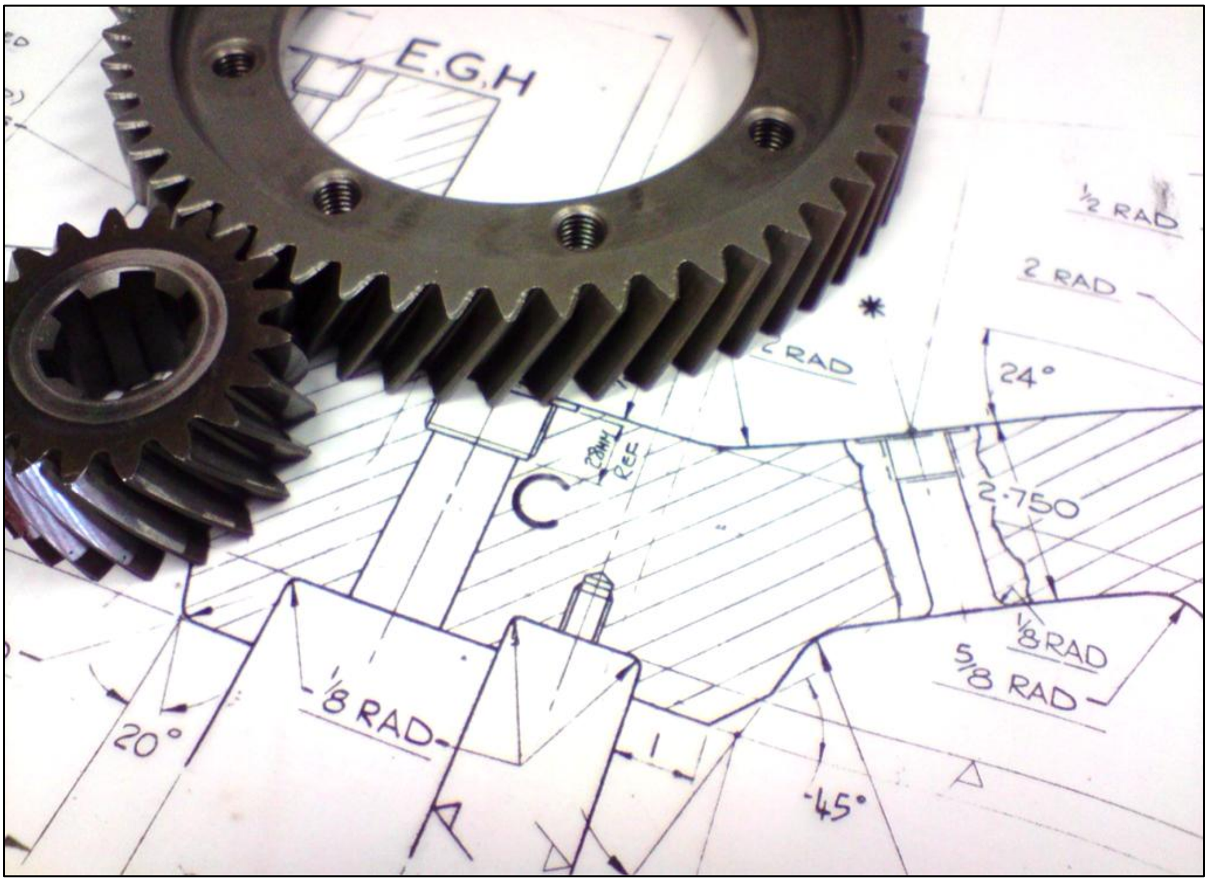
TRIBOLOGICAL DESIGN GUIDE

PART 5: WEAR

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

2nd Edition, January 2014
Prepared by S Pashneh-Tala and R Lewis, The University of Sheffield on behalf of;
Tribology Group
The Institution of Mechanical Engineers

TRIBOLOGICAL DESIGN GUIDE
PART 5: WEAR

CONTENTS

Tribology Group
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 mechanical engineers 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 engineers and scientists. 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.

WEAR

Wear is the progressive damage, involving material loss, which occurs on the surface of a component as a result of its motion relative to adjacent working parts. Wear has the potential to occur to some degree between any contacting components, even if the contact appears fixed. Wear can lead to a loss of mechanical performance in a system and ultimately may even cause complete failure. Therefore, a reduction in wear can bring considerable cost savings through reduced maintenance and energy usage.

WEAR SITUATIONS

Wear can occur in a number of different ways. In examining wear and attempting to reduce it, it is important to understand these processes. Wear occurs through three possible contact situations, with a number of possible mechanisms acting within these contacts.

The three possible contact situations that can cause wear are sliding, rolling and impact. Each situation involves a particular relative motion of the two wearing surfaces while they are in contact.

Sliding

Sliding is the relative motion of two surfaces continuously in contact. The motion is therefore tangential to each surface. Motion tangential to a surface has more potential to cause wear than motion normal to a surface. Very severe sliding conditions can lead to seizure and high heat generation in the contact, which may cause a thermal break down of the surface material.

Some typical sliding contacts in an internal combustion engine include the piston ring/liner and the valve/valve guide. As well as occurring independently, sliding is very likely to occur in combination with other wear situations.

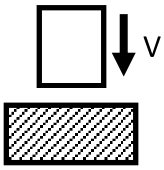
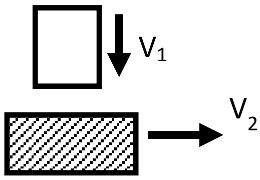
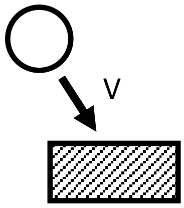
Rolling

Rolling motion occurs when one surface rotates against another. Rolling can exist under no-slip conditions, where the contacting surfaces move at the same velocity, or under slip conditions, where the contacting surfaces move at different velocities. Slip causes some sliding motion, or traction, to also occur within the contact. In rolling situations, wear usually occurs through fatigue mechanisms which act perpendicular to the contact surface. Generically, these are referred to as surface fatigue and are forms of repeated-cycle deformation that result in the formation and propagation of cracks, which ultimately lead to the loss of material particles from the surface.
Common examples of rolling contacts are the roller/race in rolling element bearings or the belt/pulley in flat belt drives.

Impact

Impact occurs through two separate surfaces coming into contact. Impact may be percussive, where a large body hits another large body, or erosive, where many small particles impact against a large body. The predominant wear mechanisms are deformation, either by a single cycle or repeated cycles. Percussive impact may occur in three different ways, depending on the relative motion of the impacting bodies (Table 1).

Table 1: Types of percussive impact wear situations

Conditions	Diagram
Perpendicular approach to surface • No sliding • The least severe form of percussive wear	
Perpendicular approach to a moving surface. • Sliding can occur • More severe than with a stationary surface	
Tangential approach to surface • Sliding can occur	

A notable example of an impact situation is the valve head/seat insert in an internal combustion engine.

If the wear situation is known, the possible mechanisms by which wear occurs can be suggested based on the type of motion, the lubrication regime and the presence of particles. This is shown in Table 2.

Table 2: Wear situations and their associated wear mechanisms (adapted from Bayer, 2002)

Wear situation	Motion/With or Without Slip	Lubed or Unlubed	With or Without Particles	Typical Mechanisms[1]				
				Adhesive	**Single-Cycle Deformation**	**Repeated - Cycle Deformation**	**Chemical**	**Thermal**
Sliding[2]	Unidirection	Lubed	Without			×		
		Unlubed	Without	×		×	×[5]	×[6]
		Lubed	With		×	×		
		Unlubed	With	×	×	×	×[5]	×[6]
	Reciprocating (large amplitude)	Lubed	Without			×		
		Unlubed	Without	×		×	×[5]	×[6]
		Lubed	With		×	×		
		Unlubed	With	×	×	×	×[5]	×[6]
	Reciprocating (small amplitude)	Lubed	Without			×		
		Unlubed	Without			×	×[5]	
		Lubed	With		×	×		
		Unlubed	With		×	×	×[5]	
Rolling[3]	With slip	Lubed	Without			×		
		Unlubed	Without	×		×		
		Lubed	With		×	×		
		Unlubed	With	×	×	×		
	Without slip	Lubed	Without			×		
		Unlubed	Without			×		
		Lubed	With			×		
		Unlubed	With			×		
Impact[4]	With slip	Lubed	Without			×		
		Unlubed	Without	×		×		
		Lubed	With		×	×		
		Unlubed	With	×	×	×		
	Without slip (compound impact)	Lubed	Without			×		
		Unlubed	Without			×		
		Lubed	With			×		
		Unlubed	With			×		

[1] Except in hostile environments, where thermal and chemical wear mechanisms can be significant and dominate the wear behaviour.

[2] Repeated-cycle deformation mechanisms tend to be dominant, but chemical mechanisms can be significant; with particles, abrasive wear can be dominant; mild to severe wear transitions with load and speed common in unlubricated situations; lubrication generally required for metal and metal-ceramic pairs; galling and fretting are forms of sliding wear.

[3] Mildest wear situation; repeated-cycle deformation mechanisms tend to be dominant; wear increases with slip and particles; with particles and slip abrasive wear can be dominant; smooth surface particles preferred.

[4] Repeated-cycle deformation mechanisms tend to be dominant; gross plastic deformation generally unacceptable, unless in short life applications; stresses should be in the elastic range for lives greater than 106 impacts; wear increases with slip.

[5] With metals.

[6] With polymers.

WEAR MECHANISMS

There is virtually an endless list of wear mechanisms that have been defined (see glossary in Bayer (2002)). Despite this there are a few generic terms, which cover the main types of wear behaviour. Some of these are described below.

Adhesive Wear

Contacting surfaces only actually touch at very tiny points due to their surface asperities. Bonding occurs at these sites forming adhesion junctions. When the surfaces move relative to each other these bonds are broken. This often results in the removal of material from one surface, causing wear, and the addition of it to another forming a transfer film. Ductile or brittle fracture can occur in the asperity contact, as shown in Figure 1. In severe cases, galling may occur where macroscopic portions of material are torn from one surface. Additionally, particulate debris may be generated during the breaking of the adhesion junctions. This may then contribute to other wear mechanisms.

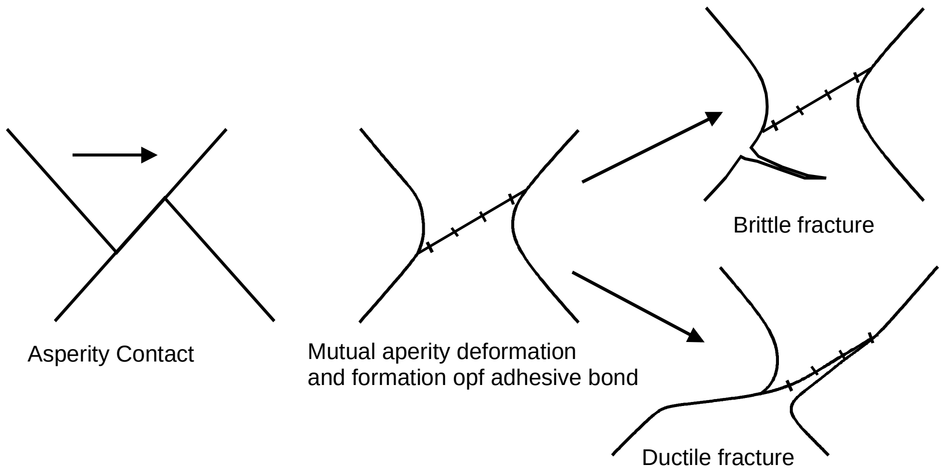


Figure 1: Ductile and brittle fracture in adhesive wear (adapted from Stachowiak and Batchelor, 2001)

Abrasive Wear

Abrasive wear occurs due to contact between materials of differing hardness (Figure 2). In two-body abrasive wear, the asperities of a harder surface cause material removal from a softer one as they move against it. In three-body abrasive wear, hard particles trapped between two contacting, softer, surfaces cause material removal as the surfaces move relative to each other. These particles may be contaminants from the operating environment or could be the product of another wear mechanism such as adhesion or oxidation (discussed later).

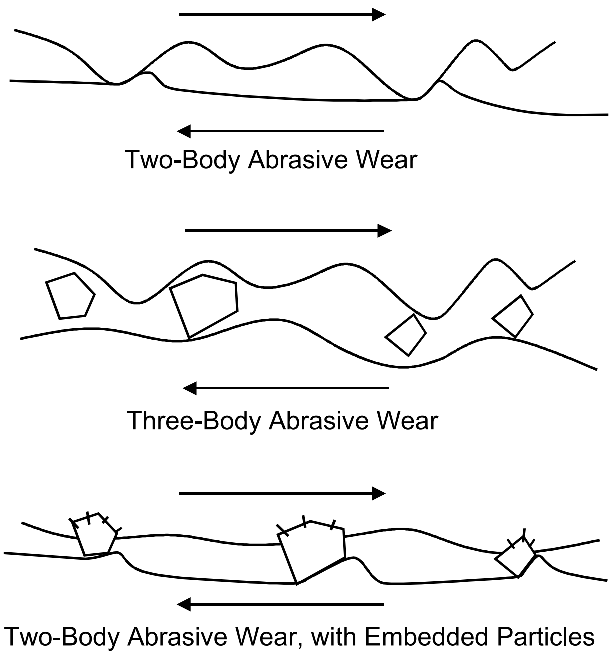


Figure 2: Abrasive wear mechanisms

Abrasive wear gives a characteristic surface appearance consisting of long parallel grooves running in the sliding direction as shown in Figure 3. The volume and size of the grooves varies considerably from light scratching severe gouging. Industrial surveys have shown that abrasive wear accounts for up to about 50% of wear problems.

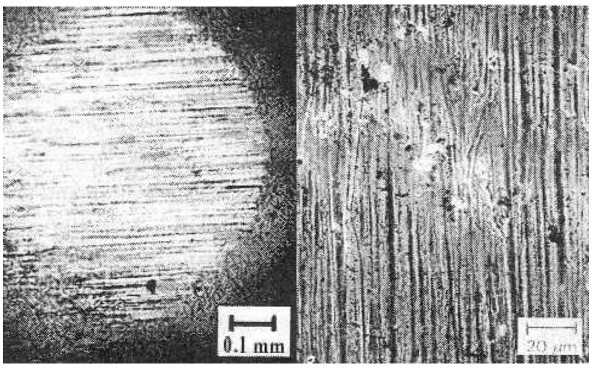


Figure 3: Abrasive wear features (resulting from severe 3-body abrasion) (Swanson and Klann, 1981)

Fatigue Wear

Fatigue wear is associated with the repeated application of loading between contact faces. It can therefore occur as a result of sliding, rolling or impact situations. Repeated loading results in crack formation and propagation within the contacting bodies. This may occur at or below the surface. In ductile materials, this produces deformed layers and wear due to material delamination. Brittle materials may experience rapid crack growth and fracture, releasing material and causing wear. Common fatigue wear features are spalls or pits on the material surface (Figure 4).

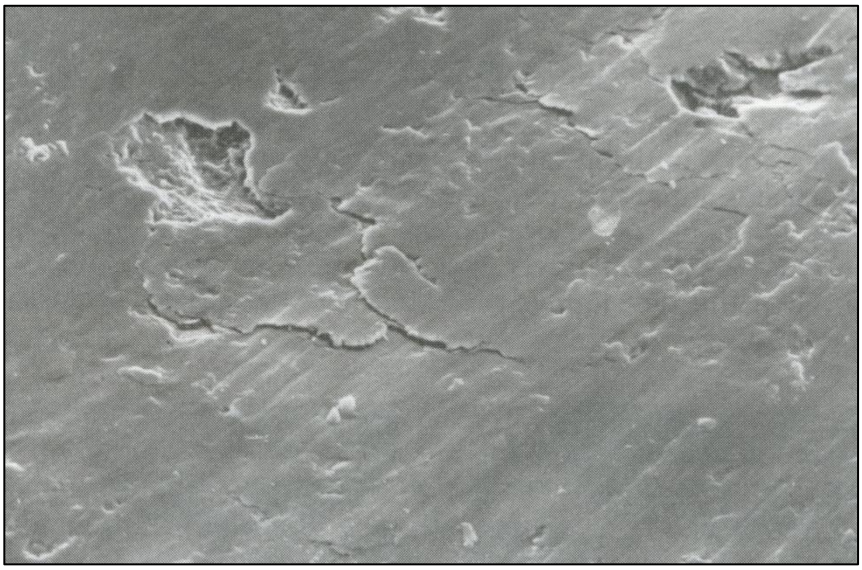


Figure 4: Common fatigue wear features (Stachowiak and Batchelor, 2001)

Oxidative processes can play an important part in contributing to fatigue wear. Oxide layers forming across the contact surfaces may be more prone to cracking, due to their altered material properties, and oxidation around surface cracks prevents them healing, thus increasing the potential for their propagation. Some of the possible loading scenarios associated with fatigue wear are shown in Figure 5.

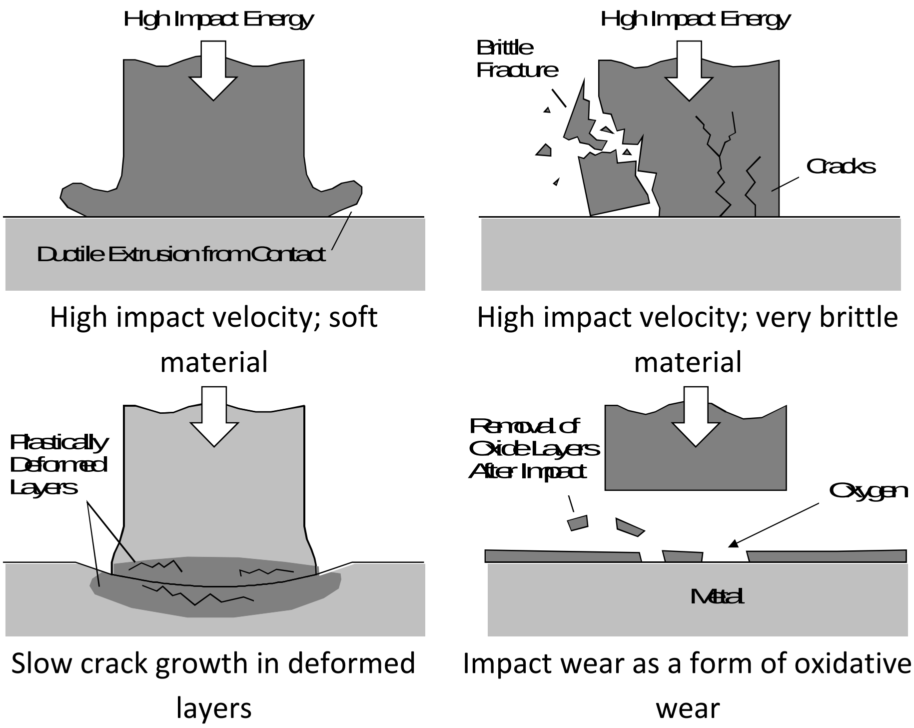


Figure 5: Impact wear features (adapted from Stachowiak and Batchelor, 2001)

Oxidative Wear

Oxidative wear occurs due to the formation of oxide layers on the surface of a material and thus is related to the ability of a material to oxidise and the availability of oxygen. High temperatures are often required to power the oxidation reaction and therefore this type of wear is usually associated with increased surface velocities. Wear occurs through the constant removal and regrowth of the oxide layer within the contact area. This requires the contribution of another wear mechanism such as adhesion or abrasion. The rate of wear is often slower than those associated with mechanical wear processes. The material removal process is shown in Figure 6, along with a typical oxidative wear surface.

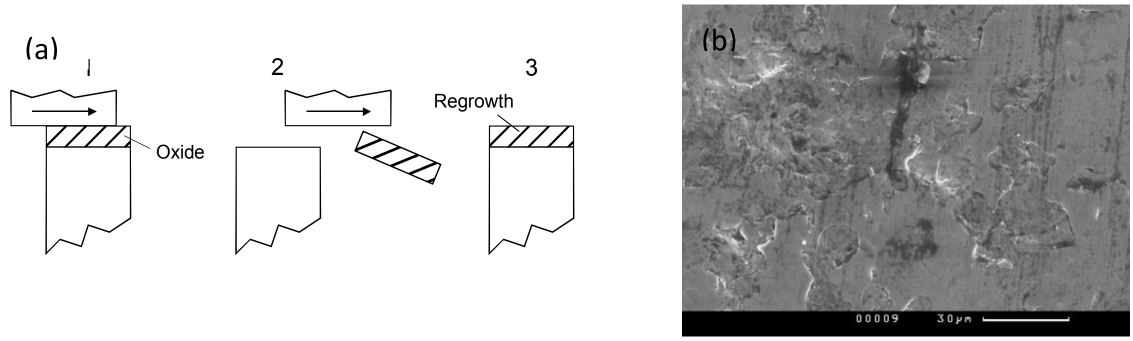


Figure 6: Oxidative wear: (a) mechanisms and (b) surface features

Corrosive Wear

Occurring in a similar manner to oxidative wear, this is caused by a chemical reaction between the surface of a material and some reagent, such as a reactive lubricant or foreign chemical. The reaction produces a surface layer with different properties to the original material. This often allows it to be more easily removed by other wear mechanisms operating within the contact such as adhesion or abrasion. The removal of the reacted material reveals new material for further reaction and removal, causing wear. There are some instances where chemical reaction can produce a durable layer that has lubricating properties and actually contributes to reducing wear.

Thermal Wear

Thermal wear is associated with the increased temperatures occurring due to friction between contacting surfaces. If frictional heating is sufficient, softening or melting of material may occur, causing it to be displaced like a viscous fluid. Thermal effects may also cause thermal fatigue or cracking which can lead to material release and wear.

Fretting

Fretting may occur when contacts are subjected to short amplitude reciprocating sliding for a large number of cycles. As such, it may be observed between contacts that are nominally stationary, such as two plates bolted together or interference fits, where vibrations cause small-amplitude oscillatory motions. Surface damage results along with a reduction in fatigue life. Wear debris are often retained between the contacting surfaces and may then contribute to additional wear by abrasion.

Interaction of Mechanisms

When examining wear in components it is typical to find evidence of multiple mechanisms. These may have occurred independently or may be associated with different stages of a complex wear process. For example, in a lubricated contact, a sudden change in load could cause failure in local lubrication around a "high spot" leading to surface contact and adhesive wear. Other regions in the contact will show evidence of different wear processes, as they did not suffer lubrication failure. Alternatively, the periodic passage of a hard, third body, particle through a contact could result in abrasive wear that would otherwise be absent.

Wear mechanisms can also interact with each other. Adhesive or two-body abrasive wear may release debris into a contact causing additional three-body abrasive wear. Thermal effects can accelerate adhesive and abrasive wear by increasing junction formation or by softening a surface allowing it to be more easily broken by a harder third body particle. Corrosive or oxidative wear are accelerated by the constant removal of reacted surface layers by other wear mechanisms, such as abrasion or percussive impact. This reveals new material for chemical reaction and release.

WEAR RATES AND TRANSITIONS

It is common for machine components to be run together for the first time under reduced loading conditions in order to precondition moving contacts. This process is known as "running-in" and improves component conformity, topography and frictional compatibility. A number of mechanical wear processes may occur, such as abrasion and adhesion. The wear rate during running-in is usually initially quite high, but then reduces as the surfaces become smoother. After a suitable period, full load conditions can be applied without any sudden increase in wear rate. A typical component history is shown in Figure 7. Once running-in is complete, a steady low-wear-rate regime is maintained for the majority of the life of the component. Fatigue processes may become dominant after significant service life, leading to a further wear transition resulting in a return to high wear rates.

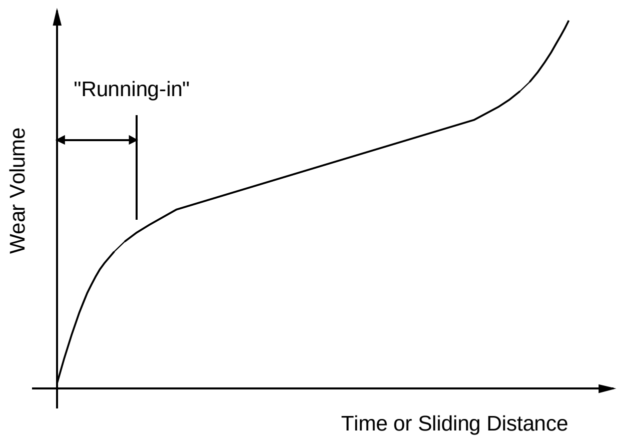


Figure 7: Wear transitions

Wear is often classified as being mild or severe. This is not based on any particular numerical value of wear rate, but on the general observation that for any pair of materials, increasing the severity of the loading, for example by increasing either the normal load, sliding speed or bulk temperature, leads at some stage to a sudden jump in the wear rate. The differences in the two regimes are shown in Table 3.

The mechanisms most associated with severe wear are adhesive or thermal. Increasing temperatures in a contact, and the resulting thermal softening, can lead to a further transition in to a catastrophic wear regime.

Table 3: Mild versus severe wear (Williams, 1994)

Mild Wear	**Severe Wear**
Results in extremely smooth surfaces (often smoother than the original)	Results in rough, deeply torn surfaces (much rougher than the original)
Debris extremely small, typically only 100nm diameter	Large metallic wear debris, typically up to 0.01mm diameter
High electrical contact resistance, little true metallic contact	Low contact resistance, true metallic junctions formed

WEAR MODELLING AND MAPPING

Wear modelling can be a valuable tool for predicting potential wear in new designs or for understanding wear observed in used components and aid in developing improvements. Although there are many models available for friction and lubrication, wear modelling tools are less prevalent.

Wear modelling

The best known wear model is that for sliding contacts, attributed to Archard, but developed initially by Holm:

$$V = \frac{KPS}{h}$$

where V is the wear volume, P is the normal force, S is the sliding distance, h is the penetration hardness and K is an empirical coefficient.

Values for K based on specific material combinations can be found in the literature (Table 4 and Figure 8). If a published value for the specific material combination of interest cannot be found, then wear testing may be performed to determine one (discussed in the next section).

Table 4: Archard wear coefficients for mild steel versus a range of different materials (Williams, 1994)

Material	**Archard Wear Coefficient, K**
Mild steel (on mild steel)	7×10^{-3}
α/β brass	6×10^{-4}
PTFE	2.5×10^{-5}
Copper-beryllium	3.7×10^{-5}
Hard tool steel	1.3×10^{-4}
Ferritic stainless steel	1.7×10^{-5}
Polythene	1.3×10^{-7}
PMMA	7×10^{-6}

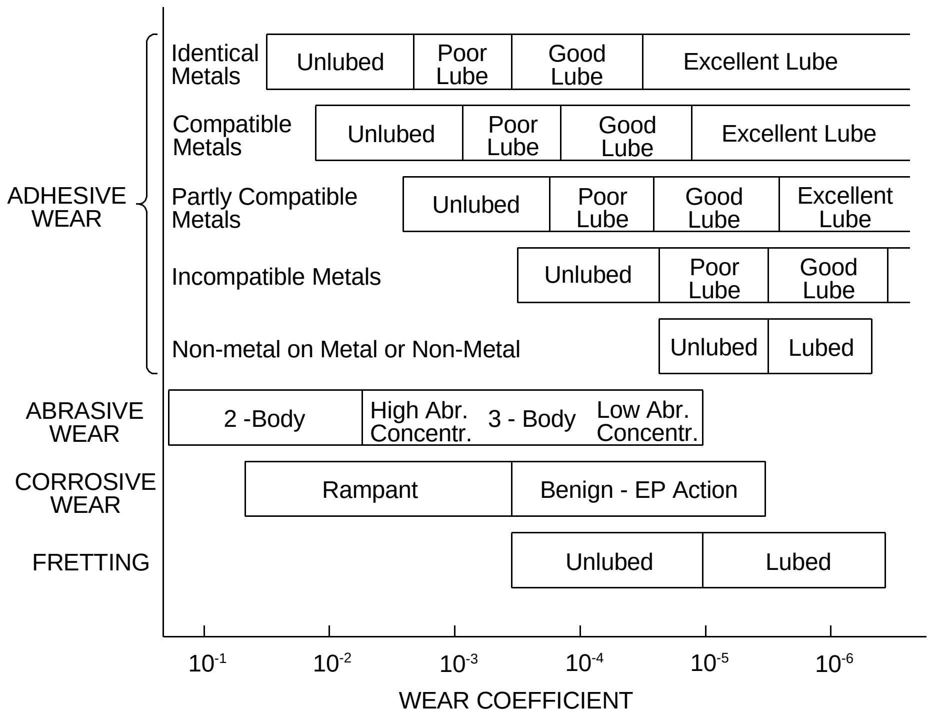


Figure 8: Wear coefficients to be anticipated in various sliding situations (Rabinowicz, 1981)

A number of other models have been derived, including those for predicting wear due to abrasion, adhesion and impact. A number of these are outlined in Table 5.

Table 5: Wear models

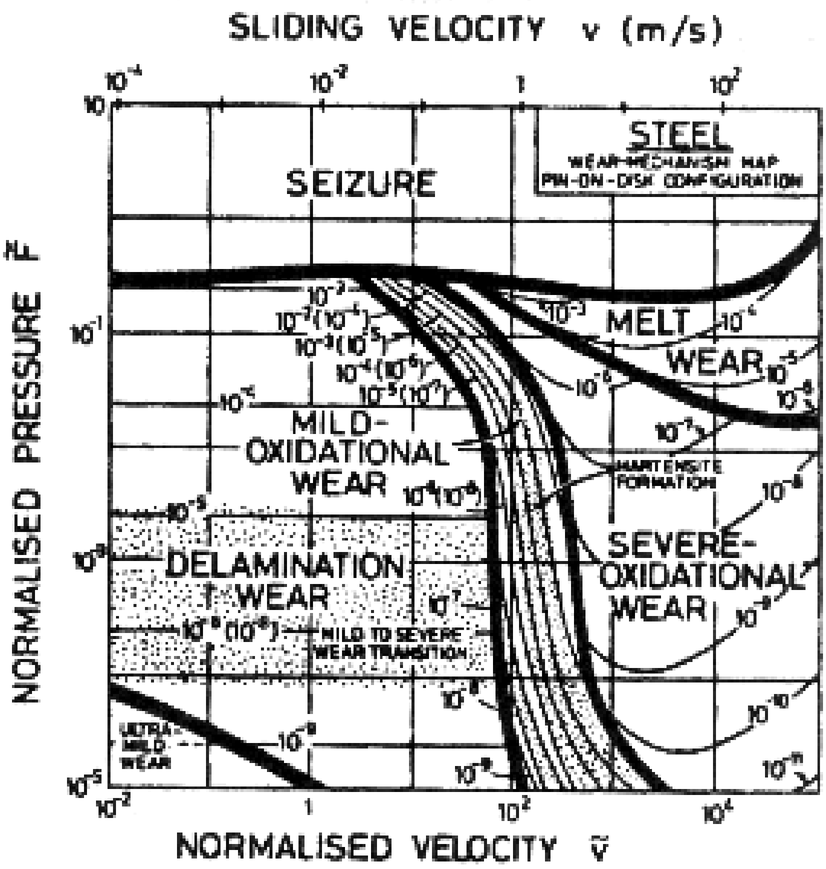
Wear Mechanism	Model	Parameters
Sliding adhesive wear	$V = \frac{KPS}{h}$	V is the wear volume P is the normal force S is the sliding distance h is the penetration hardness K is an empirical coefficient
Percussive Impact wear	$V = KNv^n$	V is the wear volume v is the impact velocity N is the number of impacts K and n are empirical wear constants
Zero Wear-Relationship for Compound Impact	$N_0 = \frac{2000}{1+\beta}\left(\Gamma_r^{'} \frac{\sigma_y}{\sigma_m}\right)^9$	N_0 is the number of impacts to exceed zero wear σ_y is the yield stress in tension σ_m is the maximum contact stress $\Gamma_r^{'}$ and β are empirical constants
Abrasive Wear	$V = \frac{2k \tan \theta PS}{\pi h}$	V is the wear volume P is the normal force S is the sliding distance h is the penetration hardness 2θ is the included angle of the abrasive k is an empirical coefficient

Another model of interest is the Bayer Zero Wear Model (Bayer, 1962) which states that wear can be reduced to a negligible value, or eliminated entirely, by keeping the stress in the vicinity of the region of contact below a certain value. This value is a function of the materials and lubricants used. The model was developed using work carried out on a large range of material combinations to establish at which conditions there was zero wear.

Wear mapping

Wear maps can be used to assess the possible wear mechanisms that may affect a component in service and help avoid undesirable transitions, such as from mild to severe wear.

Lim and Ashby used the Archard model to develop their widely referenced wear map for a steel-on-steel, un-lubricated contact (Figure 9). The thick lines on the map separate different wear mechanisms and thin lines are contours of equal wear rate. The map is based on the parameters: normalised wear ($\tilde{Q}$), normalised pressure ($\tilde{F}$), and normalised sliding velocity ($\tilde{v}$).



$$\tilde{Q} = \frac{V}{A_n}$$

$$\tilde{F} = \frac{F_N}{AH}$$

$$\tilde{v} = \frac{v r_0}{a_0}$$

where:

V = Wear volume

A_n = Apparent contact area

F_N = Normal load

H = Hardness of the softer material

v = Sliding velocity

r_0 = Radius of the pin

Figure 9: Lim and Ashby wear map for unlubricated sliding of a steel-steel couple (Lim and Ashby, 1987)

A number of other wear maps for various materials are available in the literature. These may relate to different wear situations, such as rolling or sliding contacts, or more specific applications, such as gears or automotive engineering. Some examples are given in Figures 10 and 11 and the list below.

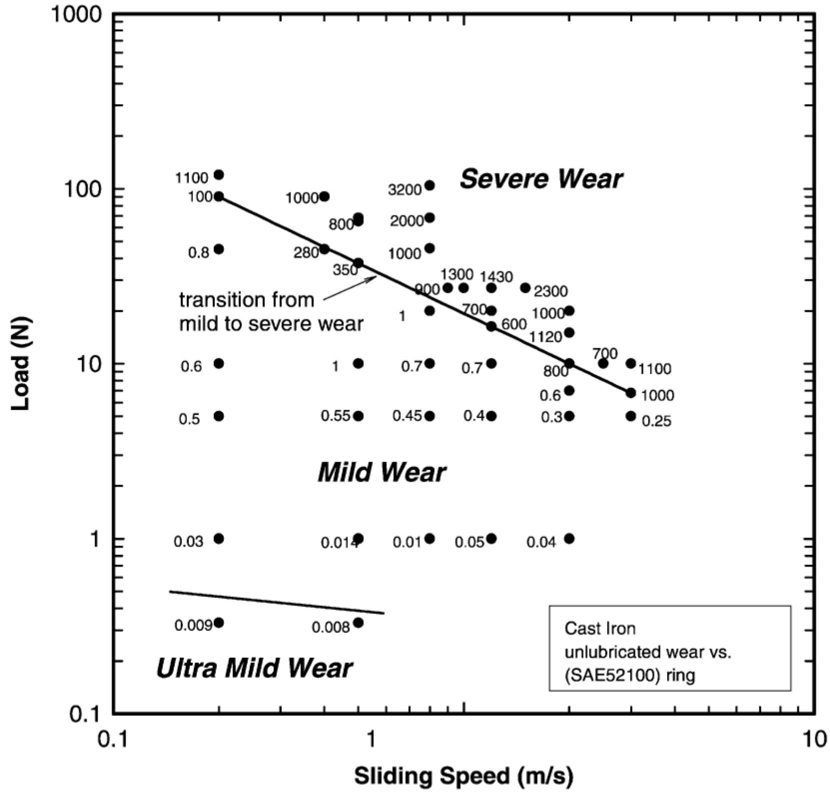


Figure 10: Wear map for grey cast iron (wear rates are given by multiplying the values indicated by 10^{-3})(Riahi and Alpas, 2003)

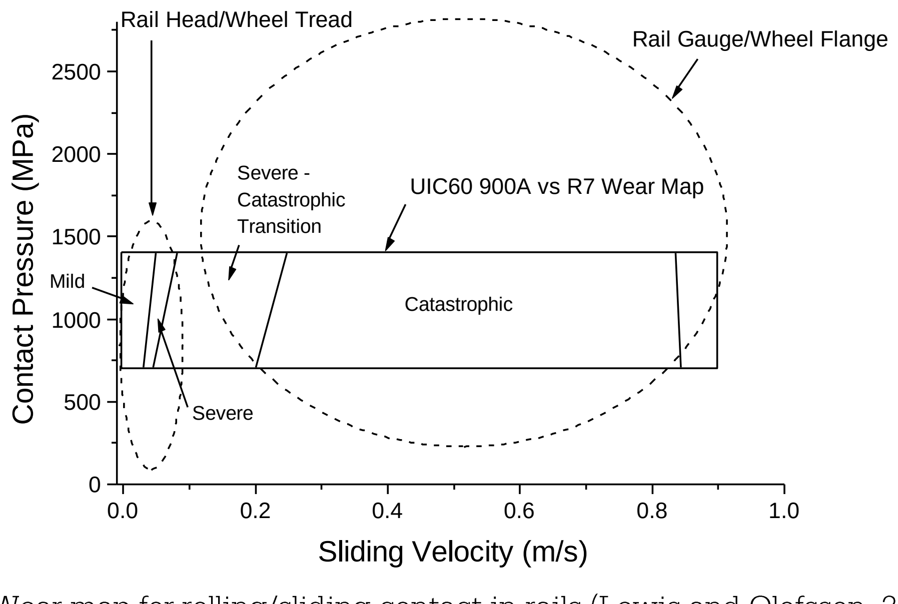


Figure 11: Wear map for rolling/sliding contact in rails (Lewis and Olofsson, 2004)

Additionally:

- Ceramics (e.g. Adachi et al. (1997))
- Gears (e.g. Taki, (2007))
- Automotive engineering (e.g. Wilson et al. (2000))

WEAR TESTING

The examination of wear processes through testing may be required for a number of reasons:

- Characterization of the tribological behaviour of materials and lubricants
- Investigation of tribological processes
- Validation of modelling approaches
- Evaluation of the function, performance, maintainability, reliability, life, or efficiency of engineering tribosystems or components
- Quality control of components

Wear experiments must be carefully designed in order to meet the objectives of the investigation. The type of test, the equipment to be used, the test conditions and the data that must be collected have to be selected precisely with respect to the aims of the testing.

Categories of Test

Wear test can be categorised depending on the structure and function of the tribo-machinery, tribosystem, tribo-component or specimen to be studied. These are shown in Table 6 in descending order of complexity.

Table 6: Categories of wear test

Test Type	Description
Machinery Field Tests	Testing of actual tribo-machinery under practical operating conditions
Machinery Bench Tests	Testing of actual tribo-machinery under practical-orientated (simplified, simulated or accelerated) operating conditions
Systems Bench Tests	Testing of specific tribo-systems under practice-orientated operating conditions
Component Bench Tests	Testing of specific tribo-components under practice-oriented operating conditions
Specimen Tests	Testing of arbitrary test specimens under practice-oriented or laboratory operating conditions

Machinery field tests are the most complex. These utilise actual operating systems and components with actual loading regimes and environmental conditions, but offer the least amount of control over variables. As the tests are simplified, moving from complete tribosystems to the use actual components or simple specimens with simulated loading and environmental conditions, the control over individual variables increases. This allows the influence of different parameters on wear to be studied.

Factors such as the time taken to run the tests and their cost must also be considered in wear testing. Generally, the more complex the test category selected the longer the tests take to run and the greater the cost.

Table 7 shows a range of different methods, shown in order of increasing complexity, which could be used to test engine components, including some standard ASTM tests. The test conditions that can be applied and the types of wear measurement that can be taken are also given.

Table 7: The increasing complexity of different types of wear test for automotive engine components

	Test Method	**Type of Wear Test**	**Test Conditions**	**Measured Quantity**
INCREASING COMPLEXITY ↓	Crossed Cylinder (ASTM G 83-83)	Adhesive	High contact stress High sliding velocity No lubrication	Weight loss
	Block-on-Ring (ASTM G 77-83)	Adhesive (Sliding)	High contact stress Sliding speed High temperature No lubrication	Weight loss Friction
	Thrust Washer	Adhesive/Abrasive	High contact stress Sliding speed High temperature No lubrication	Weight loss Wear depth Wear profile Cycles to failure
	Bench Test-Rigs	General	Valve gear lube Speed Temperature Spring load Seating velocity	Oil residue analysis Wear depth Wear profile
	Motorised or Fired Engine Tests	General	Engine operating conditions Speed Torque	

Designing a Wear Test Methodology

Careful consideration in testing wear is critical given the equipment, time and costs that may be involved. Attempting to replicate a tribosystem in a laboratory and testing all the possible permutations of material, geometry, operating conditions and the like to try to determine the causes of a wear problem is cumbersome and expensive.

It is, therefore, good practice to generate an overall wear testing methodology to give a framework for any individual tests or experiments that are performed to fit into, regardless of their complexity.

ASTM has developed a guide to developing and selecting wear tests. This refers to many of the ASTM standards for wear testing. It is best to adhere to these, as it allows comparison with previous testing performed using the same standards. This is not always possible, as the majority of standards relate to specimen tests and thus, will not always be applicable if specific components are being examined.

Standard Specimen Test Apparatus

A wide range of standard test apparatus is available off-the-shelf for specimen testing. These test-rigs use a range of simple specimen contacts, depending on the type of motion and wear mechanism to be simulated. Some of these are listed below and shown in Figure 12:

- Pin-on-disk (unidirectional sliding – used for materials testing)
- Pin-on-plate (linearly reciprocating – used for materials/coating testing)
- Four ball (rolling/sliding – used for lubricant evaluation)
- Ball-on-flat (unidirectional/linearly reciprocating – used for materials/coating testing)
- Twin disc (rolling/sliding – used for wear/rolling contact fatigue testing, e.g. wheel/rail materials, gear materials etc.)
- Dry sand/rubber wheel (used for abrasion testing)
- Ball-cratering (used for abrasion testing)

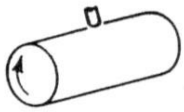
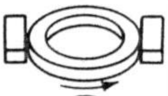
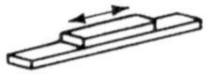
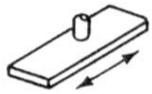
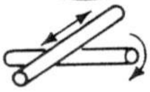
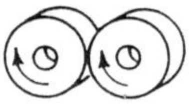
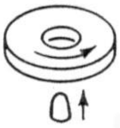
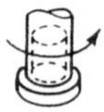
Geometry	Motion	Geometry	Motion
	Unidirectional sliding		Reciprocating sliding
	Unidirectional or oscillatory sliding		Unidirectional sliding
	Unidirectional sliding		Oscillatory sliding
	Unidirectional sliding		Small amplitude oscillatory sliding (fretting motion)
	Unidirectional sliding		Small amplitude oscillatory sliding (fretting motion)
	Unidirectional sliding or unidirectional sliding plus oscillatory motion		
	Unidirectional sliding		Pure rolling and rolling plus sliding
	Normal impact and normal impact plus sliding		Unidirectional sliding

Figure 12: Some standard wear test configurations (adapted from phoenix-tribology.com)

ASTM publish standard test methods for such apparatus. For example: G133 Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear; G99 Test Method for Wear Testing with a Pin-on-Disc Apparatus.

Design of Laboratory Tests

When designing an experimental strategy a number of factors have to be considered. All tests require consideration of which parameters to control and measure and how this can be achieved, how many tests to run (repeatability versus parameter variation) and what parameter ranges to include. If the test is intended to simulate a component in operation, how to determine the validity of this simulation also requires thought. Additionally, the intended use of the data obtained is important. It may be used as an input for a wear model, or to validate one.

The basic characteristics and relevant parameters of laboratory and simulative tests are shown in Figure 13 below:

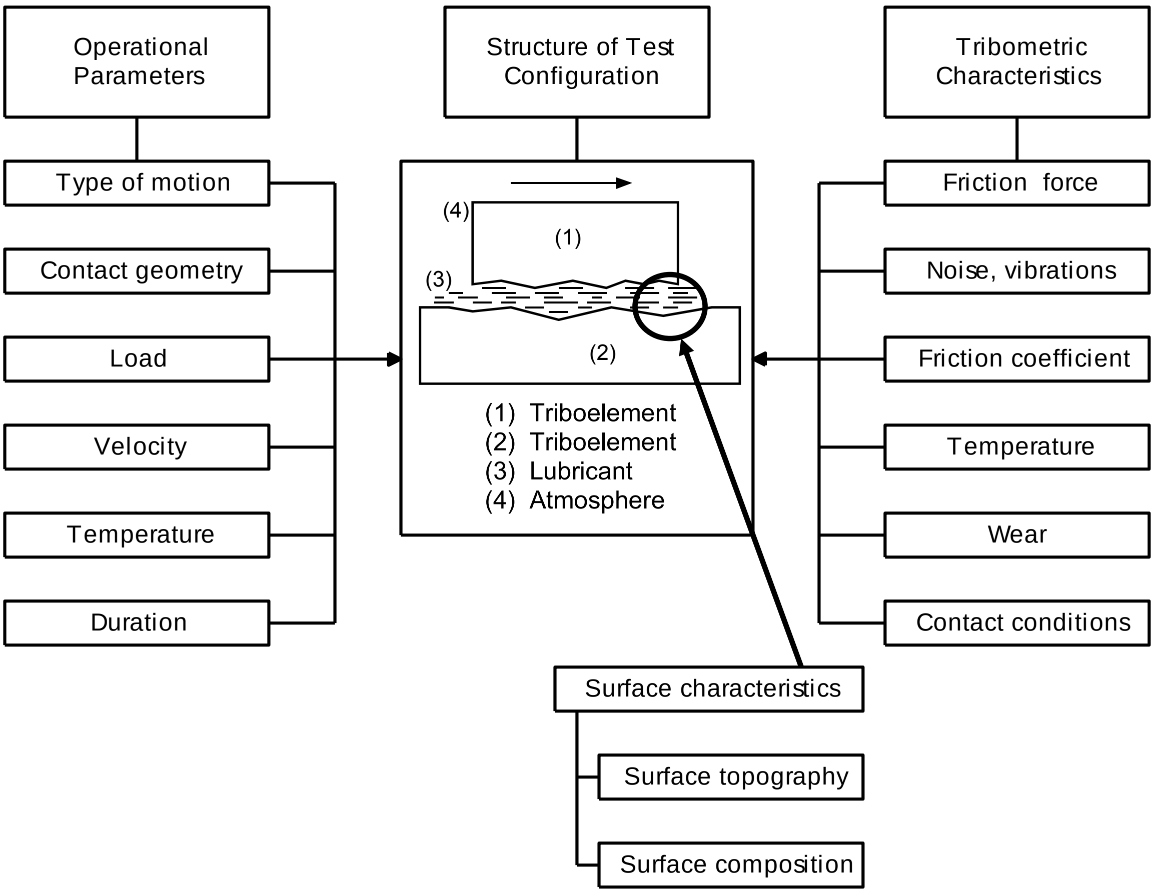


Figure 13: Test design flow chart (adapted from Bayer, 2002)

The design of laboratory wear tests can be carried out using the following process:

1. Select the triboelements: (1) and (2) that will be examined in the tests. For example, if a wheel-on-rail contact was being examined, the wheel and rail would be triboelements (1) and (2), respectively.
2. Select suitable test specimens of triboelements (1) and (2). These could be the complete components, for component testing and upwards, or a smaller piece of sample material, for specimen testing (see table above).

3. Choose a suitable test configuration for the test specimens of triboelement (1) and triboelement (2) and specify the geometry of the test configuration, materials characteristics and properties and surface characteristics. If entire components have been selected for the tests, the testing apparatus must be able to incorporate these. If sample specimens are being used, it may be possible to select a standardised testing set-up.
4. Characterise the interfacial element (3) (for example, the lubricant) and the environmental medium or atmosphere (4) in terms of their chemical nature, composition and chemical and physical properties.
5. Choose a suitable set of operational parameters, including type of motion, load, velocity, temperature and test duration. It may be necessary to control these, via feedback mechanisms. This adds complexity to the test set-up, but will allow more confidence in the test method.
6. Perform the tests as functions of varied structural parameters (e.g. hardness or roughness) and operational parameters (load and velocity, for example). This is more appropriate for exploratory testing.
7. Measure interesting tribometric characteristics, such as friction, wear, temperature rise, noise or vibrations. Decide how these characteristics will be measured. Data may need to be recorded during the testing so appropriate instrumentation will be required.
8. Characterise the worn surfaces. Wear will need to be quantified, by mass loss or geometry change.

It is important to consider the number of tests that are required to obtain good quality results. The number of tests may be constrained by costs and time allocation, so it must be decided whether to test many different configurations of test parameters or to repeat tests at a few configurations to study variability. Using many different configurations will allow the performance of a component or model validation to be explored over a wider range of conditions, but not take into account the possible scatter at one set of conditions. Repeating testing at a few configurations will lead to a higher overall confidence in the results, at the expense of knowledge of the overall parameter space. The parameter ranges selected should reflect the range of possible conditions in the actual application.

It is vital that the condition and preparation of specimens is kept under tight control. Specimen preparation varies depending on the test and the materials involved, but in general surface roughness, geometry, microstructure and hardness must all be controlled. Lack of attention to this detail can cause scatter in the results and a lack of repeatability. It should be noted that the specimen under consideration, the counterface and the wear producing medium, a third body abrasive for example, must all be controlled with equal vigour.

The accuracy of a test simulation can be assessed qualitatively using visual and optical inspection to compare wear features from wear test specimens with those from actual field operation. This can give confidence in the test method. Quantitative information, such as wear rates, can then be considered.

REFERENCES

Adachi, K., Kato, K., Chen, N., 1997, “Wear Map of Ceramics”, Wear, Vol. 203, pp291-301.

Archard, J.F., 1953, “Contact and Rubbing of Flat Surfaces,” Journal of Applied Physics, Vol. 24, No. 8, pp981-988.

ASTM G190 - 06 Standard Guide for Developing and Selecting Wear Tests.

Bayer, R.G., W.C., Clinton, Nelson, C.W., Schumacher, R.A., 1962, “Engineering Model of Wear”, Wear, 5, pp378-391.

Holm, R., 1946, Electric Contacts, Almqvist & Wiksells Boktryckeri AB, Uppsala, Sweden.

Lewis, R., Olofsson, U., 2004, “Mapping Rail Wear Regimes and Transitions”, Wear, Vol. 257, No. 7-9, pp721-729.

Lim, S.C. and Ashby, M.F., 1987, “Wear Mechanism Maps”, Acta Metal., Vol. 35, No. 1, pp 1–24.

Rabinowicz, E., 1981, “The Wear Coefficient - Magnitude, Scatter, Uses”, ASME Paper 80-C2/LUB-4, Journal of Lubrication Technology - Transactions of the ASME, Vol. 103, pp188-194.

Riahi, A.R., Alpas, A.T., 2003, “Wear Map for Grey Cast Iron”, Wear, Vol. 255, pp401-409.

Taki, T., 2007, “Study on Constructing Wear Maps of Gears”, Journal of Japanese Society of Tribologists, Vol. 52, No. 8, pp615-621.

Wilson, S., Riahi, A.R., Alpas, A.T., 2000, “Wear Maps for Manufacturing and Automotive Engineering”, International Symposium on Ecomaterials held in conjunction with the 39th Annual Conference on Metallurgists of CIM, Ottawa, Canada, Aug 22-23.

DATA SOURCES

Textbooks:

Engineering Tribology
G W Stachowiak and A W Batchelor, Butterworth-Heinemann, 2001.

Engineering Tribology
J A Williams, Oxford University Press, 1994.

Tribology
I M Hutchings, Butterworth-Heinemann, 2001.

Wear Analysis for Engineers
R G Bayer, HNB publishing, 2002.