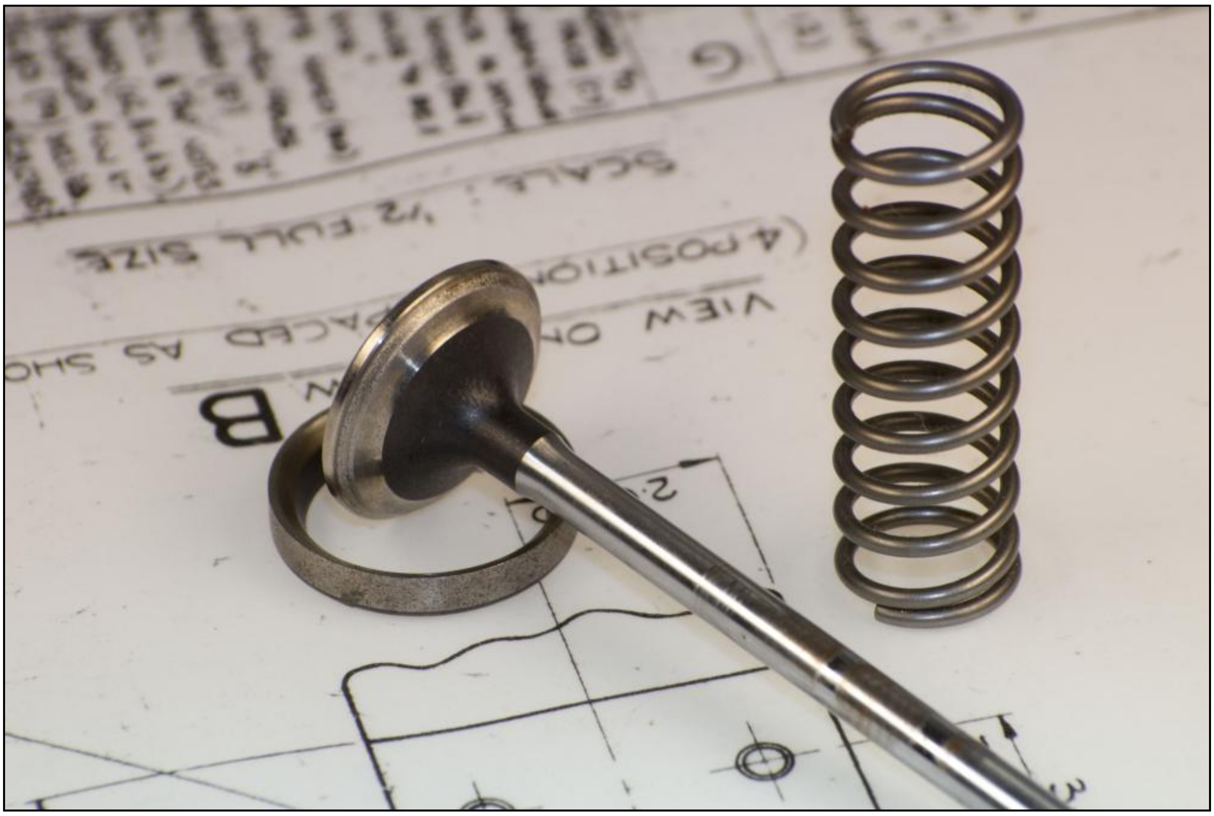
TRIBOLOGICAL DESIGN GUIDE
PART 4: THE WEAR ANALYSIS PROCESS

Institution of MECHANICAL ENGINEERS



Tribology Group

The IMechE Tribology Group has produced this guide as Part 5 of a series of guides on Tribological Design which it wishes to make freely available for student use in connection with their studies. Part 1 is on Bearings, Part 2 covers Lubrication, Part 3 discusses Contact Mechanics and Part 4 focuses on a Wear Analysis Process and Part 5 on Wear; copies may be obtained from:

Institution of Mechanical Engineers, 1 Birdcage Walk, Westminster, London, SW1H 9JJ

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Tribology Group
The Institution of Mechanical Engineers

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PART 4: THE WEAR ANALYSIS PROCESS

CONTENTS

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The Institution of Mechanical Engineers
1st Edition

FOREWORD

The design of machines elements involves consideration of:

- Kinematic function
- Strength
- Mechanical efficiency
- Required life

Friction and wear directly affect mechanical efficiency and may also undermine kinematic function and strength to the point of premature failure. Wear directly limits life at acceptable performance level.

Tribological considerations in machine element design are no less important than considerations of kinematic function and strength.

Kinematics and strength are comprehensively covered as core subjects in the education and training of engineers and scientists and are commonly addressed in the practice of Engineering Design. The subject of Tribology is much more variably covered and, in consequence, tribological considerations are often overlooked in the subject of Design.

In view of its importance, the Tribology Group of the Institution of Mechanical Engineers is anxious to encourage the inclusion of tribological considerations in the practice of Design in the education of mechanical engineers. To this end, the Tribology Group has prepared a collection of Tribological Design Guides to offer to students of engineering in connection with their design studies. The hope is that, by making such data readily available, awareness in tribological design will be encouraged. The data presented will not, of itself, permit complete tribological design but references are included to more comprehensive sources of data and detailed design procedures.

It is the hope of the Tribology Group that those involved with the education of engineers and scientists will find it useful to reproduce this document for distribution to students or for incorporation into their own in-house produced Design Data Handbooks.

INTRODUCTION

Wear is the progressive damage and loss of material which occurs on the surface of a machine component due to its relative motion with another. It is an important consideration in engineering design, as excessive or unexpected wear can cause reduced operating performance or failure.

This guide covers a *Wear Analysis Process* which can be utilised to assess potential wear issues in new designs or find solutions to wear problems occurring in existing equipment. The process is outlined, along with supporting material to aid in conducting each stage of the analysis. Additional resources may be found in Parts 1 to 3 of this book series which cover Wear, Lubrication and Contact Mechanics, respectively. Methods for mitigating wear problems are also discussed followed by a case study demonstrating the successful implementation of the process.

THE WEAR ANALYSIS PROCESS

The wear analysis process involves a combination of experimental and theoretical techniques. The key to the process is to consider all aspects of the problem, not just examine singular issues. In industry, wear related issues are commonly solved by conducting wear tests using varied materials to determine a solution. Using the wear analysis process encourages a broader consideration of the problem with contact geometry, level of lubrication and component dynamics all examined. Although appearing complex, the process need not be. Approximate and rudimentary information on wear relationships may be adequate. Wear testing may or may not even be required i.e. the process may be performed using purely available data.

Figure 1 outlines the wear analysis process. The procedure essentially involves the development of an engineering model of the wear process under consideration. This model can then be used to evaluate and optimise parameters to ensure suitable wear performance. The process begins with examination and ends with verification. It may be utilised to direct the redesign of existing equipment, where unexpected wear life reductions have occurred or wear life differences have been found between different installations. Additionally, the process can be useful during the development of new equipment to help design around potential wear issues or to assess the effects of design changes or altered performance requirements.

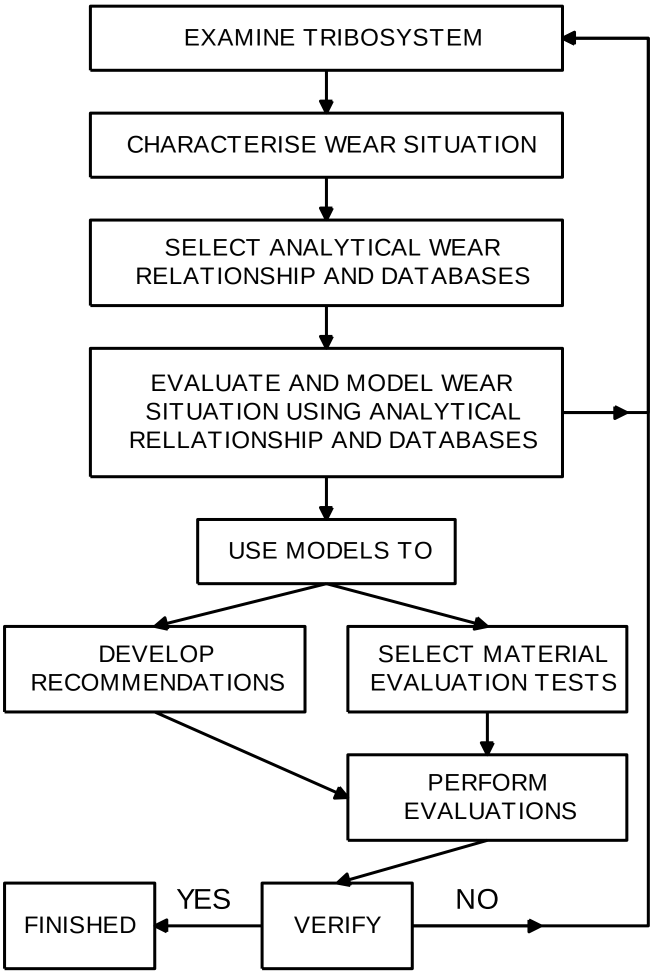


Figure 1: The "Wear Analysis Process"

EXAMINATION OF THE TRIBOSYSTEM

The first stage of the wear analysis process involves gathering data. This requires an examination of the whole tribosystem, not just worn components or areas where wear is anticipated in a new design. The reason for the wear problem may be related to a different part of the overall system under consideration.

In many instances it is possible to identify two systems, a *microtribosystem* and a *macrotribosystem*. Microtribosystems are specific wear points or wearing contacts and macrotribosystems are the mechanisms in which wear occurs. Figure 2 shows a valvetrain mechanism from an automotive engine. This is a macrotribosystem. The contacts between the various components of the mechanism form the microtribosystems, such as those between the valve and seat insert, rocker arm and valve tip and the cam and rocker arm. Microsystem parameters are related to the macrosystem, for example, a change in the valve profile would alter the closing velocity of the valve and affect the wear occurring in the valve and seat insert microsystem.

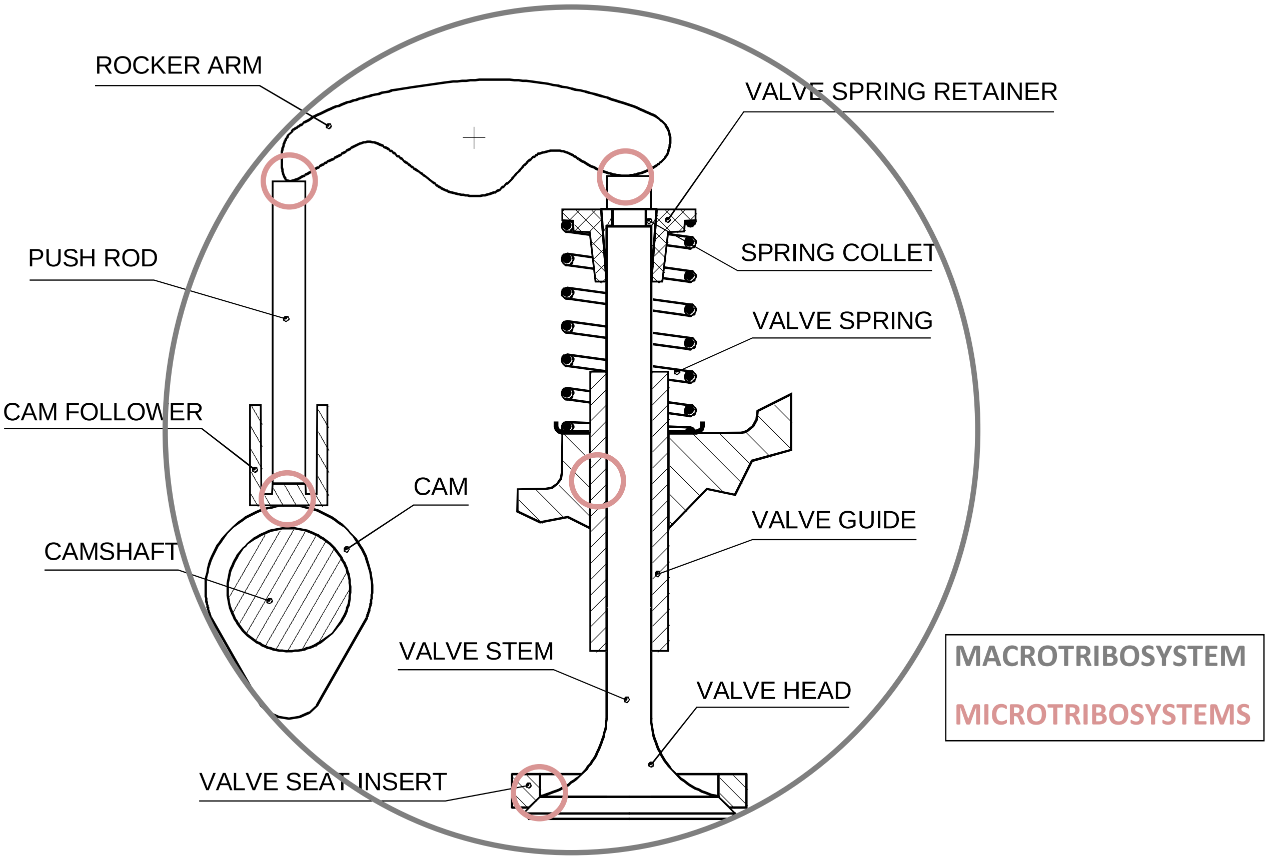


Figure 2: A valvetrain system illustrating both macro and microtribosystems

When performing the wear analysis process, both micro and macrotribosystems must be considered. The wear relationships used in the wear analysis are based on microsystem parameters which are determined by conditions associated with the macrosystem. Additionally, wear problems may be resolved or avoided by appropriate selection of both micro and macrosystem parameters.

Table 1 shows the typical data that may be collected relating to the tribosystem. It is unlikely that all of this will be easily available, but maximising the information gathered will improve the performance of the wear analysis process. The minimum required data relating to wear is the amount of wear and the usage (this may be in time or number of cycles). Other parameters such as load, operating speed and environmental conditions, such as temperature and humidity, are very useful, as they play a significant role in wear processes.

Table 1: Typical data that might be gathered during the examination stage

Component Information	**Contact Condition Information**	**Lubrication Information**
Geometry Dimensions Materials	Orientation Location Loading Motion	Type of lubrication Lubricant Conditions
Environmental Information	**Wear Information**	
Temperature Humidity Atmosphere Contamination	Amount of wear } Minimum required Usage } Appearance Location of wear	

CHARACTERISATION

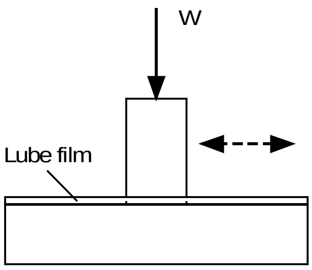
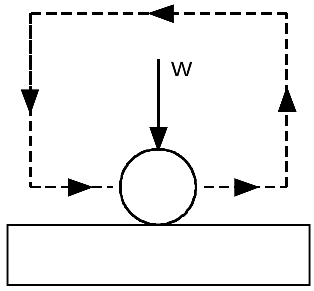
Wear behaviour is very complex with many different relationships describing wear processes. Characterization is essential to provide the basis for selecting the appropriate models of wear behaviour to use in the modelling and evaluation stage of the Wear Analysis Process. It involves collating all the data relating to the wear issue into a useful description of the wear situation.

Characterization should contain the following elements:

- Description of the motion causing wear
- Description of the contact geometry
- Nature of the loading
- Description of the materials
- Type of lubrication
- Predominant wear features
- Surface roughness
- Description of the operating environment
- Wear magnitude
- Associated usage

Wear mechanisms and their characteristic features, lubrication modelling and contact mechanics theory are covered in detail in Parts 1, 2 and 3 of this series, respectively. These should be consulted during the characterization stage of the Wear Analysis Process. Some example characterizations are presented in Table 2.

Table 2: Example wear characterizations

Parameter	Example 1 	Example 2 
Motion	Reciprocating sliding	Unidirectional sliding (smaller member separates for return stroke)
Geometry	Flat against flat	Cylinder on flat (cylinder is smaller member)
Loading	Nominally constant	Smaller member spring loaded against flat; nominally constant
Materials	Soft metal (larger flat) contacting harder metal (smaller flat)	Both are case-hardened steel
Lubrication	Thin oil film	None
Wear	(a) Morphology typical of mild	(a) Intermittent wear track on

Features	sliding wear; (b) non-uniform wear track, suggestive of misalignment	larger surface, suggestive of separation and impact during sliding; (b) morphological features typical of impact and sliding motions
Roughness	Ground finish on both, 0.25-1μm	Polished finish on both, 0.2-0.5μm
Environment	Room	Room
Wear and usage	Wear track on larger flat, 250-1000μm deep after 6 months of operation; no observable wear on harder part; device operates at 10rpm, 16 hr/day	200μm float on cylindrical surface after approximately 10^4 cycles of operation

MODELLING, TESTING AND EVALUATION

This stage is the core of the wear analysis process. It involves selecting an appropriate analytical relationship that describes the wear situation characterized and then using this to influence design parameters.

There are four steps in this stage:

1. Determine which relationships to use.

2. Develop a mathematical model relating wear life to the selected design parameters. This may require wear testing.

3. Verify the model to check accuracy (if not acceptable, modify or use an alternative).

4. Use the model to optimize parameters and establish design changes required.

Wear modelling and analytical relationships used to predict wear are discussed in Part 1 of this series. Many of these use semi-empirical formulae that may require data relating to specific materials that is not easily available. In these cases, wear testing will need to be conducted to obtain the required values. Wear testing methodologies are also covered in Part 1 of this series from Machinery Field Tests down to Specimen Tests and the use of standard testing apparatus.

PROCESS IMPLEMENTATION

The Wear Analysis Process can be used for short term problem solving, for example if a piece of equipment is out of service and needs to be resolved as soon as possible or for longer term design problems, when models will be developed for integration into design codes and a deeper understanding of the problem is necessary.

CASE STUDY: COMBATING ENGINE VALVE RECESSION

Introduction

Valve recession occurs in an automotive engine when wear causes the valve to sink or recede into the seat insert, as shown in Figure 3. Excessive recession leads to valves not seating correctly and cylinder pressure loss. Leaking hot combustion gases can also cause valve guttering or torching, which will accelerate valve failure.

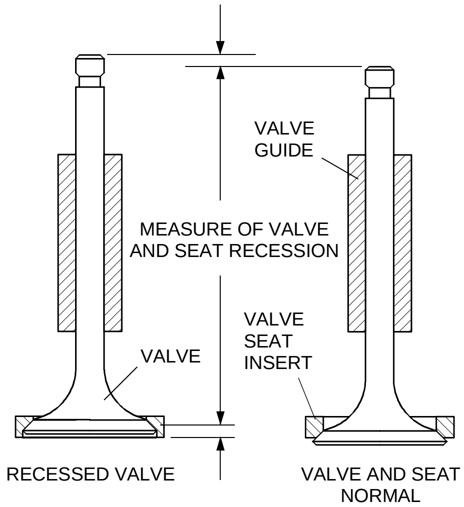


Figure 3: Valve recession

Dynamometer engine testing is often used to establish short-term solutions to such problems, however, this is time consuming and does not necessarily reveal the actual causes of wear. A long-term approach was required in order to understand the fundamental wear mechanisms and the effects of varying engine operating conditions or design changes to the valvetrain. This information was then used to develop tools for predicting wear and for solving problems more quickly when they occur.

Identified Wear Issue

A wear issue was identified in a production automotive diesel engine with direct acting cams. The engine was undergoing design upgrades, one of which was the change from indirect to direct injection. This meant the inclusion of holes in the cylinder-head between the inlet and exhaust ports to accept the fuel injectors. A new valve seat insert material was also being trialled in the tests. The material had solid lubricants incorporated, which were thought to help improve machinability and reduce sliding wear problems at the valve/seat interface. The valve, seat insert and operating system are shown in Figure 4.

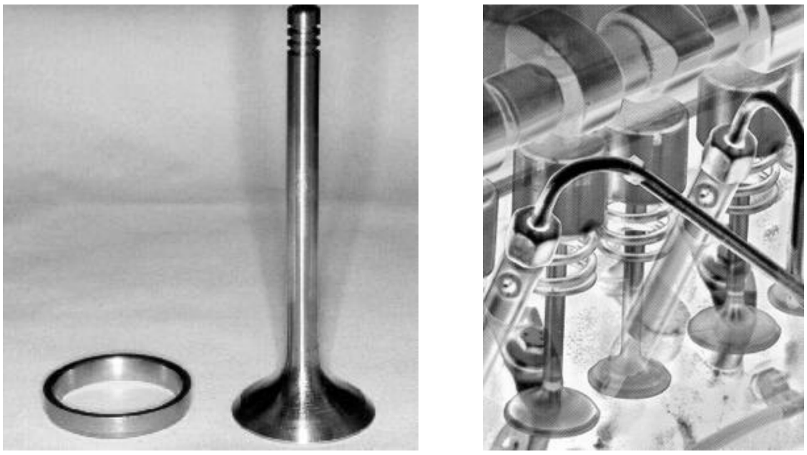


Figure 4: Valve, seat insert and valve operating system

During pre-production engine testing, the new seat insert material exhibited excessive wear (0.3mm of recession in 100 hours).

Evaluation

The macro and microtribosystems associated with the engine's valves were examined. Since the engine used direct acting cams, the macrosystem included only the valve, valve seat, valve guide, cam, cam follower and valve spring as shown in Figure 5. Microsystems were formed by the valve head and valve seat; the valve stem and guide and the cam and cam follower. Data relating to the tribosystems was gathered to allow characterization of the wear problem. This included: wear observations, loading, component materials, contact geometries, lubrication and environmental conditions.

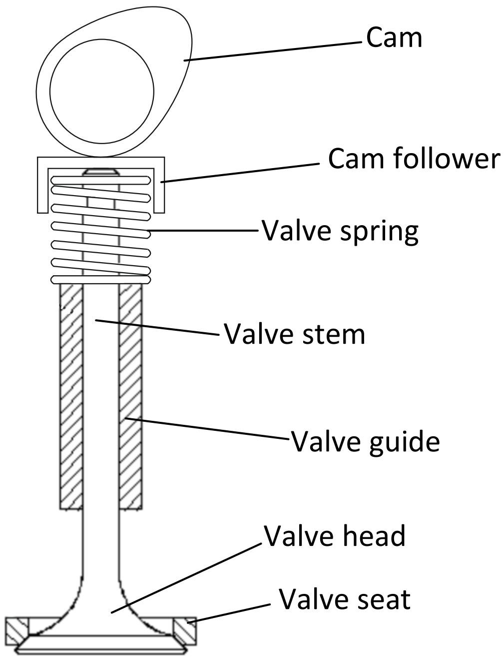
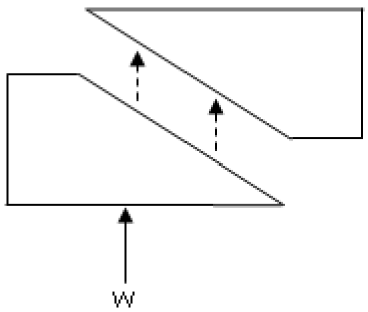
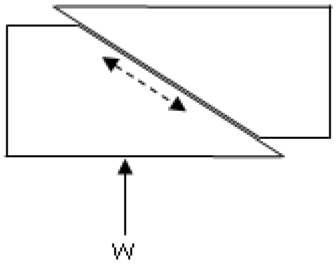


Figure 5: Valvetrain macrotribosystem for a diesel engine with direct acting cams

Characterisation

The analysis of the valvetrain tribosystem identified two separate wear mechanisms acting on the valve seat. The first was due to the impact between the valve head and seat during valve closure, under the force of the valve spring. The second was due to micro-sliding between the valve head and seat due to elastic deformations of the valve head under the pressures generated by the combustion events in the cylinder. These were characterized as shown in Table 3.

Table 3: Valve wear characterisation

Parameter	Mechanism 1 	Mechanism 2 
Motion	Impact (contacting faces are parallel, but at an angle to the direction of motion)	Bidirectional sliding (valve head slides against seat)
Geometry	Flat against flat	Flat against flat
Loading	Shock loading through impact reducing to a constant contact load thereafter (forces generated by in-cylinder combustion not considered)	Load varies as in-cylinder pressures change during engine combustion stroke. Sliding direction is at an angle to the load applied.
Lubrication	Solid lubricant in valve seat	
Wear Features	Circumferential ridges and valleys	Radial scratches on the seat insert seating faces
Environment	High temperature due to in-cylinder combustion	
Wear and usage	0.3mm of recession in 100 hours of engine testing	

Modelling, Testing and Evaluation

In order to develop a model to predict valve recession, both wear mechanisms had to be accounted for. These were considered separately, as they had distinct loading events. Impact and sliding wear equations were adapted and combined to produce an overall model. This required various wear tests to be conducted using specially produced laboratory test equipment (figure 6). Impact wear between the valve head and seat was examined using a simple, cam based, test rig while sliding wear due to combustion pressures was examined using a hydraulic loading apparatus. Two more complex test rigs which included actual valve drive components (one modular and one based on a motorised cylinder head) were used to assess the effects of valvetrain dynamics on valve seat wear. Finally, engine testing was conducted to simulate the actual component operating environment (temperature, pressures, etc.). These rigs were used to investigate the fundamental wear mechanisms and the effect of critical engine operating parameters. Table 4 summarises the increasing complexity levels at which the wear process was examined.

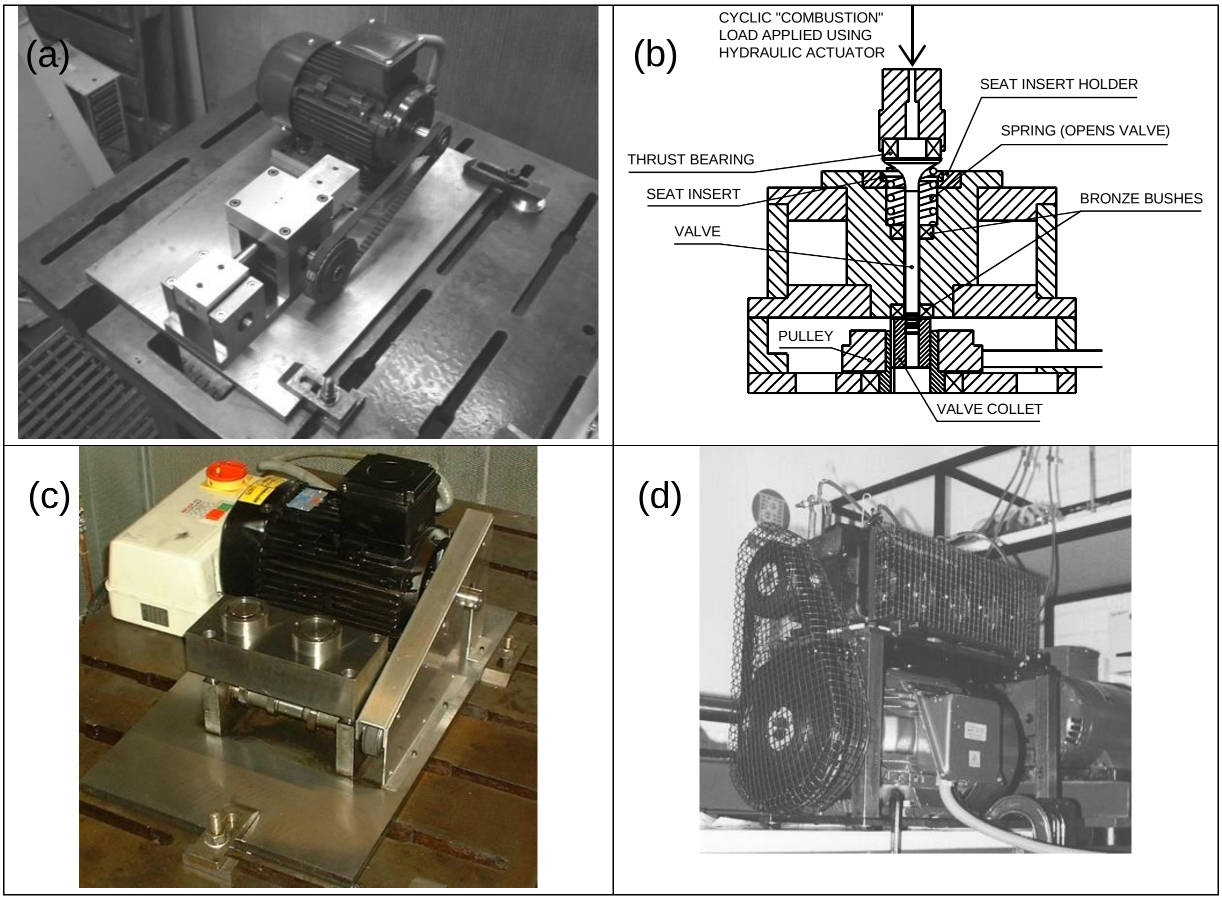


Figure 6: (a) Impact wear tester; (b) hydraulic test apparatus; (c) modular test rig and (d) motorised cylinder-head

Table 4: Levels of experimental testing

Level	Aims of Test/Experiment	Types of Test/Experiment
1 – Material Level	Investigation of primary material properties	Impact wear testing of 'thick shim' test specimens of modified cylinder head and valve seat insert materials
2 – Component Level	Investigation of interactions between geometry and materials	Hydraulic cylinder head rig to investigate the wear due to valve sliding due to combustion pressure
3 – System Level	Investigation of individual wear mechanisms and/or the effect of system dynamics	Motorised cylinder head rig to investigate wear due to impact from valve train dynamics, Modular test rig to investigate the wear due to different valve and valve seat material combinations and the effect of contact geometry
4 – Integrated Level	Investigation of interaction between wear mechanisms at realistic operating conditions	Firing single cylinder test engine to recreate actual pressures, temperatures, environment etc.
5 – Actual Level	Investigation at 'real world' level	Engine durability dynamometer test

The laboratory test rigs produced similar wear results to those produced under actual engine operation. These can be seen in Figure 7. Additionally, engine operating parameters such as valve closing velocity, combustion load and valve/seat misalignment were found to have a strong influence on valve seat wear (Figure 8).

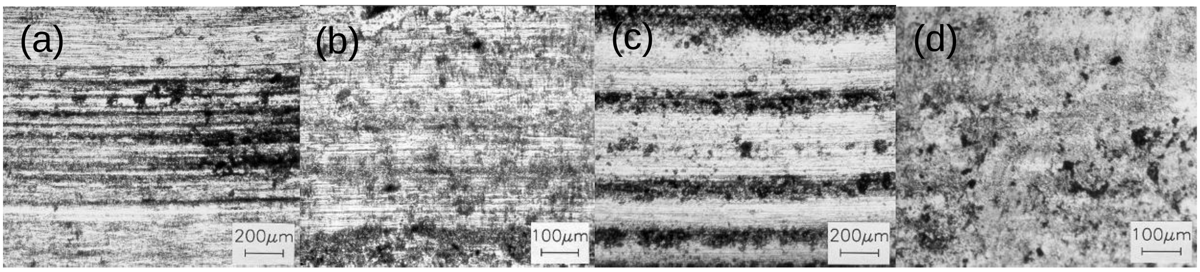


Figure 7: Laboratory tested valve (a) and seat insert (b) compared with engine tested valve (c) and seat insert (d)

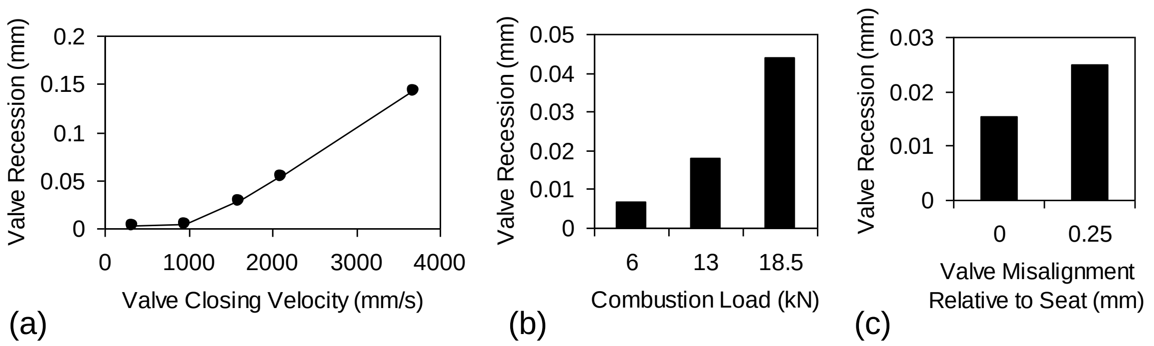


Figure 8: Valve recession with cast tool steel seat inserts for increasing (a) valve closing velocity (after 100 000 cycles); (b) combustion load (after 25000 cycles) and (c) valve misalignment (after 25000 cycles)

Using the data generated in the laboratory tests, a model was developed of the form:

$$V = \left(\frac{k\overline{P}N\delta}{H} + KN\left(\frac{1}{2}mv^2\right)^n \right)\left(\frac{A_i}{A}\right)^j$$

where V is the wear volume; $\overline{P}$ is the average load at the valve/seat interface; N is the number of cycles; δ is the slip at the valve/seat interface; H is the seat hardness; k is a sliding wear coefficient determined from wear tests; m is the mass of valve and follower; v is the valve closing velocity and K and n are impact wear constants determined during wear testing.
The factor, 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 in order to incorporate the change in pressure at the interface and other effects likely to cause a reduction in the wear rate with time, such as work hardening. The constant j was determined empirically using wear test data.

The model allows the wear volume after a number of cycles to be predicted based on the valvetrain geometry and component materials. This is then easily converted into valve recession. Figure 9 shows model predictions against measured data from engine tests using cast and sintered tool steel valve seat inserts. The model produces a good prediction of valve recession.

Knowledge built-up during failure analysis, bench testing and modelling has been combined to develop a flow chart for use in solving valve recession problems that do occur, more quickly, as shown in Figure 10.

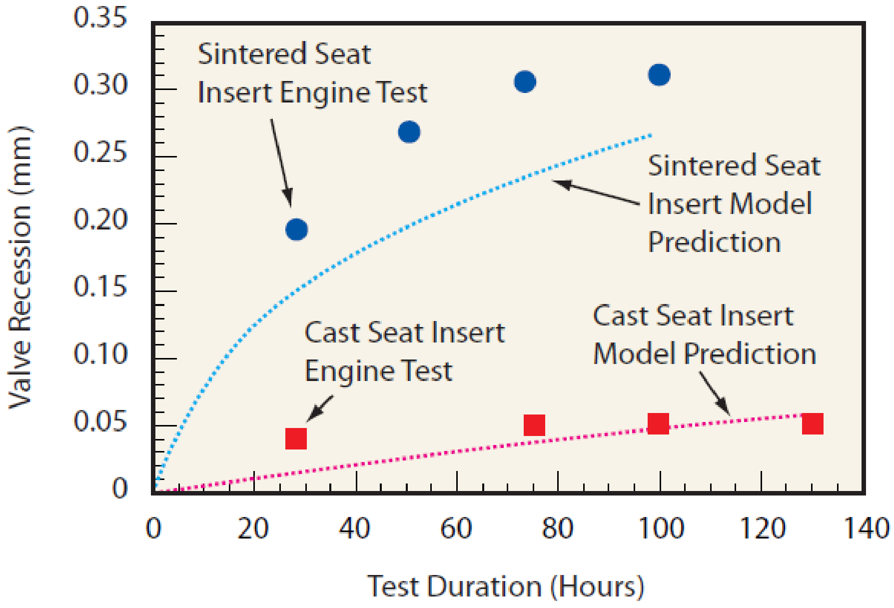


Figure 9: Model predictions versus engine test data (reproduced from Lewis and Dwyer-Joyce, 2003)

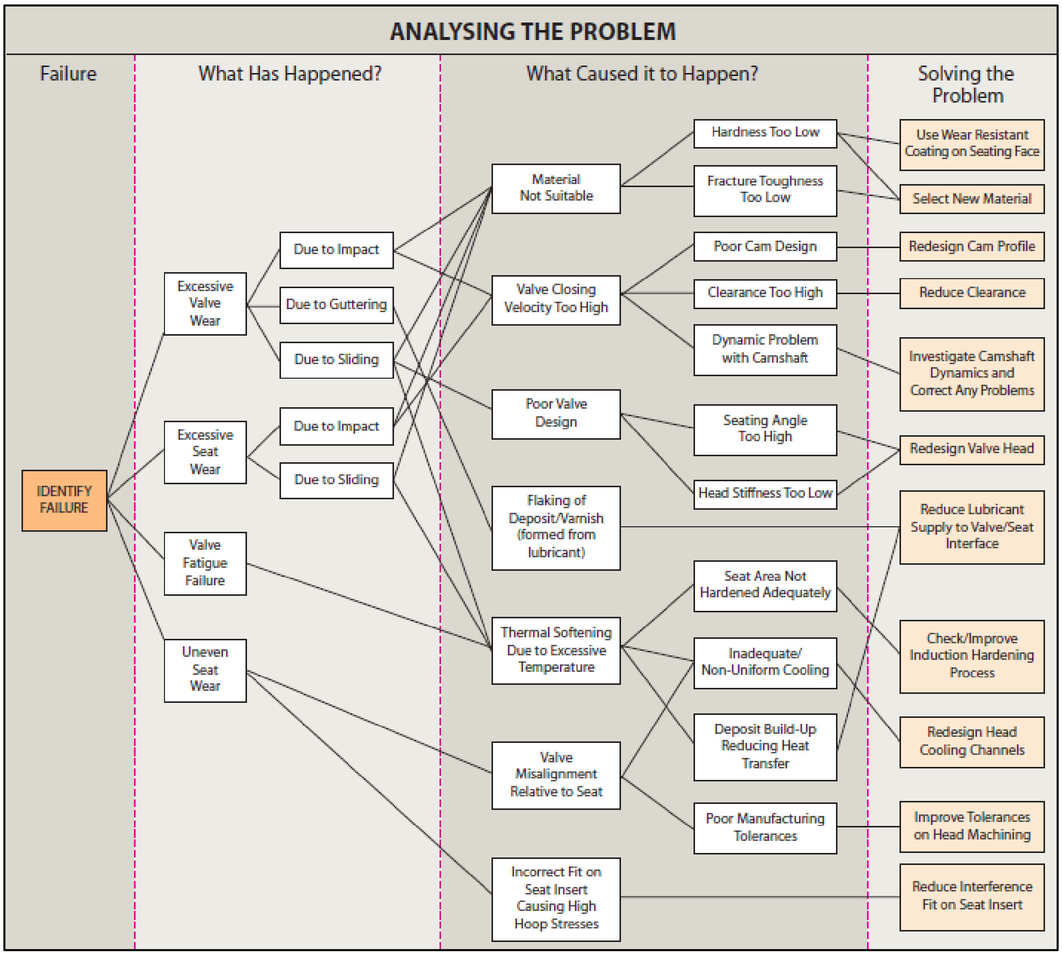


Figure 10: Flow chart for solving valve/seat failure problems (reproduced from Lewis and Dwyer-Joyce, 2003)

Adopted Solution

The short term solution for the recession problem was to replace the seat insert material with a material exhibiting higher toughness to reduce the effect of impact wear on valve closure. The structure of the original material meant it had good resistance to sliding wear, but low fracture toughness. The impact issue was also addressed by altering the inlet cam profile slightly to reduce the valve closing velocity.

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 outputs from these (loads and deformations) are used as inputs to the model to predict recession rates for a given design. In this way it may be possible to design out the causes of valve recession.

OPTIONS FOR REDUCING WEAR

Review previous investigations

Before implementing the Wear Analysis Process, it is prudent to examine the body of previously published material to establish whether the wear mechanisms related to the component in question have been examined previously. Table 5 lists a small sample of recent works conducted relating to automotive engine components. These cover wear testing methods, understanding wear mechanisms and methods for reducing wear.

Unfortunately, there are few generic tools for engine components to help predict or reduce wear occurring that may be used in the design process. The case study presented in this book is one and two other good examples are the computational model developed by Mukras et al. (2007) for studying wear in oscillating pin joints and the work carried out by Kim & Kotkoff (1990) using zero-wear model (Bayer, 1962) to design out the excessive wear of a new injector coupling.
This is clearly an area where a great deal of work can be done by researchers and academics to improve knowledge transfer and produce usable wear prediction tools.

Table 5: Recent work on wear of automotive engine components

Engine Component	Reference	Focus of Work
Piston pins	Morgenstern et al. (2008)	Reducing wear (coatings)
Piston ring and cylinder wall	Papadopoulos et al. (2007)	Wear testing Identifying wear mechanisms
Piston ring and cylinder liner	Skopp et al. (2007)	Reducing wear (coatings)
Piston ring and cylinder liner	Truhan et al. (2005)	Wear testing method
Cylinder liners	Tomanik (2008)	Reducing wear (surface finish)
Piston rings	Etsion & Sher (2009)	Reducing wear and friction (laser texturing)
Piston rings	Kawai (2006)	Reducing wear (coatings)
Valve lifters	Lindolm & Svahn (2006)	Reducing wear (coatings)
Cam	Flocker (2008)	Reducing wear (design)
Cam followers	Lawes et al. (2007)	Reducing wear (coatings)
Valves/seat inserts	Lewis & Dwyer-Joyce (2002a & 2002b)	Identifying wear mechanisms Reducing wear (design/materials)
Valve Guides	Blau et al. (1999)	Wear testing of new material
General	Borghi et al. (2008)	(surface texturing)
Whole engine	Becker (2004)	(materials)

Once a wear issue has been identified and investigated there are a number of options available in order to elicit a reduction in wear. These may involve altering the design of components, using different materials or applying surface coatings or treatments. The latter are becoming increasingly popular, particularly in automotive applications. This is being driven by the desire to reduce lubricant consumption and the increased use of lighter, less wear resistant materials.

Surface Coatings

A variety of surface coating techniques have been developed for use in combatting wear. These include electroplating, thermal spraying and vapour or plasma deposition. Figure 10 illustrates the various applications for these methods in a modern automobile. Many publications covering the selection of surface coatings have been produced. For example, Holmberg & Matthews (1994) contains a great detail of information on coatings and their application methods and also includes a guide to selecting the correct coating for the application of concern.

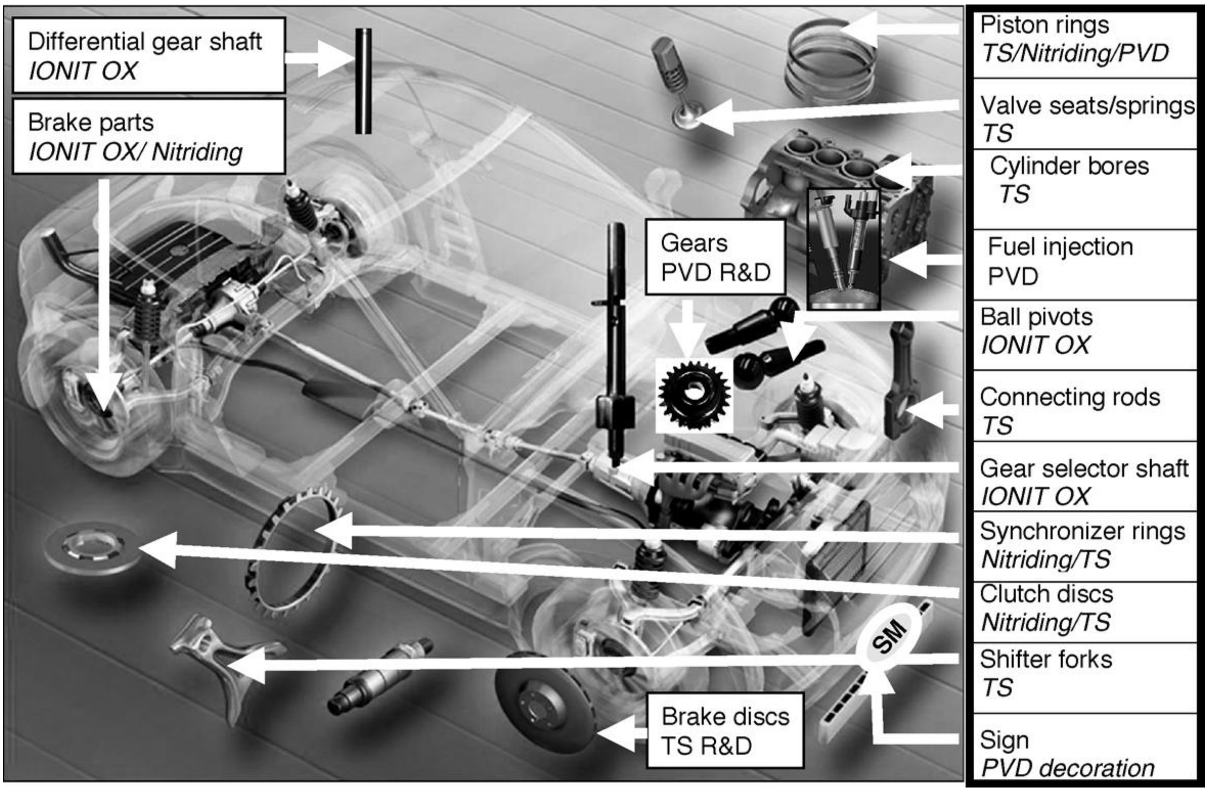


Figure 10: Automobile components suitable for treatment by surface technologies (Vetter et al., 2005)

Surface Treatments

Alongside surface coatings, the alteration of surfaces by texturing is becoming more popular. This involves the creation of small surface dimples or other features, using lasers, which aid in lubricant retention and thus wear reduction. This technology has been developed for piston rings and liners in automotive engines, but is now being considered for other high-wear components.

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