
Published paper
Lewis, R., Dwyer-Joyce, R.S., Slatter, T. and Brooks, A. (2004) *Valve recession: From experiment to predictive model.* VDI Berichte (1813). pp. 79-93.

VALVE RECESSION: FROM EXPERIMENT TO PREDICTIVE MODEL

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Abstract

Increasing demands on engine performance and cost reductions have meant that advances made in materials and production technology are often outpaced This frequently results in wear problems occurring with engine components. Few models exist for predicting wear, and consequently each wear problem has to be investigated, the cause isolated and remedial action taken. The objective of this work was to carry out experimental studies to investigate valve and seat insert wear mechanisms and use the test results to develop a recession prediction tool to assess the potential for valve recession and solve problems that occur more quickly.

Experimental apparatus has been developed that is capable of providing a valid simulation of the wear of diesel automotive inlet valves and seats. Test methodologies developed have isolated the effects of impact and sliding.

A semi-empirical wear model for predicting valve recession has been developed based on data gathered during the bench testing. A software program, RECESS, was developed to run the model. Model predictions are compared with engine dynamometer tests and bench tests. The model can be used to give a quantitative prediction of the valve recession to be expected with a particular material pair or a qualitative assessment of how parameters need to be altered in order to reduce recession.

The valve recession model can be integrated into an industrial environment in order to help reduce costs and timescales involved in solving valve/seat wear problems.

Introduction

As a result of demands for increased engine performance and design changes to bring about cost reductions, wear of some engine components, such as valves and seat inserts continues to cause problems. This is despite advances in valve and seat materials and production techniques.

The drive for reduced oil consumption and exhaust emissions, the phasing out of leaded petrol, reductions in the sulphur content of diesel fuel and the introduction of alternative fuels such as gas also have implications for valve and seat wear.

At present no models exist that can be used to quantify valve or seat life. Each valve/seat wear problem that arises, therefore, has to be investigated, the cause of the problem isolated and remedial action taken. This is an expensive and time consuming process and is difficult to fit in with the ever-decreasing lead-times being used in engine development programmes.

A long-term approach is required in order to understand fundamental wear mechanisms and the effect of varying engine operating conditions or design changes to the valve train. This information can then be used to develop tools for predicting wear and for solving problems more quickly if they do occur.

The objective of this work was therefore to investigate valve and seat wear mechanisms using specially design bench test apparatus and to use the results, along with data collected during a review of literature and failure analysis of actual valves and seats, to develop a recession prediction tool for use in industry.

Valve and Seat Insert Wear Testing

Two laboratory based test methods (hydraulic component loading apparatus and motorised cylinder-heads) capable of providing a valid simulation of the wear of diesel automotive inlet valves and seats have been developed [1, 2]. These were used in the course of bench test work to investigate the fundamental wear mechanisms and the effect of critical engine operating parameters.

The first rig, shown in Figure 1, is designed to be mounted in a hydraulic fatigue test machine. It is able to simulate both combustion loading and impact of the valve on the seat on valve closure. Test methodologies developed have isolated the effects of impact and sliding.

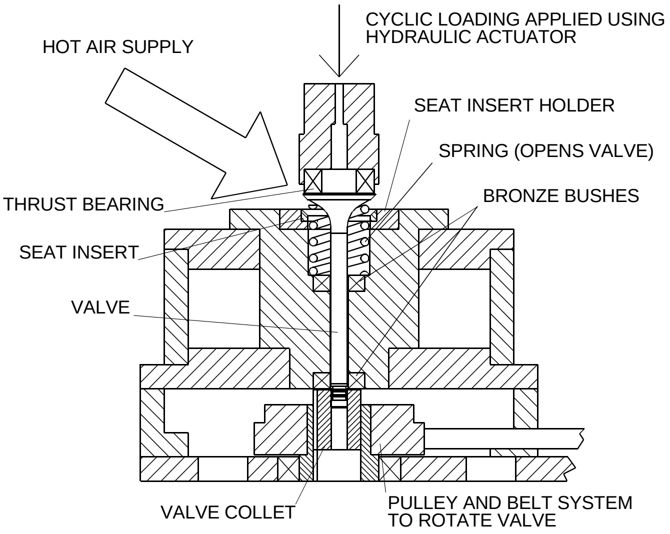


Figure 1. Hydraulic Loading Test-Rig

Two motorised cylinder-head rigs have been built (as shown in Figure 2): one based on a 1.8 litre diesel engine with direct acting cam and follower arrangement and the second on a 2.5 litre diesel engine, which uses rocker arms. These can be used to investigate impact wear of valve and seats over a range of closing velocities.

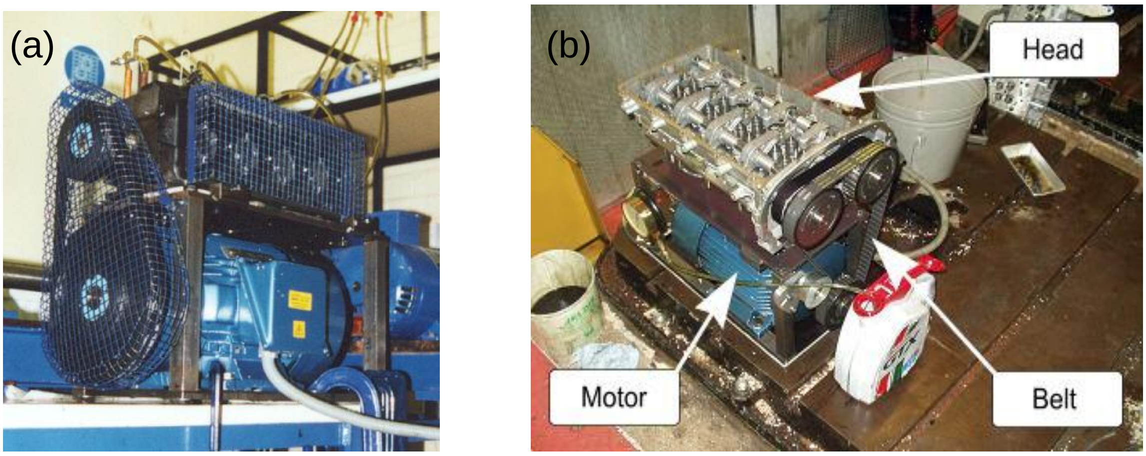


Figure 2. Motorised Cylinder-Head Test-Rigs (a) 1.8 litre diesel and (b) 2.5 litre diesel

Valve Wear Mechanisms

Investigations carried out using the test-rigs have shown that the diesel engine inlet valve and seat insert wear problem involves two distinct mechanisms [1, 3]:

- Impact as the valve strikes the seat on closure.

- Micro-sliding at the valve/seat interface caused by elastic deformation of the valve head and engine block as it is pressed into the seat by the combustion pressure.

Impact on valve closure causes plastic deformation of the seating face surface, which leads to the formation of a series of ridges and valleys circumferentially around the axis of the valve seating face [1, 4]. It also leads to surface cracking and subsequent material loss from seat inserts at high closing velocities [2]. Sliding causes the formation of radial scratches on the seat insert seating faces [1, 4]. Figure 3 illustrates these wear features, and compares valves and seats from hydraulic loading apparatus tests with those from dynamometer engine tests to indicate the validity of the test methodologies developed.

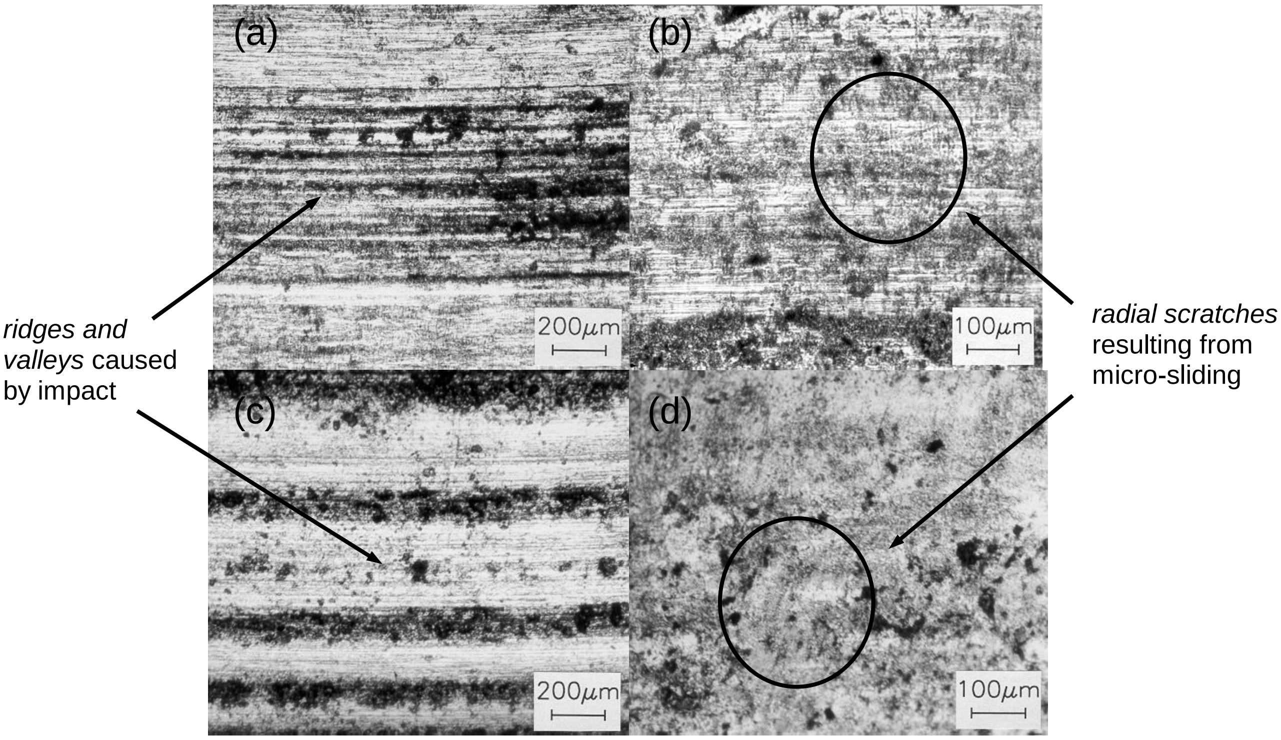


Figure 3. Laboratory Tested Valve (a) and Seat Insert (b) Compared with Engine Tested Valve (c) and Seat Insert (d)

Effect on Wear of Engine Operating Parameters

The prevailing wear mechanisms have been shown to be more severe when critical operating parameters such as valve closing velocity, combustion load and valve misalignment relative to the seat insert are increased, as shown in Figure 4 [3].

Increasing the combustion loading caused a greater amount of sliding at the valve/seat interface. Raising the valve closing velocity caused an increase in impact wear. Surface cracking and subsequent material loss was prevalent on seats and greater plastic deformation on the valve seating faces was observed. Recession was found to be approximately proportional to the square of the closing velocity (i.e. the valve kinetic energy on closing). Misalignment of the valve caused the valve wear scar widths at the point of contact to increase significantly, leading to increased sliding and hence greater wear.

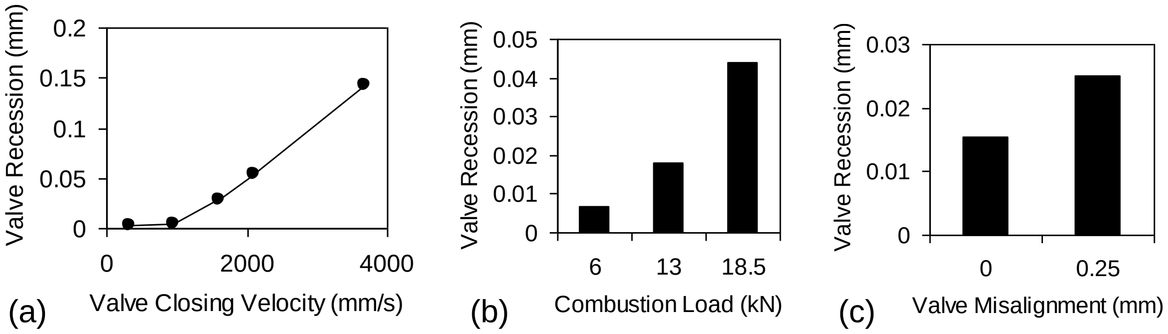


Figure 4. Valve Recession with Cast Tool Steel Seat Inserts for Increasing (a) Valve Closing Velocity (after 100 000 cycles); (b) Combustion Load (after 25000 cycles) and (c) Radial Valve Misalignment (relative to seat position) (after 25000 cycles)

Valve rotation ensured even wear and promoted debris removal from the valve/seat interface. This is useful in reducing abrasive wear and the build-up of deposits and subsequent hot spots.

Valve Recession Modelling

Development of the Model

In developing the model it was decided to consider the impact and micro-sliding wear mechanisms separately as they occur as two independent events in the valve operating cycle. Approaches for modelling the wear mechanisms were identified and parameters were then derived either directly from the valve and seat design and engine operating conditions or from bench test results. An allowance for effects such as misalignment and variation in lubrication were also built in. The two parts were then combined to form the final valve recession model.

Sliding Wear Calculation

An Archard type wear law [5] was used for modelling the sliding wear component:

$$V = \frac{kP_c x}{h} \tag{1}$$

The wear volume, V, is proportional to the contact force, P_c (N), the sliding distance, x (m) and the penetration hardness of the wearing surface, h (N/m^2). The non-dimensional wear coefficient, k, is determined empirically.

The peak load normal to the direction of sliding at the valve/seat interface, P_c, was calculated using the peak combustion pressure, p_p, and the valve head geometry:

$$P_c = \frac{p_p \pi R_v^{\ 2}}{(1+\mu)\sin\theta_v} \tag{2}$$

where θ_V is the valve seating face angle (°) and μ is the coefficient of friction at the valve/seat interface. The load on the valve seat during a combustion cycle is initially zero then rises to P_c and falls back down to zero. For the purposes of calculating the sliding wear volume an average load, $\overline{P}$, was assumed equal to half P_c. In the absence of other data μ was estimated to be 0.1 for the valve/seat interface, which is a typical value for boundary lubricated steel surfaces.

Data generated for slip at the interface by Mathis et al. [6] using finite element analysis was used in this model. It was assumed that slip at the interface, δ, is proportional to combustion load P_c. The total sliding distance is calculated by multiplying the slip, δ, by the number of loading cycles, N.

Wear coefficients were taken from data generated for sliding metals by Rabinowicz [7]. These were derived for different material pairings and states of lubrication using Equation 1. The lubrication states for the valve/seat insert material pairings used in this study are shown in Table 1 as well as the wear coefficients taken.

The hardness used was that of the softer of the two materials (valve and seat). Hardness’ of the valve and seat materials used are shown in Table 1.

Impact Wear Calculation

The deformation observed on the valve seating faces and surface cracking on the seat inserts observed during bench tests on the motorised cylinder-heads are characteristic of wear features attributed to processes leading to wear by single or multiple impact of particles [8]. It was therefore decided to use a relationship of the same form as that used in erosion studies to model wear mass, W, due to the impact of the valve on the seat during valve closure:

$$W = KNe^{n} \tag{3}$$

where e is the impact energy per cycle (J) (given by $mv^2/2$, where m is mass of valve and follower added to half the mass of valve spring (Kg) and v is the valve velocity at impact (m/s)), and K and n are empirically determined wear constants.

Valve closing velocities are derived from valve lift curves for the engine under consideration. The closing velocity is taken as that at the initial valve clearance, c_i. As the valve recesses the valve clearance at closure will decrease thereby decreasing the valve closing velocity. This is considered in the application of the model.

Values of K and n for the seat materials used in these studies were derived using an iterative process to fit Equation 3 to experimental data from motorised cylinder-head tests. Equation 3 was used to calculate wear volumes rather than wear mass to fit in with Archard’s sliding wear equation (Equation 1) when combining the two to create the final model. These were then used to calculate recession values using equations derived from the seat geometry. At each data point the velocity was recalculated to take account of the change in lift due to recession. The results of this process for tests run with a cast seat insert in the 1.8 litre diesel engine cylinder-head rig (based on a tool steel matrix) are shown in Figure 5.

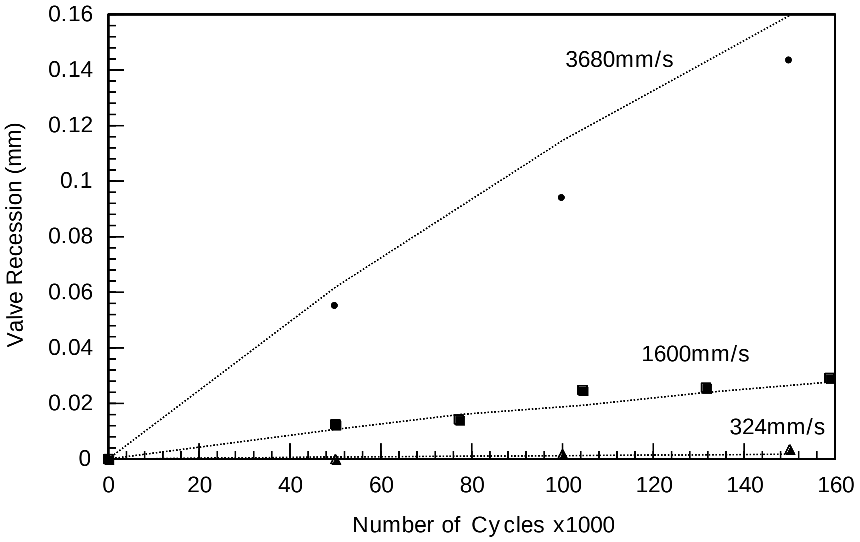


Figure 5. Modelling of Valve Recession for Three Different Closing Velocities on the 1.8 litre Motorised Cylinder-Head (data points - experimental data, broken line - model prediction)

As can be seen, the values of *K* and *n* derived give good correlation over a range of velocities. The values of *K* and *n* for sintered (also based on a tool steel matrix) and cast insert materials are listed in Table 1.

Recession Calculation

The equations for sliding and impact wear (1 and 3) were put together to give the final wear model. In order to incorporate the change in pressure at the interface and any other effects likely to lead to a reduction in the wear rate with time, such as work hardening, a term consisting of the ratio of the initial valve/seat contact area, A_i, to the contact area after *N* cycles, *A*, to the power of a constant *j* was included. *j* was determined empirically using bench and engine test data.

$$V = \left(\frac{k\bar{P}N\delta}{h} + KNe^n \right) \left(\frac{A_i}{A} \right)^j \tag{4}$$

Equation 4 gives a wear volume, which is then converted to a recession value, *r*, using equations derived from the seat geometry. Equation 5 gives *r* in terms of *V* for the case where valve and seat angles are equal:

$$r = \left(\sqrt{\frac{V}{\pi R_i \cos\theta_s \sin\theta_s} + w_i^{\,2}} - w_i \right) \sin\theta_s \tag{5}$$

where R_i is the initial seat insert radius, θ_s is the seat insert seating face angle and w_i is the initial seat insert seating face width (as measured). R_i can be calculated using w_i and the radius and seating face width as specified for the seat insert (R_d and w_d), as shown in Figure 6.

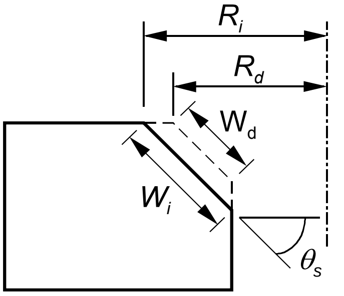


Figure 6. Calculation of Initial Seat Insert Radius

Implementation of the Model

A flow chart outlining the use of the model is shown in Figure 7. The wear volume is determined incrementally. The initial valve closing velocity and contact area are used to calculate the volume of material removed over the first N cycles. This is then converted to recession and new values for the clearance (and hence closing velocity) and contact area are determined. The calculation is repeated until the total number of iterated cycles equals the required run duration.

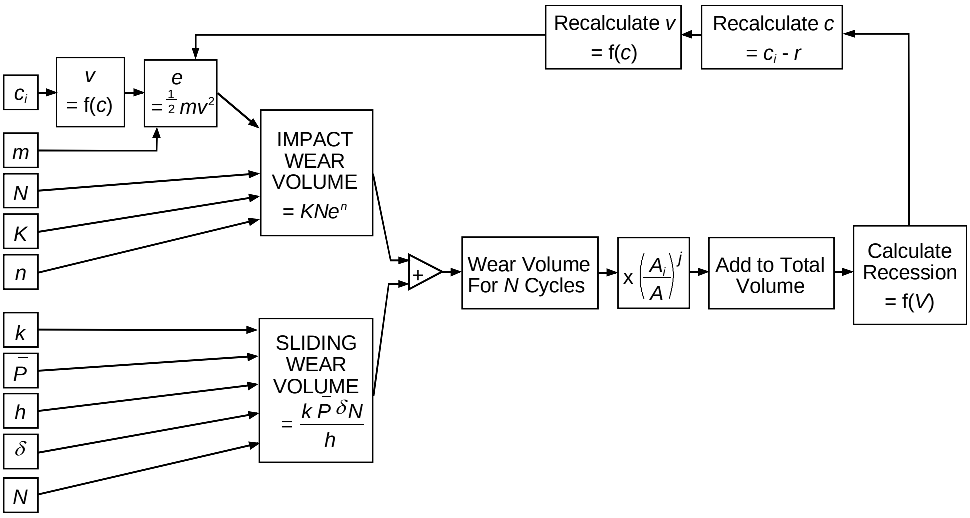
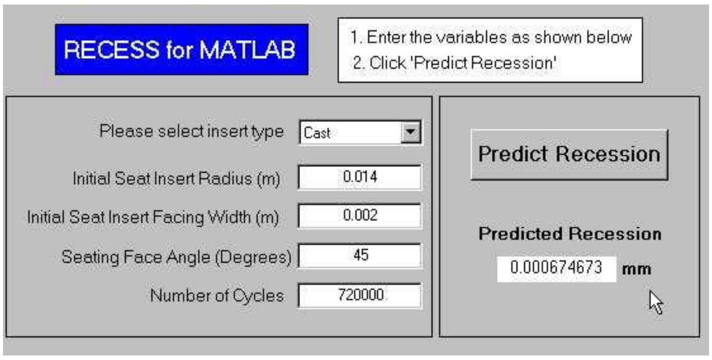


Figure 7. Valve Recession Model Application Flow Chart

In order to provide a tool for running the valve wear model, an iterative software programme called RECESS was developed. Within the programme the recession calculation is carried out in three stages. In the first and second the sliding and impact wear volumes, V_s and V_i, are calculated for N cycles. In the final stage, V_s and V_i are added together to calculate the wear volume for the set of N cycles. This is then used to calculate the recession value, r, for the total number of cycles.

RECESS has now been developed into a location independent design tool. A version has been created to operate within the MatLab environment (see Figure 8) and also as a Java applet. A website has been developed to provide a portal to the valve wear prediction software (see Figure 9), which means that RECESS could be used from anywhere in the world.

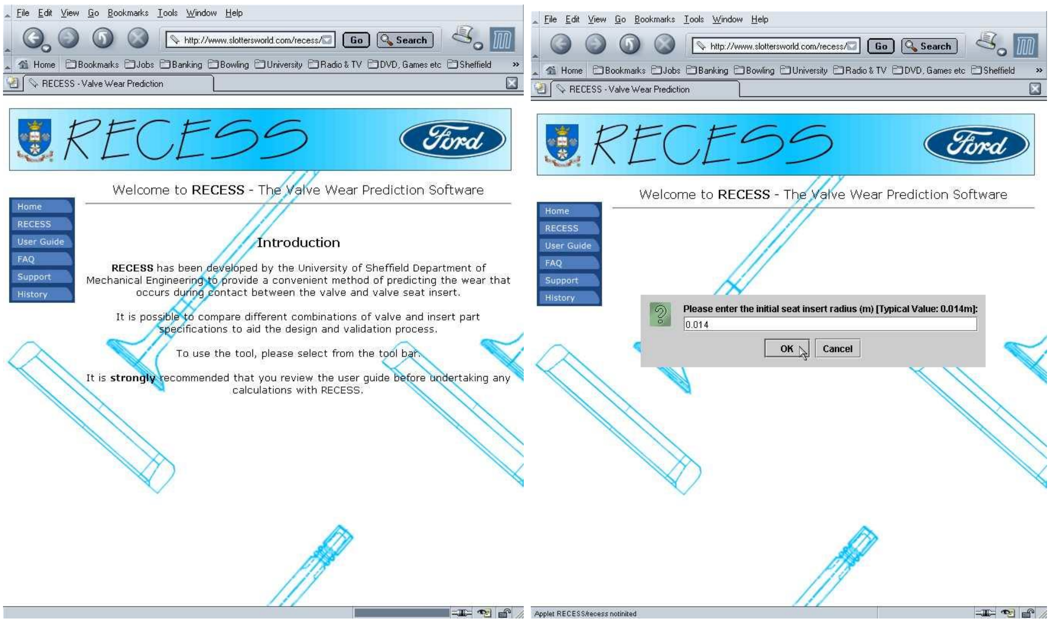


1. Enter the variables as shown below
2. Click 'Predict Recession'

Please select insert type: Cast
Initial Seat Insert Radius (m): 0.014
Initial Seat Insert Facing Width (m): 0.002
Seating Face Angle (Degrees): 45
Number of Cycles: 720000

Predicted Recession: 0.000674673 mm

Figure 8. RECESS MatLab Tool



Welcome to **RECESS** - The Valve Wear Prediction Software

Introduction

RECESS has been developed by the University of Sheffield Department of Mechanical Engineering to provide a convenient method of predicting the wear that occurs during contact between the valve and valve seat insert.

It is possible to compare different combinations of valve and insert part specifications to aid the design and validation process.

To use the tool, please select from the tool bar.

It is **strongly** recommended that you review the user guide before undertaking any calculations with RECESS.

Welcome to **RECESS** - The Valve Wear Prediction Software

Please enter the initial seat insert radius (m) [Typical Value: 0.014m]: 0.014

Figure 9. RECESS Web Tool: (a) Home Page; (b) Start of Calculation

Validation of the Model

In order to validate the model, valve recession predictions for 1.8 litre diesel engine inlet valves were calculated for engine tests using two different seat insert materials; a cast and sintered tool steel. Initial conditions used for the engine tests are shown in Table 1.

Figure 10 shows the model prediction for engine tests run using cast and sintered inserts. As can be seen, the model produces a good prediction of valve recession. Looking at the contribution of the two mechanisms to the overall wear it was evident that impact wear was greater (about 70% of total).

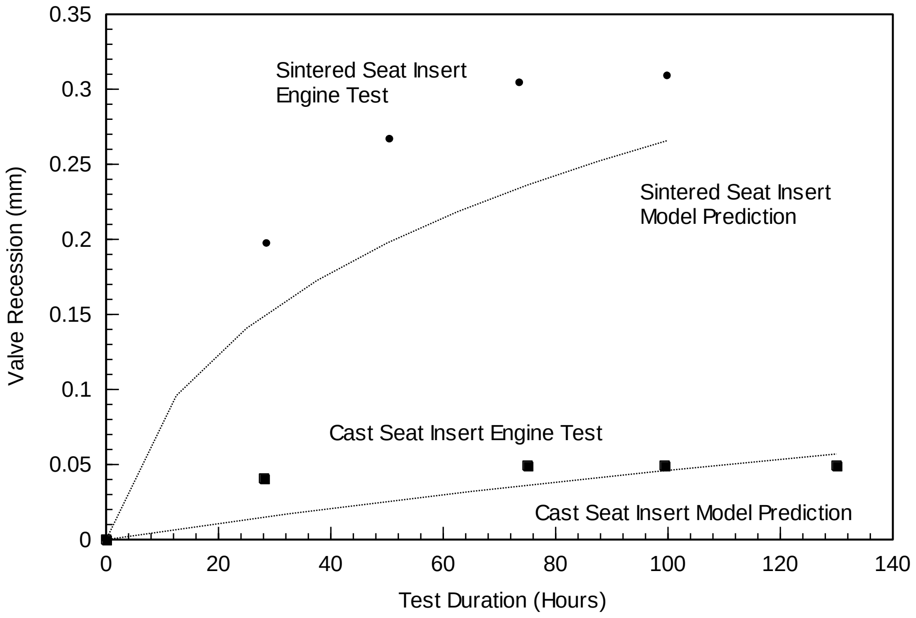


Figure 10. Model Predictions versus Engine Test Data

Model simulations were also carried out for the hydraulic loading apparatus tests for the cast and sintered materials seat inserts with a dry contact and a lubricated cast insert, where a different value was used for the value of *k*, the sliding wear coefficient. The results are shown in Figure 11. Again good correlation exists.

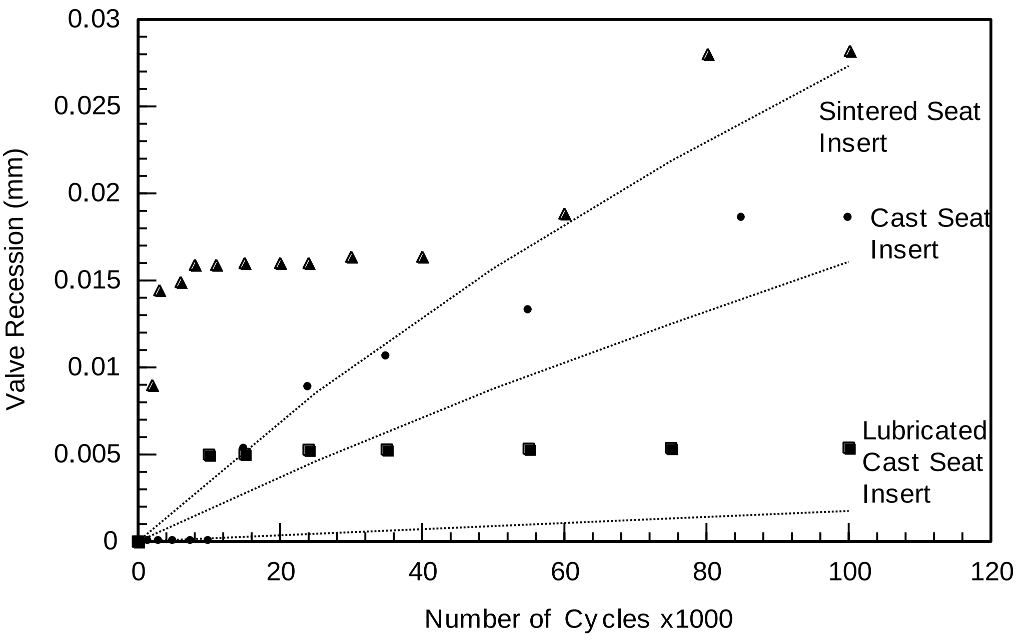


Figure 11. Model Predictions Versus Hydraulic Loading Apparatus Data for a Sintered Seat Insert, a Cast Seat Insert and a Lubricated Cast Seat Insert

Table 1. Inputs and Typical Outputs for the 1.8L Diesel Engine Test Recession Predictions

Seat Material	Cast	Sintered
Lubrication State	Poor	Poor
Sliding Wear Coefficient, k	5×10^{-5}	5×10^{-5}
Impact Wear Constant, K	5.3×10^{-14}	3.5×10^{-14}
Impact Wear Constant, n	1	0.3
Initial Seat Insert Facing Width, w_i (mm)	2	2
Initial Seat Insert Radius, R_i (mm)	16.85	16.85
Initial Seating Face Area, A_i (mm^2)	211.7	211.7
Valve Head Radius, R_v (mm)	18	18
Seating Face Angle, θ_v (°)	45	45
Coeff. of Friction at Interface, μ	0.1	0.1
Seat Hardness, h (H$_v$)	490	490
Max. Combustion Pressure, p_p (MPa)	13	13
Avg. Contact Force at Interface, $\overline{P}$ (N)	8053	8053
Slip at Interface, δ, (μm)	5.24	5.24
Valve Closing Velocity, v (mm/s)	288	288
Wear Constant, j	10	10
Number of Cycles	18.72×10^{6}	144×10^{6}
Total Wear Volume (mm^3)	0.0087	0.0289
Recession, r (mm)	0.057	0.266
Seat Insert Radius (mm)	16.9	17.1
Seat Insert Seating Face Width, w (mm)	2.08	2.26
Seating Face Area, A (mm^2)	221.0	241.5
A/A_i	0.958	0.877

Application of the Model

It has been shown that the valve recession model produces good quantitative predictions of valve recession for engine tests and other work has shown that good correlation exists with bench test results [2]. It could clearly be used, therefore, to give a quick assessment of the valve recession to be expected with a particular material pair under a particular set of engine/test-rig operating conditions. This will help speed up the process undertaken in selecting material combinations or in choosing engine operating parameters to give the least recession with a particular combination. It can also be used to give a qualitative assessment of how wear can be reduced by varying engine operating parameters and material properties.

By studying the individual contributions of impact and sliding wear it is possible to focus on the particular parameters that need to be altered in order to produce the largest reduction possible in the total wear for a particular material combination.

A new long-term approach to combating valve recession is now possible. As new engine design changes are made, the prototype valve train systems are typically modelled in multi-body simulation packages. The output from these (loads and deformations) could be used as inputs to RECESS to predict recession rates for a given design. In this way it may be possible to design out the causes of valve recession.

Conclusions

Experimental apparatus has been used to isolate the wear mechanisms leading to valve and seat insert wear, which are caused by impact of the valve on the seat and micro-sliding during combustion in the cylinder. The key engine operating parameters affecting wear have been identified as valve closing velocity, valve misalignment and combustion loading.

A valve recession prediction tool has been developed using the results of the experimental bench testing to be used in industry to assess the potential for valve recession during the development of new engines or in making design changes or changes in valvetrain dynamics and materials selection in existing engines to reduce the likelihood of valve failure problems occurring. It is in the form of a semi-empirical wear model, which combines existing models for the mechanisms of wear observed (impact and sliding). Constants required for the model were taken from curves fitted to experimental data.

The model provides a good approximation of valve recession for both engine tests and tests run on the hydraulic loading apparatus. Modelling of diesel engine tests indicated that impact was the major cause of valve recession.

The model can be used to give a quantitative prediction of the valve recession to be expected with a particular material pairing under a known set of engine/test-rig operating conditions. This will speed up the process undertaken in selecting material combinations or in choosing engine operating parameters to give the least recession. It can also be used to give a qualitative assessment of how wear can be reduced by varying engine operating parameters and material properties. For example, reducing valve closing velocity, valve mass and valve seating face angle or increasing the valve head stiffness and seat material hardness will reduce valve recession.

Software called RECESS has been written to run the prediction model. This is available as a location independent design tool. A version has been created to operate within the MatLab environment and also as a Java applet. A website has been developed to provide a portal to the valve wear prediction software, which means that RECESS could be used from anywhere in the world.

Acknowledgements

The authors gratefully acknowledge the financial support of the Ford Motor Company and the help and support of Alan Brooks of the Diesel Engines Group.

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