

A Non-Linear Finite Element Approach Applied to Diesel Piston Combustion Bowl Rim Strength Assessment

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ABSTRACT

The single piece aluminium alloy piston remains the dominant and preferred design offering for highly loaded diesel engines. Piston manufacturers have progressively developed aluminium alloys, machining capability, and design geometries to cope with increasing thermal and mechanical loading.

In conjunction with these developments, the methodology used to analyse the pistons has also improved as software and digital computers have advanced. This advancement has permitted larger more detailed models and more sophisticated simulation of the material behaviour, in response to the loading and contact conditions applied to pistons.

Transient finite element analysis was first applied to diesel pistons in the late 1970's using a linear elastic approach, coupled with a life assessment based on limited low cycle fatigue data. This methodology gave valuable insights into the mechanism of piston failures, particularly at the combustion bowl rim of diesel pistons. The life assessments derived from this approach, however, tended to be approximate and could only be used as a comparative tool to assess alternative designs and materials. This limitation arose from the linear elastic stress approach, which ignored the important effects of non-linear strain behaviour, especially under the elasto-plastic conditions that exist around the combustion bowl rim.

In combination with the improvements in analysis techniques, developments in strain based material property measurement gave further insights into the non-linear behaviour of the piston alloy and provided important data for modelling.

These developments have been incorporated into a new methodology for analysing the stress and strain response at the bowl edge, which allows a more accurate approach to life assessment and opportunities to enhance the piston design still further.

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INTRODUCTION

The key drivers affecting modern diesel engine development are emissions legislation, fuel efficiency and durability. Diesel engine technology is advancing rapidly and many innovative solutions are being introduced which affect the intake, exhaust and in-cylinder conditions significantly. Multi-stage turbocharging, variable valve timing and flexible

fuel injection systems are often adopted as a package to reduce emissions levels and to improve thermal efficiency. The improvements offered by the above measures also provide scope for diesel engine manufacturers to consider downsizing, as the power output can be maintained from a smaller engine package.

The impact of the combination of the above technologies is generally an increase in the maximum firing pressure and the thermal loading to the piston.

Near eutectic aluminium-silicon alloys have been the preferred piston material for the last fifty years and remain so today. During that time there have been many developments in alloying, heat treatment, casting technology and post-casting processes which have improved the material thermo-mechanical fatigue resistance. In addition, piston manufacturers have devised novel designs to enhance piston cooling, complex and closely controlled pin bore shaping to cater for higher gas pressure loading and skirt profiling developments to provide greater scuff resistance under the increased transverse loading.

In parallel, and in support of these advancements, design analysis methodologies and material data acquisition techniques have evolved to assist in the modelling of each type of loading condition experienced by the piston. This paper is particularly concerned with the effect of engine load cycling on crown strength. Finite element thermal transient analysis was first adopted in the late 1970's and has been used extensively since then to improve our understanding of the stress response on the crown surface to the applied loading [1,2,3,4,5,6].

In this paper, a further advance, using a non-linear thermal transient approach, has been adopted in conjunction with improved material data acquisition techniques to investigate the bowl rim stress and strain response to engine load cycling. The investigation has yielded new insights into crown failures and a new component life assessment technique is proposed, which is appropriate for areas where elasto-plastic strains are predicted.

ENGINE TEST EXPERIENCE

The piston selected for this investigation is an 80 mm nominal diameter gallery cooled light vehicle diesel piston. The engine has a known history of crown cracking at the bowl rim during durability load cycling tests (Figure 1).

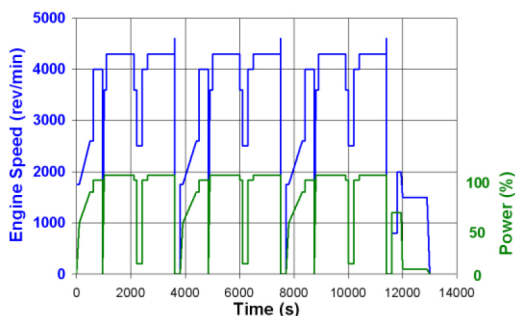


Figure 1. Engine test cycle

The 4 cylinder engine develops up to 97 kW at 4300 rev/min with maximum firing pressure of 165 bar. The engine durability test cycle, shown above, can be considered to be a simple square wave comprising three no load to full load steps. This is repeated up to 950 hours. At the end of the test

crown cracking has been observed at the bowl rim on the thrust and anti-thrust axes (Figure 2).

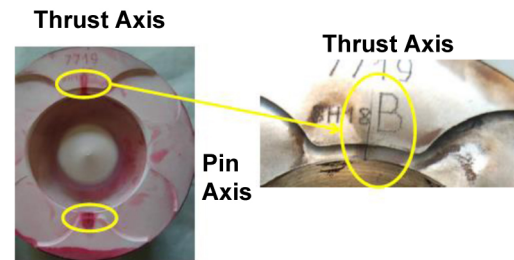


Figure 2. Bowl rim cracks

The cracks initiate at the bowl edge and propagate radially towards the top ring groove. The cracks are open at room temperature indicating that some local plastic deformation has occurred.

MATERIAL BEHAVIOUR

High Frequency, High Cycle Stress Controlled Fatigue

The high frequency mechanical loading of the combustion bowl rim area occurs as a result of a combination of the gas pressure in the cylinder, from the combustion process, and the inertia forces arising from movement of the piston assembly. The piston material in the bowl rim area is subjected to an applied stress which changes as a function of both crank angle and position on the piston at the high frequency (and thus strain rate) of combustion loading. The maximum applied load occurs close to the top dead centre firing position with the maximum applied tensile stress occurring on pin axis. The piston material must be able to withstand the alternating mechanical stress at the bowl rim after extended periods at the elevated temperature of piston operation.

The ability of the piston material to resist cracking, under the high frequency mechanical loading at the bowl rim, is typically checked by measuring the high cycle fatigue strength of the piston material using a stress controlled fatigue test at elevated temperatures. It is important that the material testing is performed on test samples taken from the piston. In addition, the fatigue test samples need to be soaked at test temperature for an extended period (minimum 100hrs) prior to testing since the properties of a piston alloy are, to some extent, controlled by precipitation hardening and will change as a function of time at elevated temperatures.

After many fatigue tests at different alternating stress levels, an S-N or Wöhler curve can be drawn for the piston alloy at each test temperature. This is a plot of alternating stress vs cycles to failure for the piston material at a particular stress ratio R (min. applied stress / max applied stress). The Basquin [7] equation can be used to describe the

relationship between applied stress and cycles to failure for a particular R value, as shown in [equation \(1\)](#).

$$\sigma_a = c N^b \quad (1)$$

where: σ_a = alternating stress amplitude (MPa)
 N = cycles to failure
 c and b are the Basquin coefficient and exponent respectively.

As Al-Si based near eutectic piston alloys do not show a fatigue limit, once the constants b and c are determined by fatigue testing, the stress controlled fatigue life of the piston alloy can be assessed from a knowledge of the applied stress amplitude.

Typically stress controlled fatigue testing to determine the Basquin equation constants and fatigue strengths is only carried out under fully reversed loading ($R=-1$) with a zero mean stress. In the combustion bowl rim of the piston, however, the mean stress is typically non-zero. The effects of a non-zero mean stress can be accounted for using the Goodman approach [8].

Unfortunately the stress controlled fatigue approach, although relatively simple in material testing terms, is really only suitable for predicting the fatigue life of the combustion bowl rim area in an isothermal condition. In reality, the temperature of the combustion bowl rim changes as a result of load changes during engine operation. As is discussed more in later sections, these temperature changes result in differential expansion and contraction between the bowl rim and the surrounding areas. This leads to significant tensile and compressive strains being applied to the piston alloy in the bowl rim area during engine operation. These applied strains can be particularly damaging to near eutectic Al-Si casting alloys, since these materials generally have low ductility and cannot resist significant applied strains without cracking. In order to model the behaviour of the piston alloy at the combustion bowl rim, it is necessary to measure the fatigue life as a function of applied strain at different temperatures, and to understand the relationship between cyclic strain and stress.

Cyclic Stress - Strain Curve

The Goodman approach [8] to investigating the effect of mean stress on stress controlled fatigue life uses stress strain behaviour from monotonic testing. In reality, however, the piston material is subjected to cyclic loading and the stress strain behaviour under cyclic loading can be very different from that measured under monotonic loading. In the case of piston alloys there can be significant cyclic hardening. It is very important to measure the stress strain curve under cyclic loading, for the piston material at different temperatures, since the thermal cycling of the combustion bowl rim region can lead to significant plasticity.

The cyclic stress strain curve for piston alloys is generally determined using either the incremental step test or the

multiple step test on a servo-hydraulic fatigue testing machine. In the incremental step test, a single test piece is subjected to repeated sets of incrementally increasing and decreasing strain levels. Material stabilization usually occurs after several strain sets allowing a stabilized hysteresis loop to be extracted. The hysteresis loops from half a stable block can then be used to obtain the cyclic stress strain curve (as shown in [Figure 3](#)) for the temperature and applied strain rate used in the test. The multiple step test is very similar, except that the strain level is kept constant in each test block until a stabilized hysteresis loop is obtained, after a short period of stress relaxation, and recorded. The strain level is then increased and a new stable hysteresis loop is obtained. As in the incremental step test, the process is repeated until a sufficient number of loops are obtained to construct the cyclic stress strain curve.

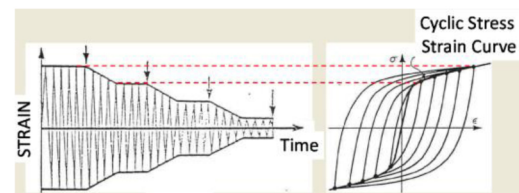


Figure 3. Cyclic Stress strain determination from incremental step test

Once the cyclic stress strain curves have been obtained, the cyclic stress-strain behaviour can be modelled using the Ramberg-Osgood equation [9] as shown in [equation \(2\)](#).

$$\sigma = K(\epsilon_{pl})^n \quad (2)$$

Where: σ = stress (MPa)
 ϵ_{pl} = plastic strain
 K = strain hardening coefficient
 n = strain hardening exponent

Once the strain hardening coefficient and exponents are determined for a particular piston alloy, as a function of temperature for a relevant strain rate, then the stress strain response of different areas of the bowl rim can be predicted in the FEA model. Obviously, in order for the FEA model to be useful for component life prediction, the fatigue life of the piston material needs to be known as a function of applied cyclic strains.

Low Frequency, Low Cycle Strain Controlled Fatigue

The low cycle fatigue life (up to 1×10^6 cycles), as a function of constant applied strain amplitude, can be determined by servo-hydraulic fatigue testing. Once the SN curve for strain controlled low cycle fatigue is determined, it can be combined with the high cycle fatigue SN curve to