCTION

The current trend in the land transportation and power production is to develop IC engines of enhanced “power-capacity” and “reduced emissions” (to follow specified international intrinsic norms). Piston, piston rings and cylinder liner are important components of an IC engine. The prime function of piston is to transmit the motion produced by liberation of chemical energy of fuel to mechanical works. Piston rings dynamically seal the gap between the moving piston and the cylinder liner surface in order to prevent the escape of the combustion gases from the combustion chamber into the crankcase and the leakage of the oil from the crankcase into the combustion chamber.



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

Fig. 1. Typical engine piston [10]

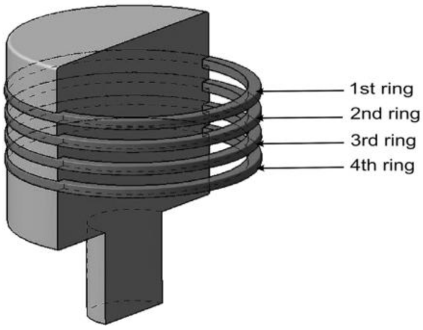


Fig. 2. Schematic illustration of a worn ring piece [25]

The manufacturing of cylinders includes boring, honing and plateau honing which has received much attention by manufacturers in recent times. The process of the surface changes which occurs during running of the engine is related to the wearing action caused by the piston ring on the bore. This action takes place of “transitional topography” where the surface generated exhibits the influence of the piston ring which modifies the machined surface. This has been made possible by improving the design of piston and reducing the failure i.e. scuffing, sculling, seizure of piston etc. The piston is one of the continuous moving parts of engine, is of pivotal importance. Piston has high dynamic loaded speed and heavy reciprocating weight develop high inertia forces, which are undesirable. The following factors may be considered for proper functioning of piston in IC Engine:

1. The piston should have enormous strength and heat resistance properties to withstand gas pressure and inertia forces. They should have minimum weight to minimize the inertia forces.
2. The material of the piston should have good and quick dissipation of heat from the crown to the rings and bearing area to the cylinder walls. It should form an effective gas and oil seal.
3. Material of the piston must possess good wearing qualities, so that the piston is able to maintain sufficient surface-hardness unto the operating temperatures.
4. Piston should have rigid construction to withstand thermal, mechanical distortion and sufficient area to prevent undue wear. It has even expansion under thermal loads so should be free as possible from discontinuities.

5. Piston should form tribo-pairs and have high reciprocation speed without noise, minimum work of friction and have little or no tendency towards corrosion and pitting-up.

II. LITERATURE REVIEW

Sunden and R. Schaub [12] presented a selection of some of the more practically orientated principles of the successful manufacture of grey cast iron piston rings greater than 175 mm in diameter, and shown that when considered with the sciences of strength of materials and diesel engineering, the subject of piston rings becomes an embodiment of the wider subject of tribology. A brief description of the most important topics of practical piston ring manufacture, and an indication of the vast size and complicated nature of an industry which concerns itself with one of the cheapest components of a diesel engine has been given. P. C. Nautiyal, et al, [23] investigated a large part of the top piston ring wear of an IC engine which takes place in boundary lubrication around top dead centre (TDC) position. A quantitative assessment of the frictional behavior using actual piston ring and cylinder liner under conditions close to TDC was made. The factors responsible for wear under these conditions have been identified as surface temperature, peak combustion pressure, total energy on the wearing surfaces and other physical properties of the material under sliding. T. H. C. Childs and F. Sabbagh [30] carried out tests to study the wear mechanisms responsible, particularly the relative importance of high cycle metal fatigue and chemical reaction film wear. Two types of cast iron used as piston rings (a grey and a carbidic iron) were used as pins and a cylinder bore material was used as the ring. Specific loads were varied from 20 to 400 M Pa and the sliding speed was 0.4 m s^{-1}. The wear mechanisms in the two types of test were possibly different, as the engine tests produced worn surfaces which when examined by an optical microscope were bright, whereas the pin-on-ring test surfaces were covered by patchy non-metallic films. Wear rates, friction coefficients, percentage metallic contact and plasticity index were measured in the pin-on-ring tests. Specific wear rates did not correlate with any parameters of contact stress severity.

D. J. Picken and H. A. Hassaan [6] paper described the theory and use of a method for estimating the service life of an internal combustion (i.c.) engine based on experimental evidence and the law of adhesive wear. A simple computer program described, which predicted the overhaul life of an IC engine from its design data and a typical sample of its particular running conditions. The use of the program for an engine generator set operating on biogas at a farm site used as an example. It was considered that the work reported showed that the limit of engine life occurred when the wear of the cylinder liner at the upper position of the piston ring became excessive. Based on this, and assuming marginal lubrication in this area was possible to do a calculation which predicted engine life for any given application. J. E. Willn [13] discussed various methods of characterizing and describing surface finish more accurately for specification purposes. Later, it was hoped that some part of the characterization may also form a correlation with the performance of the ring and bore surfaces with respect to scuffing failure. Complete surface finish characterization was a pre-requisite to ring and liner scuffing tests from which it could be possible to form some correlation between performance and some feature of the surface profile. Meanwhile, a practical and more precise method of specifying finish was required for insuring consistent results in production. Then established random analysis techniques offer a means of characterizing profiles which describe the variations more fully than the simple values of center line average or root mean square. In the majority of cases, the specimen profiles which were examined, varied randomly in amplitude but not in frequency. A. V. Sreenath and N. Raman [2] studied about the conformance between the liner and rings of an internal combustion engine and found that it depend upon mainly on the linear wear (dimensional loss) during running-in. Running-in wear studies, using the factorial design of experiments, on a compression ignition engine showed that at certain dead centre locations of piston rings the linear wear of the cylinder liner increases with increase in the initial surface roughness of the liner. The linear wear of the cast iron liner and rings decreased with increasing load but the mass wear increased with increasing load. Statistical analysis of the linear wear data showed that, during running-in, the initial surface roughness of the liner had a significant effect on running-in wear at and around such dead centre positions of rings where more than one compression ring slide over. It was observed that metal to metal contact occurs at the dead centre positions of rings during running-in. K. J. Stout and T. A. Spedding [17] considered the methods of producing engine bores and the surface profiles obtained by these methods were examined and attempted to characterize their surface topography made. The effects of wear studied and from a consideration of the surface topography of the initial machining process a characterization technique was proposed. The random part of the bored surface has a similar skewness and kurtosis to the honed surface which was due to the similarity of the effects of shearing and deformation on the surface during the two finishing operations.

William G. Agnew [33] reviewed the combustion research conducted by one automotive research laboratory of General Motors. Wieslaw Grabon et al, [32] carried out experiments on a reciprocating tester. The lubricant was supplied into the inlet side of the contact zone. The construction of tribological tester allowed to measure the friction force between specimen and counter-specimen. Tribological behaviors of cylinder liners with and without oil pockets were compared. Specimens were cut from plateau honed cylinder liners made of grey cast iron. Counter-specimens were cut from grey cast iron piston rings. The results suggested that hydrodynamic oil pocket effect was of prime importance. The positive effect of additional cylinder liner surface texturing on frictional resistance under worse lubrication conditions was smaller. Height and slope of piston ring surface topographies decreased due to wear. S. Mezghani et al, [27] investigated the various aspects of the wear modeling that caused running- in problems in honed surfaces and its implications on ring-pack friction performance. Plateau honing experiments under different conditions were carried out on an instrumented vertical honing machine. The plateau honing experiments characterized the surface modifications during running-in wear of cast-iron engine bores using advanced characterization method. The predictions were in good agreement with the measurement data of plateau and valleys surface-height parameters. The simulation model of piston ring-pack contact developed to predict friction of cylinder surfaces after plateau honing showed that smooth surfaces lead to better friction performances despite the increases of the ratio between plateau and valleys height (non-plateaued surface). E.P. Becker and K.C Ludema [9] used a laboratory simulator to identify the important variables influencing cylinder bore wear. The same characteristics of wear were observed in the simulator as in running engines, even though the simulator did not attempt to duplicate all the conditions found within an engine. A new picture of wear in cylinders was presented, consistent with the data and previous work on boundary lubrication. The qualitative model accounted for the evolution of the cylinder running surface in terms of composition and texture changes. The model was used to determine the relative importance of the many variables that can influence wear behavior, including contributions from lubricant chemistry, material properties, and mechanical loading. J. Galligan et al, [14] developed a bench test in the first part of this work and the time to failure of ring bore contacts lubricated with a fully formulated motor oil. It was found that failure times correlated well with load, frequency, test temperature and quantity of oil, but that the effect of surface finish, though present, was more difficult to quantify. The main findings in this respect were that there is an optimum finish for long life, and that liner surfaces which were initially highly polished lived which are more dispersed than those with standard finishes. The time to failure in a bench test designed to simulate scuffing failure in the bores of IC engines was shown to be linearly related to load, frequency, temperature and quantity of oil. If the first three of these exceed a critical value, or if the quantity of oil falls below a critical value, scuffing was almost instantaneous. The time to scuff was related to liner surface finish as measured by the rms slope of the top half of its profile.

S.G. Chung et al,[29] employed three types of fixed piston samplers at Nakdong River Delta. The retrieved samples were equally divided into 100 mm long pieces. Quality was evaluated using suction, shear wave velocity, and consolidation tests. The constant rate of strain consolidation test, rather than the incremental loading test, produced a better correlation with the nondestructive test results. The results suggested that the difference in sample quality was principally caused by the mechanical disturbance attributed to the different penetration mechanisms (methods) of the sampling tubes. The tip angle of sampling tubes significantly affected sample quality, whereas the length-to-diameter ratio had a relatively insignificant effect. The three methods used are in the following order: oil-operated, mechanical, and hydraulic samplers. The difference in sample quality was primarily caused by the mechanical destructuration that occurs because of different penetration mechanisms. Sample quality tends to vary with the in-situ void ratio of the clay. M. Priest, C.M. Taylor [18] reviewed the nature of the surfaces encountered in the piston assembly, valve train and journal bearings of the internal combustion engine. The mathematical models of engine tribology endeavouring to cope with the extreme complexities for the incorporation of surface topography potentially were discussed. U.I. Sj¨odin, U.L.-O. Olofsson [31] investigated the wear interaction between piston ring and piston groove in a radial piston hydraulic motor in regard to mass loss and changes in form and surface roughness. A test rig was developed to simulate the tilting movements of pistons .The results showed that wear on the piston ring groove can be up to 10 times greater than the wear on the piston ring. Factorial design analysed that the form of the piston groove significantly influences the amount of wear, the dominant wear mechanism was mild wear.The most important design variable was the length of the support surface. The preferred design was a piston groove without any support plane. Zenon Krzyzak and Pawel Pawlus [36] analysed the surfaces of a large number of piston skirts surfaces under the “zero-wear” condition were analysed. The amplitude of worn piston skirt surfaces decreased, the ordinate distribution became asymmetric, summit density increased and lay direction changed from circumferential to axial during wear. The relationship between microgeometry parameters was studied using correlation and regression analysis. It was decided to determine the local wear of piston skirts based on the changes in amplitude parameters. An increase in the initial surface height caused and increase in piston skirt wear. The local linear wear of piston skirts was bigger on the thrust side than on the anti-thrust side of the cylinder . The worn piston skirt surfaces were observed to be smoothed. The ordinate distribution became asymmetric during “zerowear”. The ratio of average slopes in axial and circumferential directions can monitor piston skirt wear. Piston skirt wear was proportional to initial profile height. Change of height parameter during wear process was bigger on the thrust side than on the anti-thrust side of the cylinder. A. Skopp, et al, [1] compared the tribological behaviour of $TinO_{2n-1}$ and $TiO_{1.95-x}$ coatings under lubricated conditions with uncoated specimen of grey cast iron. The interaction of the pairs with prototype engine oils based on esters and polyglycols were studied under mixed/boundary lubrication using the BAM test method. Lubricants were factory fill engine oils, ester-containing lubricants with low-SAP (sulphur–ash–phosphor) and/or bio-notox properties as well as polyglycole-based lubricants. The ester and polyglycole-based engine oils respond both to bio-no-tox criteria and were polymer-free. They followed different strategies to reduce zinc, phosphorus and sulphur to assure a low ash content. Based on the piston ring/cylinder liner simulation BAM test outside of engines under conditions of mixed/boundary lubrication, it is reasonable that thermally sprayed TiO_x-based cylinder liner coatings can substitute commonly used uncoated grey cast iron liner materials. The coefficient of friction was more determined by the lubricants or by an individual interaction between lubricants and a specific material or tribopairing.

L. Ceschini, et al, [16] carried out both bench tests and laboratory dry sliding tests on components for hydraulic motors involved in a boundary lubricated sliding contact, with the aim of investigating the tribological behavior and improve the durability of the components. Bench tests were carried out on a rotating shaft, consisting of a quenched and tempered 36CrNiMo4 steel, coated by a Ni7Al layer deposited by Air Flame Spray, sliding against a carburized E470 steel contacting element. Failure analysis of real components after bench tests identified the main wear mechanism as two body abrasion. Laboratory dry sliding tests allowed the investigation of the influence of normal load and sliding distance on friction and wear behavior. Those tests also used in the subsequent steps of the work for ranking candidate alternative materials for the investigated tribo system. Rohollah Ghasemi and Lennart Elmquist [25] investigated the relationship between the deformation of the matrix and the closing tendency of flake graphite.

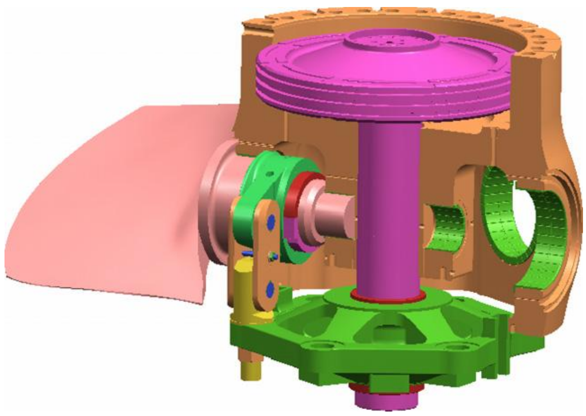


Fig. 3. Blade-control system for one blade.[35]

Two representative piston rings, which belonged to the same two-stroke marine engine but were operated for different periods of time, were studied. Initial micro structural observations indicated a uniform distribution of graphite flakes on unworn surfaces, where as worn surfaces demonstrated a tendency towards a preferred orientation. SEM and EDS analysis indicated substantial deformation of the matrix in the area around the flakes.

An insignificant corrosion attack was observed on both worn piston ring surfaces. As the orientation of the graphite flakes deviated more from the sliding direction, there was a higher chance of them maintaining their intrinsic self-lubricating nature and continuously supplying graphite to the sliding surface. C.W. Huanga and C.H. Hsuehb [5] selected Piston-on-three-ball tests by the International Organization for Standardization to establish ISO 6872 for the evaluation of the biaxial strength of dentistry–ceramic materials. The formula adopted in ISO 6872 for the fracture load-biaxial strength relationship was an approximate equation originally derived for piston-on-ring tests of mono layered discs. This formula was modified and extended to the case of multilayered discs subjected to piston-on-ring loadings recently. The purpose of their study was to evaluate the adequacy of applying the formula for piston-on-ring to piston-on-three-ball tests for both mono layered and multilayered discs. Finite element analyses were performed to simulate both piston-on-three-ball and piston-on-ring tests. Different degrees of friction between the specimen supporting surface and the loading fixture were considered in the simulations. The results depended on friction when the disc was supported by a ring, however the results became insensitive to friction when the disc was supported by three balls. The maximum tensile stress on the surface of the disc decreased when the friction increased. The results of finite element analyses demonstrated how the friction between the specimen supporting surface and the loading fixture affects the biaxial strength evaluation in piston-on-ring and piston-on-three-ball tests. Results demonstrated that Hsueh et al.'s formulae predict well the biaxial tensile strength for mono layered systems.

Dacheng Li, et al, [7] proposed a capacity-regulation system based on a novel rotary control valve for reciprocating refrigeration compressor and designed for the first time. The regulation system was mainly composed of a rotary control valve and an adaptive regulation system. The parameters for the design and control of the rotary control valve are theoretically determined. To verify the feasibility and effectiveness of the proposed system, a three-cylinder reciprocating compressor was adopted as a test device. Experimental results showed that the technology was able to realize continuous stepless capacity regulation for the compressor within the range of (0)10e100%, and power consumption decreased correspondingly with the load reduction. S. Mezghania, et. al, [27] developed a prediction friction model in the hydrodynamic contact regime between the ring and cylinder liner taking into account the real topography of the cylinder liner. The properties of groove texture were related to the oil consumption. The friction performance in the piston ring/cylinder liner contact was associated with the plateau formation. Piston ring-pack friction reduction strategies through the cylinder liner groove texture optimization were analyzed. In their study, the groove texture (grooves balance, honing angle, etc.) have been demonstrated to greatly affect friction performance. This model aimed to solve the average Reynolds equation, which depends on the real surface topographies of the cylinder liner, and describes the influence of surface irregularities on the lubricant flow under hydrodynamic lubrication conditions, considering lubricant film rupture and cavitations. Muhammet Cerit [19] determined the temperature and the stress distributions in a partial ceramic coated spark ignition (SI) engine piston. Effects of coating thickness and width on temperature and stress distributions were investigated including comparisons with results from an uncoated piston. It was observed that the coating surface temperature increase with increasing the thickness in a decreasing rate. Surface temperature of the piston with 0.4 mm coating thickness was increased up to 82 °C. The normal stress on the coated surface decreases with coating thickness, up to approximately 1 mm for which the value of stress was the minimum. The optimum coating thickness was found to be near 1 mm under the given conditions. Results indicated that temperature distributions developed at the ceramic coated piston surface can be considerably higher than those of the uncoated piston surface. Thermal analysis results indicated that the coated section of the piston, which is close to the crevice and wall quenching regions, cause an increase in the temperature. As a result of increase in temperature, a slight amount of decrease in carbon monoxide emission may be expected since CO oxidation reactions strongly depend on temperature. The von Misses stress decreased with increased coating thickness. The shear stress which causes lateral cracks increased with the coating thickness increase and reached its maximum level at the inner edge of the coated region at the interface of the substrate. Finally, it was found that the optimum coating thickness for the ceramic coating was slightly below 1 mm.

C. Friedrich a, et al, [4] conducted experiments with coating development and model wear test results from PVD coatings on piston rings for combustion engines. Piston rings were examples for the application of thin films on commonly used mechanical components. The PVD CrxN coatings were deposited by RF magnetron sputtering and characterized by their fundamental mechanical properties like thickness, hardness, residual stress and adhesion, which are important for the tribological behavior of the coating substrate compound. The contact mechanics of the tribological system piston-ring–cylinder were determined by high mechanical loading and changing geometry caused by the sliding kinematics. Therefore, the range of thickness was about 7 mm. The selected rings were made of steel DIN 1.4112 (DIN X 90 Cr Mo V 18) with a bore diameter of 97.5 mm. The results of the coating substrate characterization — high hardness, moderate compressive residual stresses and sufficient adhesion on metallic substrates — provide good behaviour of coatings in this tribological application. This was confirmed by the results of the tribological test procedures which have been performed with ring-on-disc model-wear tests and a short-stroke test rig. The wear of piston rings was investigated with respect to PVD hard coatings as a surface finish with an adjustable profile of mechanical properties. Dhananjay Kumar Srivastava et al,[8] closely related the performance of a combustion engine with the friction force and wear between cylinder liner and piston rings. This friction force was significantly reduced by optimizing the surface topography of cylinder liners. The experiments were carried out for evaluating wear and friction in simulated engine conditions using Cameron–Plint wear testers, Pin-on-disk testers, SRV testers, etc. A non-firing engine simulator was developed in order to simulate engine conditions to a closer extent compared to these machines. This simulator operated at similar linear speed, stroke, and load as real engine and simulated almost all engine operating conditions, except firing pressures. Energy dispersive analysis (EDS) was carried out of liner and top ring for evaluating materials transfer. Coefficient of friction between three different liner segments and ring was evaluated using an SRV wear tester. Coefficient of friction in the piston ring–liner interface increases with increasing average surface roughness for liner. Surface profile and SEM tests were conducted on liner and rings at different stroke position, which reveal that highest amount wear takes place at TDC location. Even at the BDC location, the wear was higher than the mid-stroke position because of failure of hydrodynamic lubrication regime. The major elements of liner material were iron, manganese, chromium and silicon. During the experiment, concentration of silica went up. In the ring, the hard chrome plating weared out with time and the base metals got exposed towards the end of the experiment. YujunLi et al, [34] developed a novel vibration-based fault diagnostic method to identify the vital components of a diesel engine that have abnormal clearance. The advantage of this method was that it does not require the comparison of current operating parameters to those collected as the baseline.The proposed method employs the timing of impacts caused by two contacting components as the prime diagnostic feature. To extract the features that distinguish the components with abnormal clearance from those with normal clearance, the characteristics of the vibrations generated by a diesel engine typically used in manufacturing were analyzed in this research.

F.S. Silva [10] analysed the fatigue-damaged pistons from petrol/diesel engines, as well as automobiles including trains. The study of damages initiation in the piston at the crown, ring grooves, pin holes and skirt was assessed. An assessment was made through the Case studies as well as the analysis of the thermal/mechanical fatigue damages the pistons. The stress distribution during the combustion was determined through the linear static stress analysis, using ''cosmos works''. Stresses at the piston crown, pin holes, grooves and skirt was also determined. For the confirmation of the crack initiation sites, a fractographic study was also done. The fatigue was a problem for the engine pistons, however, it was not responsible for being the largest part of the damaged pistons. The limitation of weight reduction promoted thinner walls, which cause higher stresses. The priority of fuel consumption reduction and more power was in contradiction as another constraint. Z.W. Wang et al, [35] predicted the failure conditions in the piston rods, in Kaplan turbines and the stresses were analyzed. The pressure oscillations over the turbine blades transfered the forces to the piston rods. The analysis of the dynamic stresses were done at thirteen operating conditions using CFD analyses of the flow, along with the analysis of the stresses to the dynamic loads.

The predicted position of the maximum stress concentration was in good agreement with the actual fracture position. The excessive dynamic stresses at the rated output resulted the crack to grow ending to fracture, in the AGC mode, The mean and dynamic stresses were smaller than that of the retainer ring structure due to the pre tightening force in the structure. G. Floweday et al, [11] Studed diesel engine piston failures, during a bench dynamometer engine durability test, which was aimed to evaluate the effects of various fuels on the life of the fuel system components in diesel engine cars. During the test, a number of pistons, cylinder heads and turbocharger failures were experienced. The study aimed at finding the reasons of the piston failures during the tests. Investigation of the fractured pistons revealed that due to excessive thermo-mechanical loading, thermo-mechanical fatigue initiation took place as a result of silicon phase cracking and subsequent micro-crack formation. Micro cracks with progressive formations lead to flaws upto sufficient magnitude for initiating the propagation by high cycle fatigue mechanisms.

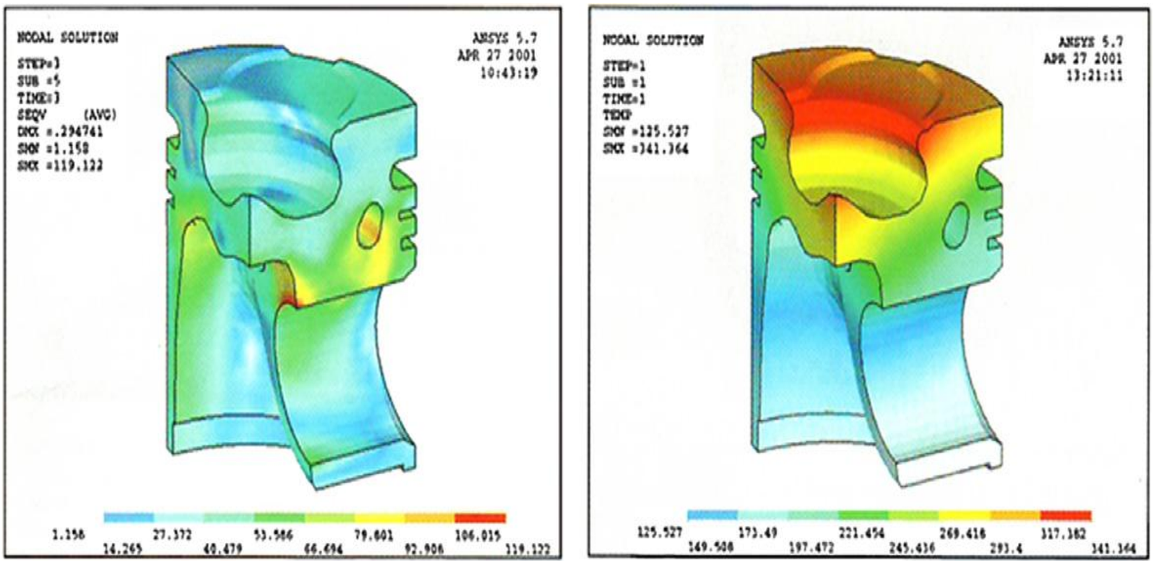


Fig. 4. Contour plot showing the distribution of stress (left) and temperature (right) in a diesel piston due to the combined thermal and pressure loads experienced in an engine. (Reprinted with permission from SAE R-345_2004 SAE International).[11]

Over-fuelling along with the combination of elevated and poorly controlled post intercooler air temperature caused the excessive thermo-mechanical piston loading. No evidence was found supporting the failures to be related with the test fuel formulations. The piston failure may be attributed to, minor over-fuelling and associated thermo-mechanical overload of the pistons, because of the use of neutral injector codes in the engine ECUs, as it deactivates the ECU's function of recalibration of the fuel injector. The damage of the Surface and hairline cracking of the reference fuelled engine piston, the indications of reduced radiation thermal loading as well as spray penetration with the test fuels gave strong indication that fuel formulations were not contributing to the piston failures. Roop Lal et al, [26] made studies on cylinder liner and piston rings interface. Published data on friction and wear was collected from various researchers and concluded. The oil film thichness played important roll and finally affected the performance of engine. Surface roughness of tribo pair material at the junction producing friction and it varied throughout the stroke length of piston. Loss of power in lubrication had the shear force due to boundary conditions. The tribological performance in IC engine could understood when friction and wear were considered. The necessaity to study the factors influencing reliability and performance along with wear was expressed . From the view point of tribo element it was very important to know the specific load, speeds and temperatures for the major components of engine like piston assembly, valve train, the journal bearing and lower viscocity engine oil for lubrication.

O.P. Singh et al, [22] investigated experimentally the seizure failure of piston with numerical simulation of thermal elasto-hydrodynamic lubrication (EHL).

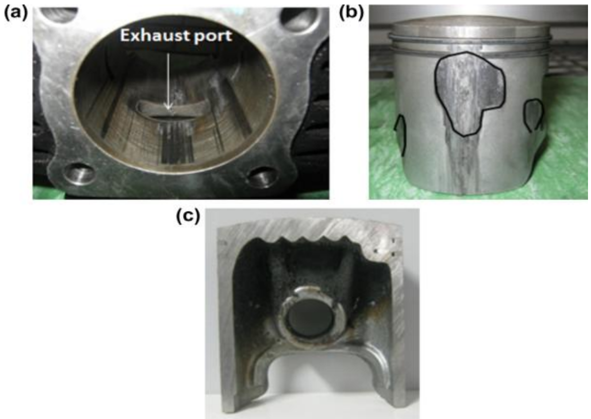


Fig. 5. (a) Seized cylinder liner, (b) seized piston and (c) cut section of the piston showing burnt oil under the crown and skirt. [22]

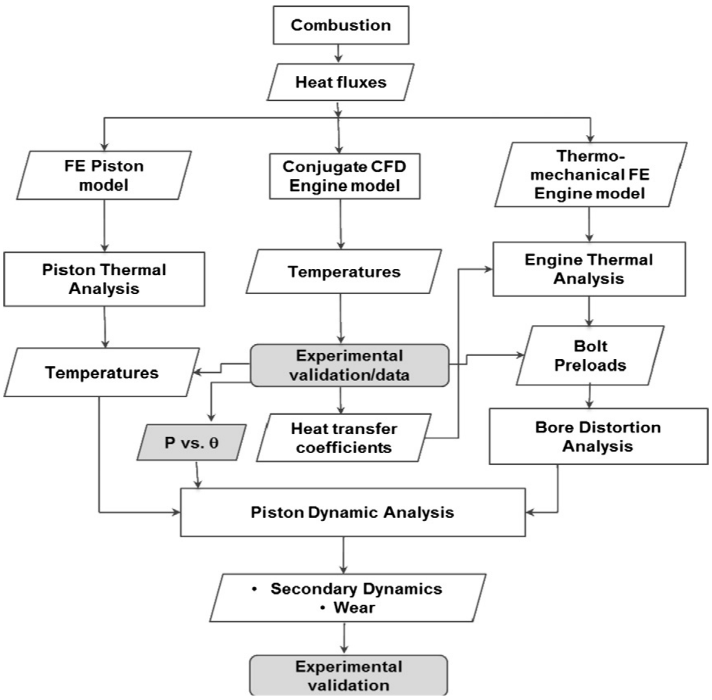


Fig. 6. Flow chart showing steps used in the numerical model of piston hydrodynamic simulation.[22]

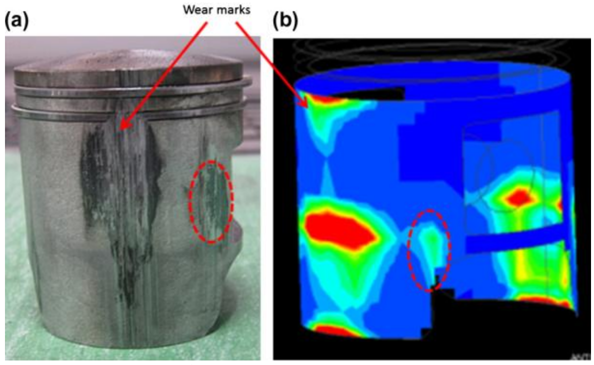


Fig. 7. Correlation of seized marks obtained from the test results and the cumulative wear plot from numerical simulation.[22]

A metallurgical investigation of the piston, rings and liner was done in terms of chemical composition, chemical analysis and hardness. The results indicated large decrease in clearances between the piston and liner at 28°C after TDC. The variation in frictional power over the cycle exhibited sudden increase in magnitude at that location after TDC. The predicted wear mark locations compared well with the test results. The overheating happened to be the root cause of the current piston seizure. Pistons coated with molybdenum material, although enhanced the piston life, but with the problem of skinning off the coating under severe conditions of temperatures and pressures. B. Zhang et al, [3] performed the design as well as experimental validation of a double acting free piston expander in which a slider-based control scheme was used for realizing a full expansion process for the expander. A model was developed for determining the geometric parameters of the expander along with the auxiliary compressor. The results showed that the expander worked stably in a wide range of pressure differences/ratios. R. Mikalsen and A.P. Roskilly [24] reviewed the history of free-piston I C engines, from the air compressors and gas generators used in the mid-20th century Salient features of the free-piston engine has been presented and the effects on engine operation has been discussed, along with comparative advantages and disadvantages with the conventional engines has been discussed.

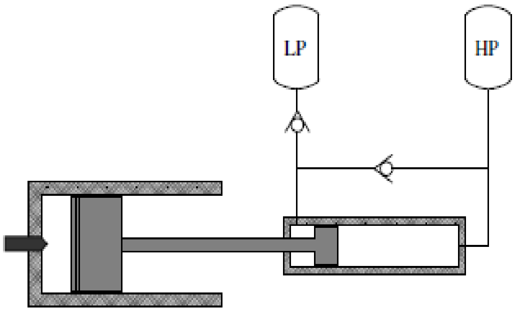


Fig. 8. Single piston hydraulic free-piston engine [24]

Muhammet Cerit and Mehmet Coban [20] improved the performance of a diesel engine, by finding out both temperature and thermal stress distributions on an aluminum piston crown with zirconia coating in a plasma sprayed magnesia-stabilized environment. Effects of the coating thickness varying between 0.2 to 1.6 mm has been investigated, and the results has been compared with that of an uncoated piston, using finite element method. Higher combustion chamber temperature was developed by means of TBC, resulting increase in thermal efficiency of the engine. The engine performance improved with reduction in the piston (substrate) surface temperature. The thermal performance of the piston also increased with increase in coating thickness. From the analysis it was found that the calculated stress values was lower than the allowable stress values of the materials.

III. Summary

Experiments revealed that friction coefficient increases with increasing surface roughness of liner surface. The linear wear of the cast iron liner and rings decreased with increasing load but the mass wear increased with increasing load.

The thermal stress is related to coating thickness. It increases with the coating thickness on the SUBS. The greatest value of the normal stress which produces spalling of the ceramic is produced on the bond coat. It is nearly twice the value of the maximum normal stress on the substrate. The thermal performance of the piston increases with increased coating thickness. Stress values obtained from FEA were compared with the mechanical properties of the aluminum alloy and zirconia material and it was concluded that calculated stress values were lower than the allowable stress values of the materials.

The ratio of average slopes in axial and circumferential directions can monitor piston skirt wear. The free material liberated due to deep scoring between the piston and liner snowballs, changes its phase from solid to molten state and finally makes its way into the rings. It locks the rings and thus leading the complete engine seizure failure.

Surface thermal damage and hairline cracking of the reference fuelled engine piston, as well as the indications of marginally reduced radiation thermal loading and spray penetration associated with the test fuels gave strong indication that the fuel formulations did not contribute to the piston failures. The fractographic and microstructural analyses reveal regarding selection of correct material for piston fabrication.

The piston failures were determined to have occurred due to Surface thermal damage of the piston bowl lip, Crack initiation by thermal micro-cracking and erosion of primary silicon particles, leading to threshold flaw size, Propagation by thermo-mechanical high and low cycle fatigue and Brittle fast fracture at the critical crack length. Subsequent fuel and flame impingement resulting in piston burn through and loss of engine compression.

The main causes contributing to the piston wear and failures was the use of neutral injector codes in the engine ECUs which deactivated the ECU's function of automatic recalibration of the fuel injector flow rates, resulting in minor over-fuelling and associated thermo-mechanical overload of the failed pistons. Further poorly controlled post intercooler air temperatures and an elevated set point, resulting in overheating of the piston and other combustion chamber components.

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