6.3 A METHODOLOGY FOR COATING SELECTION

An improved approach to coating selection should thus allow progressive elimination and lend itself to a computerised implementation. Furthermore, an approach which avoids the identification of one dominant wear mechanism would be desirable. A systematic framework fulfilling these goals is described below. This is intended to provide a basis for minimising the probability of tribological problems by indicating the material property limitations and characteristics needed (Matthews et. al., 1992b).

The approach is based on matching the requirements of the application - what is needed? - with the combinations of properties that can be offered by different coatings - what is possible? - as shown in figure 6.2. The possible solutions are found by progressively eliminating those coatings that do not possess the required combination of properties. In order to achieve a successful marriage between the needs and the possibilities, it is necessary to express the requirements in a way that can be directly compared to the known properties and characteristics of coatings and coating processes. In effect, the component design engineer must translate the requirements into a language that can be understood by the coating process engineer. The different stages of the methodology and how the selection procedure is implemented are shown in figure 6.2.

The purpose of stages 1, 2 and 3 is to derive the correct tribological requirements needed for the match by successively refining the design specification. It is convenient to make a distinction between surface functional requirements (stage 4), non-functional requirements (stage 5) and economic and procurement requirements (stage 6). Various aspects that should be taken into consideration concerning the functional tribological and coating requirements (stages 3 and 4) have been critically discussed by Godet et al. (1991). Brief descriptions of the stages are given below. Examples of the contents of each stage are provided in Table 6.1.

Stage 1: Application and design study. This stage is similar to the early part of all engineering design procedures and involves selection of the global design requirements leading to a general design specification and a definition of the expected working conditions for the complete design (Pahl and Beitz, 1984). The tribologically critical components are identified.

Stage 2: Component specification. The second stage involves a more detailed analysis of the critical components. For each of these, the specific contact and service conditions, such as contact geometries, forces, velocities, environment, etc., and the applicable constraints, such as overall component dimensions and dimensional accuracies, costs, desired lifetime, etc., are specified. It is necessary to distinguish between the part to be considered for coating (designated part 1) and any counterpart (designated part 2) that

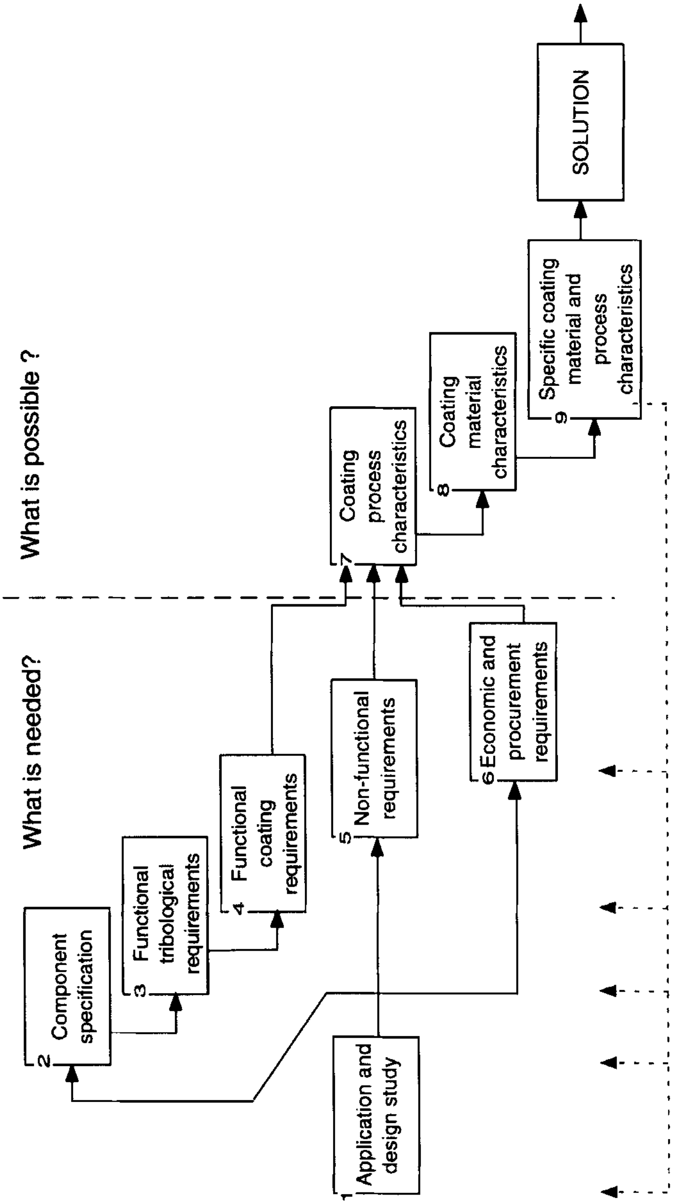


Fig. 6.2. Methodology for tribological coating selection.

TABLE 6.1.

Examples of the information provided at the different stages in the coating selection methodology.

STAGE	EXAMPLES (3 and 4 dependent on the applicable tribological situation)
1.	General working conditions, appraisal of design requirements, overall machinery design, identification of critical components.
2.	Geometry of the contact between parts 1 and 2. Material and surface roughness of part 2. Working environment: abrasive particles, liquid, gas, temperature. Forces on the contact. Velocities involved. Nature of the motion involved. Desired lifetime. Maximum allowable tolerance.
3.	Friction or traction force requirements: initial and steady-state. Noise and vibration. Avoidance of localised plastic deformation, fracture, surface fatigue and fretting. Wear rate.
4.	Yield strength of substrate in relation to the reduced elastic modulus. Thickness requirement for coating. Wear factor in relation to the counterpart. Required coating and substrate hardnesses. Surface roughness. Preferred coating types.
5.	Dimensions and weights of parts to be considered for coating. Maximum allowable dimensional changes associated with the coating or coating process. Thickness tolerance. Finishing requirements. Requirement for the masking-off of certain parts of the component from coating. Requirement for coating to penetrate holes and recesses. Desired surface colour. Preferred coating materials and processes. Any limitations on the substrate material for the coating.
6.	Allowable costs. Delivery time. Availability in-house, locally and worldwide. Legal and environmental constraints.
7.	Partial-coating ability. Penetration ability. Environmental-friendliness. Ranges of possible thickness, precision of thickness, deposition rate, process temperature and relative distortion of workpiece, maximum coatable dimensions, cost per unit surface area, surface roughness change, relative adhesion and permissible substrates.
8.	Ranges of colour, elastic modulus, Poisson's ratio, hardness, wear factor and friction coefficient.
9.	Narrower and combined ranges or specific values for the properties given in 7 and 8.

is involved in the tribological contact. It is assumed that the material of part 2 is pre-specified. The next stage in the methodology is to convert the specifications in stage 2 into requirements of the coatings and coating processes to be considered.

Stage 3: Functional tribological requirements. The functional tribological requirements are those that are essential to the tribological performance of the design and will include noise and vibration limitations as well as friction or traction force requirements and allowable wear-rates.

Stage 4: Functional coating requirements. These are the required limits on the appropriate surface properties, needed in order to fulfill the functional tribological requirements under the applicable service conditions. Typical limits are yield strength and elastic modulus, hardness, surface roughness, thickness of the coating, wear factor etc.

Stage 5: Non-functional requirements. These requirements are not essential to the tribological function of the component but, nonetheless, represent important constraints on the coating materials and processes that can be applied. Examples are the dimensions required to be coated, maximum allowable dimensional changes associated with the coating or coating process, the need to mask-off certain parts of the component from coating, desired surface colour, preferred coating materials and processess etc.

Stage 6: Economic and procurement requirements. Aspects concerning the allowable costs of the final component and the ease with which a coating can be obtained, either in-house or externally, are covered by these requirements. Also included are legal, environmental and availability factors which may prohibit or favour certain coatings or coating processes.

Stage 7: Coating process characteristics. Stages 7, 8 and 9 can be thought of as filters, positively eliminating those coating processes or coatings that are not able to meet the requirements in stages 4, 5 and 6. Stages 7 and 8 can be considered as coarse filters because they are concerned with the invariable characteristics of particular coating processes or coating materials. Stage 7 deals with the process characteristics and property-ranges that are valid for all coatings applied using a certain process such as CVD, PVD or plasma thermal spraying. In this way, if a requirement such as a maximum allowable coating thickness or maximum as-coated surface roughness does not fall within the range that is practically feasible for a particular process, then all coatings applied using this process can be eliminated. If a particular coating material is required, only those processes capable of depositing this material need be considered.

Stage 8: Coating material characteristics. Similar to stage 7, stage 8 concerns coating material property-ranges and characteristics that, for practical purposes, can be considered to be independent of the coating process used. For example, the hardness of titanium nitride typically lies between 1500 and 2500 kgmm^{-2}, irrespective of whether a CVD or a PVD process is used. Similarly, the elastic modulus of this material will probably not vary greatly with the deposition process utilised.

Stage 9: Specific coating material and process characteristics. This stage is in some respects a refinement of stages 7 and 8, dealing with the property-ranges and characteristics for specific coating material-process combinations. In this way, a differentiation can be made between the property-ranges of similar coatings deposited by different processes or varied conditions.

The most difficult aspects of the methodology involve the specification of the required tribological behaviour of the surface (stage 3) and the conversion of this information into surface property requirements (stage 4). We have earlier seen that tribological quantities such as friction coefficient and wear rate are strongly influenced by the tribological system, depending not only on the natures of the interacting surfaces involved in the tribological contact, but also on system conditions including forces, velocities, temperature, atmosphere, etc.

The system parameters are often variable and are not mutually independent, adding further complexity to the problem of predicting tribological behaviour. It is therefore not surprising that, in spite of intensive research, there are many questions in connection to the relationships between material surface properties, tribological system conditions and tribological behaviour which are still today unclear.

However, it is still possible to define which material surface properties influence the tribological mechanisms occurring and are therefore important in determining the friction and wear behaviour of coated surfaces. This subject was reviewed in chapter 3 and on that basis the following parameters can be considered to be of importance:

- Young's modulus and Poisson's ratio of the coating and substrate.
- Yield and tensile strength of the coating and substrate.
- Shear strength of the coating and of the coating-substrate interface.
- Thickness of the coating.
- Roughness of the mating surfaces.
- Shear strength and thicknesses of any microfilms present on the coating surface or generated during service.

Ideally the design values for the above properties would be derived from knowledge of the required wear rate and friction coefficient and the known service conditions.

However, for the reasons outlined previously, the general understanding of the tribological phenomena involved, in addition to the theoretical models concerning the contact mechanics of layered surfaces, are not yet at a stage that enables comprehensive relationships to be derived from fundamental principles. Moreover, data on several of the properties listed above, in particular interface shear strengths and properties of microfilms, are not available for the majority of coatings.

An alternative approach is to combine some of the more practically-applicable contact mechanics theories with rules of thumb that, although not yet fully explainable on theoretical grounds, are nonetheless well established with tribological design engineers. Such an approach to tribological design has been suggested previously (Thijsse, 1989) and has been further developed (Matthews et al., 1993). The intention of this approach is not to calculate the exact property requirements but rather to provide, with a reasonable safety margin, a reliable indication of the material property limitations and characteristics needed. This enables the design engineer to effectively minimise the probability of tribological problems occurring in service.

6.4 SELECTION RULES

The design methodology described above is founded on a number of practical design rules, each of which has one or more materials selection criteria associated with it. Depending on the design situation one, or more commonly several, of these rules are appropriate. By applying the rules successively, the materials selection requirements are progressively refined. The methodology can accommodate many of the possible general tribological problems that occur in practical design situations. The selection of which rules are appropriate for a particular design situations is based on the following factors:

- The service conditions under which the component is required to perform, including the type of relative motion between the surfaces.
- The limitations of the rules.
- The constraints imposed by the application of the materials used.

It is very important to note that the methodology is based on the rules which relate to the classification of the contact type or types, not to the identification of a dominant wear mechanism. This approach recognises that more than one wear mechanism may occur in a given contact.

The following rules have been identified using contact conditions illustrated in figure 6.3.

Rule 1. Contact stresses

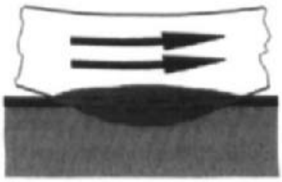
Rule 2. Sliding

Rule 3. Surface fatigue

Rule 4. Fretting

Rule 5. Abrasion

Rule 6. Impact



Rule 7. Chemical dissolution

Fig. 6.3. Tribological contact conditions covered by the coating selection methodology rules.

Rule 1: Contact stresses. The most important criterion that must be satisfied by the contacting materials in many potential wear situations is that plastic deformation or fracture in the contact region must be avoided under both stationary and moving conditions. In the case of coated and surface treated materials, this also applies to the substrate material. If considerable plastic deformation or fracture does occur, severe wear is likely to take place from the onset of motion (Tangena, 1987). This does not include failure of roughness peaks, which is inevitable in most contact situations.

Coated and surface-treated surfaces require special consideration because the mechanical properties are non-isotropic. The variation in these properties with the depth from the surface must be taken into account. Separate consideration is required for the following 3 situations:

- Uncoated and untreated materials where the yield strength (σ_y), the elastic modulus (E) and Poisson's ratio (ν) are independent of the depth from the outermost surface.
- Surface treated materials where σ_y is dependent on the depth from the outermost surface but E and ν can be considered for practical purposes to be independent of the depth.
- Coated and surface treated materials where σ_y, E and ν are all dependent on the depth from the outermost surface.

The rule is based on the theory and analytical solutions developed by Johnson (1985) and Hamilton and Goodman (1966). For coated surfaces, use is made of the analytical solutions provided by Leroy and Villechaise (1990). It is important to note that the minimum allowable strengths for materials calculated in this rule are not intended to be used to provide accurate estimates of the maximum stresses actually occurring. Because the rule is intended for design purposes, the "worst case" situation is used as the basis for the calculations.

Rule 2: Sliding. To practising design engineers, it is often the lifetime of the component, defined by the wear rate, rather than the physical background of the wear that is important. We have seen earlier that wear and friction behaviour depend greatly on the specific tribological system of the application. Nevertheless a useful indication of whether or not wear problems are likely to occur in practice, without differentiating between wear mechanisms, can be obtained by using the wear factor proposed by Archard (1980).

Depending on the test method used, laboratory tribological tests carried out under appropriate consistent conditions can provide the required information. An important prerequisite, valid both for the test data and for the design situation, is that plastic deformation or fracture in the contact region must not take place under conditions of stationary contact. The criteria contained in the contact stresses rule (rule 1) must therefore have been satisfied.

Collections of tribological data are available in numerous publications (e.g. Bhushan and Gupta, 1991). The values of the wear factors and friction coefficients must be considered as approximate rather that absolute. However, approximate values are, in practice, sufficient to ensure that a component is designed with a safety factor great enough to avoid the occurrence of tribological problems.

It is necessary to compare the maximum permissible wear factor with the probable wear factors of different material combinations under similar conditions. Although the latter data must be available to the designer, it is possible in some cases to modify the data according to knowledge of the approximate effects of changing different elements of the tribological system.

<u>Rule 3: Surface Fatigue.</u> Surface fatigue is a complex phenomenon influenced by a large number of factors such as surface roughness and defects, shape, coarseness and distribution of carbides and inclusions. However, empirical relationships between the contact stress, the lubrication regime, the number of cyclic load changes, the composition and the hardness of steels can be compiled from data available in the literature (Neirmann, 1960; and Rowe and Armstrong, 1982). Practical experience has shown that these relationships can be used successfully as a design tool to minimize the chances of failure occurring due to surface fatigue.

The maximum shear stress in a rolling contact is, in the majority of engineering design situations, located some ten to hundred micrometres below the surface. In addition, when the roughnesses of the surfaces are taken into account, it has been shown by Sainsot et al. (1990) that for hard thin 10 to 20 μm thick coatings on soft substrates, the highest stresses tend to be concentrated at the interface between the coating and the substrate. Because the properties change in a discontinuous way at this interface, extra stresses can be present and there is a greater probability of crack initiation. This would indicate that, in order to minimize the probability of surface fatigue, reliable solutions can be hard to find when applying hard wear-resistant surface coatings deposited by PVD and CVD processes, for which the maximum thickness attainable is of the order of ten microns, as for a single TiN layer on steel. Diffusion processes such as carburising and nitriding, which introduce compressive stresses and produce thicker surface layers, are generally more beneficial. Recent research suggests that very thin, with a thickness even less than 0.1 μm, hard PVD coatings may be advantageous also, as discussed in chapters 4 and 7.

<u>Rule 4: Fretting.</u> If the surfaces of two parts in contact oscillate in a tangential direction

with a small amplitude compared to the dimensions of the contact, the wear particles formed cannot be released from the contact. Subsequent oxidation of these particles will increase the total volume of material in the contact area, through which there is a possibility that the system will jam. Furthermore, the surface will be roughened by the fretting process, which increases the possibility of fatigue.

Fretting wear or fretting corrosion can occur in electrical switch contacts, mechanical detachable joints such as press-fitted, bolted or rivetted joints, and in precision-engineering constructions which are digitally-controlled and exhibit limit-cycling. The results of fretting are loss of fit in mechanical joints, seizure or high friction in moveable joints and high electrical resistance in electrical contacts.

The low-amplitude movements necessary for fretting to occur can originate from undamped machine vibrations, electronic position control or thermal expansion-contraction effects. In order to minimize the chances of problems occurring in a potential fretting wear situation, use can be made of certain coatings and surface treatments which have been proven to provide effective solutions. Examples are phosphating and sulphiding treatments, MoS_2 coatings and ceramic coatings. In the latter case, both surfaces would normally require coating.

Rule 5: Abrasion. Rules are under development to indicate the properties required to resist abrasion, which take into account parameters such as particle velocity, size and shape etc. One such rule deals with the specific case when foreign particles, not originating from wear in the contact, are present in the contact. This is based on simple rules of thumb (Eyre, 1992), which are applied by practising tribological design engineers. It provides a minimum surface hardness requirement and, in the case of coatings, a thickness requirement. When this hardness requirement cannot be met by the available coatings, the non-proportionality between hardness and abrasion resistance, which is observed when comparing different material types, is approximated using empirical relationships compiled from published data (Krushov, 1974).

Rule 6 : Impact. The maximum value of the contact pressure occurring in a contact as a result of an elastic impact between two massive bodies can be estimated from published contact mechanics theory (Johnson, 1985).

Rule 7 : Chemical dissolution. Wear due to the chemical effects of dissolution and diffusion can be accomodated by using rules such as those developed by Kramer and Suh (1980). The wear dealt with here is typically that occurring in metal cutting and at high temperature contacts, where chemical processes become dominant.

6.5 EXPERT SYSTEMS

The methodology described here represents an evolving model, which will be refined and perfected as improvements in coatings and our knowledge of their tribological behaviour occur. Also the availability of computer hardware and software with ever greater capabilities will enable considerable strides to be made in overcoming the coating selection problem.

In particular, the development of computer expert systems (also called knowledge-based systems) will have an increasing impact. Expert systems are defined as computer programmes which are specifically developed to encode expert knowledge and make it easily available to the user, often in a conversation mode. Over the past 20 years specific programming languages, such as LISP (McCarthy, 1962) and PROLOG (Clocksin and Mellish, 1981), have been developed which are particularly suited to this purpose. Today expert systems are extensively produced on advanced non-dedicated computer languages such as C++. Also, commercial programming shells (Harmon, 1988) are now commonly available. They facilitate rapid system development by the provision of a neutral problem solving system, which can be adapted to any requirement by the addition of domain-specific rules.

Unlike conventional hard wired programmes, most expert systems have a separate reasoning module or interpreter, which manipulates knowledge to reach a conclusion. This allows the knowledge base, e.g. containing coating property experience, to be stored separately in the programme. The difference between a conventional programme and an expert system is illustrated by figure 6.4.

Because the knowledge is separate from the inference procedure the information can be updated easily without rewriting the whole system. The knowledge used for a consultation and the decision path can be monitored, to provide an explanation for any decisions reached. This latter point is especially important if designers are to have confidence in the system.

There are two main kinds of knowledge in an expert system. The first is the hard data, for example material properties. The second knowledge comprises the heuristic rules or specialist expertise used in the methodology of selection. An everyday illustration of this distinction is that of the taxi driver. The map of the city is the basic data, while the heuristics are represented by his knowledge of the relative merits of alternative routes under the likely conditions of traffic at various times.

There are many computer programs which are described as expert systems but which are merely database systems with only the first type of knowledge. Of course one of the problems encountered in constructing a knowledge base is acquiring or eliciting the expert knowledge, most of which will be diffuse and in the head of the expert. Given that the expertise can be obtained, the problem remains of how to represent it in the computer. Many forms of representation techniques are available to the system builder. RULES are the most common method of representing knowledge, but FRAMES are often used to assign particular attributes to knowledge elements. SEMANTIC NETS are used in conjuction with FRAMES to represent the relationship between one frame and another, such that the logical model of the problem can be extended. Further information on knowledge elicitation and representation can be found in Jackson (1990).

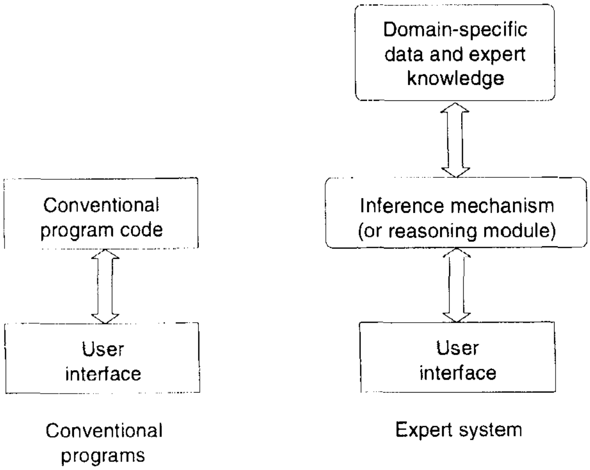


Fig. 6.4. Comparison of a conventional computer program and an expert system.

Despite the large volume of literature published about expert systems, very little has been written about the use of such systems for coating selection. There exist several database systems for materials selection but considerably fewer knowledge-based ones (Tallian, 1987). Database systems generally only perform searches of materials based on data sets entered by the user, returning materials whose specifications match or exceed those entered. Expert or knowledge based systems are generally characterised by their ability to avoid asking for unnecessary data input and the inclusion of some form of selection procedure rather than a simple search.

Brief details of systems of relevance are listed in table 6.2. Of these the following can be described as on-line databases (i.e. they are accessed remotely): CETIM, COMETA,

TABLE 6.2.

Some current expert systems and data bases.

Name	Subject	Type	Host	Number of Materials
ACHILLES	Corrosion resistance	Rule-based	UNIX/PC	
ARMES	Mineral pro	Rule-based	PC	
CAPS/CAMPUS	Polymers	Database	PC	5000
CETIM	Material selection	Database	Remote	6000
COATING SELECTOR	Painting practices for ferrous metals	Rule-based	PC	40
COMETA	Power industry components	Database	Remote	200
DIXPERT/ROTA	Rotating machinery failure prediction	Rule-based	VAX	
EPOS	ICI Plastics grades	Database	PC	570
H-DATA	Hydrogen/metal interaction	Database	Remote	
HTM-DB	High temperature materials	Database	Remote	10000
INFOS	Metal cutting data	Database	Remote	32000
MATUS	Material supplier information	Database	Remote	10000
MDF/1	Published metal and alloy data	Database	Remote	25000
METSEL 2	Metal selector	Database	PC	100
MPR SELECTOR	PM material database	Database	PC	500
PAL	Adhesive selector	Rule-based	PC	300
PERITUS	Materials selector	Database	Remote or PC	1500
PLASCAMS	Plastics selector	Database	PC	350
POLYMAT	Polymer materials	Database	Remote	6000
PRIME	Process industry corrosion materials	Rule based	UNIX	
SOLMA	Castings, forgings and rolled parts	Database	Remote	10000
STICK	Adhesives selection	Knowledge based	PC	80
THERMODATA	Thermodynamic data	Database	Remote	35000
TRIBEXSY	Tribology	Rule-based	Remote	
TRIBSEL	Wear resistance	Rule-based	PC	

H-DATA, HTM-DB, INFOS, MATUS, MDF/I, POLYMAT, SOLMA, THERMODATA, PERITUS. The following are primarily stand-alone databases: CAPS/CAMPUS, COATINGS SELECTOR, EPOS, METSEL 2, MPR SELECTOR, PLASCAMS, STICK.

Some expert systems in the tribology field are described below:

TRIBSEL (Hull University). A number of coating selection expert systems have been developed at the University of Hull over the past ten years. Each one has to some extent been a development of earlier systems (Matthews and Swift, 1983; Syan et al., 1986 and 1987; and Matthews et al., 1991b). The initial work tended to emphasise the identification of wear mechanisms, and to apply mathematical models. In practice the number of occasions when a strictly mathematical approach to selection can be utilized was found to be very limited. Even the metal cutting situation, which is well documented and was thought to be covered by only two dominant wear mechanisms, has been found to be difficult to model (Kramer and Judd, 1985). Given these facts it was necessary to devise a system which could short-circuit the need to identify the wear mechanisms.

The system used an approach based on 15 main criteria which were found to be inherent in the reasoning processes carried out by human experts. These criteria are listed in table 6.3.

Of course, these cannot be fully specified by just 15 questions, and 31 factors were identified which together sufficiently define all of the criteria. These are broken down into 5 factor groups:

(1) operating constraints,
(2) processing constraints,
(3) geometrical constraints,
(4) topographical constraints and
(5) economic constraints.

Three sample rules are given in table 6.4.

The approach used has been to consider coating and treatment technologies in generic groups. A consultation will start with the hypothesis that all of these will be suitable. As the user supplies information about a particular application the system uses the rules in its knowledge base to reject any that are unsuitable. Thus the process is one of progressive elimination, which as mentioned earlier is considered desirable.

TABLE 6.3.

Criteria used in coating selection.

Operating temperature
Operating environment
Counterface material
Counterface hardness
Substrate material
Substrate hardness
Contact pressure
Contact geometry
Relative motion type
Relative speeds
Surface finish
Component size and shape
Coating thickness and uniformity
Quantity of parts
Economics, including versatility

Within the heading of operating constraints come factors such as the maximum or minimum operating temperature, the operating environment, contact type (point, line, etc), and loading type (rolling, sliding, impact, etc). In essence the system is based on an enormous amount of case history information, as recalled by several human experts after a lifetime of experience. This information was extracted by asking them when particular coating or treatment types were or were not successful. An advocate of the wear mechanism identification approach might argue that the questioning in this factor group category is merely identifying the likely wear types. At no point, however, is such information requested from the computer, neither does it possess any knowledge of wear mechanisms per se.

Certain coatings are eliminated because of their nonsuitability for the operating constraints imposed by the processing method. These include factors such as the maximum dimension of the component which can be coated, the processing temperature and its possible influence on the component, and production capability factors such as the throughput required.

Next come geometrical constraints, such as the coating uniformity and re-entrant penetration capability of the process. These are followed by questions relating to the topographical constraints which cover aspects such as the surface finish requirements.

TABLE 6.4.

Sample rules from TRIBSEL coating selection expert system.

Operating environment rule:	Material constraint rule:	Geometrical constraint rule:
if operating temperature is < 200 degrees C *and not* solid erosion *and not* liquid erosion or cavitation *then* mechanical surface working is a possible choice	*if* ferrous material *and* substrate surface finish < 6 microns *and* counterface hardness < 800 VPN *then* carburising is a possible choice	*if* melting temperature > 1000 degrees C *and* re-entrant capability < 0.5 *and not* complex shape category *then* welded carbide is a possible choice

When particular coatings or treatments cannot meet the needs indicated by the designer under each of these headings, they are rejected. The designer can ask why a particular question is being asked, and the system will respond by explaining the particular reasoning path it is using at that time. It will ultimately provide a list of coatings or treatments that will satisfy all of the indicated demands - or if none exist it will respond accordingly. The system has relative cost information encoded and information about economic quantities and availability which is also available to the designer. A case history file of similar applications is also incorporated, which the computer will display if it meets an application which it has seen before.

Development of the TRIBSEL system has been superceded by other systems (e.g. PRECEPT) which build on the methodology described earlier, in effect combining the heuristic approach used in TRIBSEL with the best available theoretical models which predict tribological behaviour.

DIXPERT system (Technical Research Centre of Finland). DIXPERT (Holmberg et al., 1989) is an expert system for diagnosis and prediction of failure in rotating machinery. Seventeen different classes of fault and their remedies are included. DIXPERT has direct data input from sensors attached to the machine of interest, as well as a conventional user interface. DIXPERT is rule based and is written in LISTP with the expert system toolkit EPITOOL running on a VAXstation.

PRECEPT system (Hull University, Lucas Engineering and Systems, CETIM and Philips). These organisations combined to build on their respective expertise in expert systems and material, coating and treatment selection. The system is concerned with engineering component properties for resistance to fatigue, wear, corrosion and localised plastic deformation. This is intended to improve the quality of design and specification of mechanical components used typically in aerospace, automotive, electrical, electronic and textile industries. The intention is to develop a methodology which makes full use of a set of case studies and to encapsulate the results in a knowledge based system to assist design engineers in both small and medium enterprises and large manufacturing industries. The project has produced prototype systems for evaluation by potential users (Robinson et al., 1993).

TRIBEXSY system (Philips). The Philips TRIBEXSY tribological consultation system is designed to remove the need for an interview with the tribology expert when a wear problem arises. TRIBEXSY's dialogue based approach guides the user through an analysis of the symptoms of the wear problem, by asking questions about the materials involved, their operating environment, the nature of the contact regime and the appearance of the damage to the components. This leads to an identification of the type of wear taking place. The program then searches for possible ways of overcoming the wear problem, by suggesting the use of different materials, coatings and lubrication regimes. As before, the user is asked questions about operating conditions and component geometry, in addition to being questioned as to the possible use of alternative materials and slight design changes.

TRIBEXSY may also be used for consultation in a design situation before a problem arises, although as with all expert systems, the more often unknown is entered in response to the system's questioning, the less reliable will be the solutions proposed. TRIBEXSY is text-based, and runs on a VAX system via remote terminals.

PRIME system (Leuven University). PRIME is an acronym for PRocess Industries' Materials Expert (Vancoille and Bogaerts, 1986). The PRIME system is intended to select materials to resist corrosion in process industry applications. It is graphics-based, and intended to be developed as an extension to CAD systems running in a UNIX environment. PRIME's user interface is a combination of selecting icons, menus and entering data. Three groups of data entry are available, none of which need be entered if they are unknown. The groups are as follows: industry, process or operation data (details of the type of industry narrows the search area), operating environment data, and equipment data, which allows the specification of the type of component in general terms. PRIME allows the user to specify two words for when a component , for example a heat exchanger pipe, is exposed to different environments at the same time. PRIME's rule base is divided into shallow and deep, and the level of searching is user definable.

Shallow rules are those which are easily found in material data books for example, while deep rules are those less easily defined, such as economy or availability. The programme may be questioned as to the reasoning behind its conclusions.

ACHILLES (Harwell/NPL). The ACHILLES system has been developed at the Metals Technology Centre at the United Kingdom Atomic Energy Authority at Harwell, in conjunction with the National Physics Laboratoy (Wright et al, 1987). ACHILLES consists of a suite of eight expert system modules to help the designer choose materials, carbon and stainless steel, to operate in corrosive environments. Modules contain information for specific areas of the corrosion domain, for example cathodic protection or sea water corrosion. ACHILLES is a menu driven system using both text and graphics, running on a PC. The user is presented with a series of multiple choice questions, starting with the industry and environments being considered, moving on to detailed operating parameters such as the components and materials to be considered and their chemical environment.

ARMES system (AMIRA). ARMES has been developed for the Australian Mineral Industries Research Association to provide advice on the type of wear resistant facing material to be used for a given mix of operating conditions in the mineral processing industry. The ARMES demonstration version runs on a PC in text only, although character based graphics are used, written using the EXSYS system shell. The user is required to enter, in an interactive mode, details of the material being handled and, since the field of use of this system is quite narrow, the type of component under consideration. The questions asked by the system will depend on the responses of the user.

ARMES contains a database of mineral ore and wear-resistant facing material properties and a rule base by which the two are matched. The system provides a recommended material and a second choice, with costs of both. ARMES' rules are expressed in the IF-THEN-ELSE format, using backward chaining to arrive at a solution. The EXSYS shell allows probabilities to be attached to rules, so that an indication of the confidence in the solution may be derived. Context sensitive help is available in ARMES so that the user may request an explanation of any question asked. It is possible to answer unknown to questions, thereby indicating uncertainty.

6.6 CLOSING KNOWLEDGE GAPS

The authors, in their roles as coatings researchers, are often asked to advise on the selection of a suitable coating to fulfill a given operating need, often as a means of solving a wear problem which has arisen due to poor tribological design.

Engineers, materials scientists and others who seek from coatings the same kind of easily specified performance and reliability parameters they achieve with a material chosen for its bulk strength, are often frustrated by the apparent variability associated with selecting a surface coating. The reasons for this are twofold. One is the difficulty in understanding exactly what the contact conditions are, e.g. in terms of reaction products, operating pressures and temperatures. The second is the lack of comparative data about specific coatings. The successful consultant in this field is the one with the broadest experience of different coatings and specifically the conditions under which they will and will not operate.

It seems that advanced computer and programming techniques such as expert systems can help in the coating selection problem. One reason for this is that they can encode the knowledge of many experts. However, this cannot be the only solution - otherwise new untried coatings would never be specified. There is the clear need to bring together the separate skills of the coatings process developer, the coatings evaluator and the tribological modeller to design and optimize coatings to meet preset needs, with well defined quality and reliability. In this way the potential of tribological coatings will be fully achieved, to the benefit of a wider range of application sectors. Some of those sectors currently benefitting are reviewed in the following chapter.