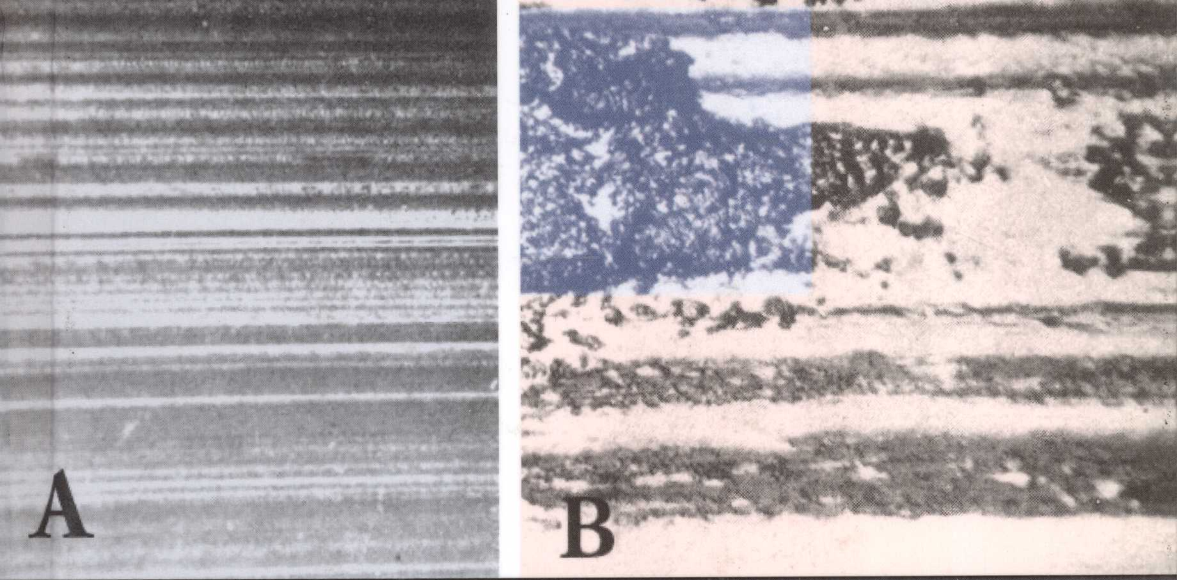
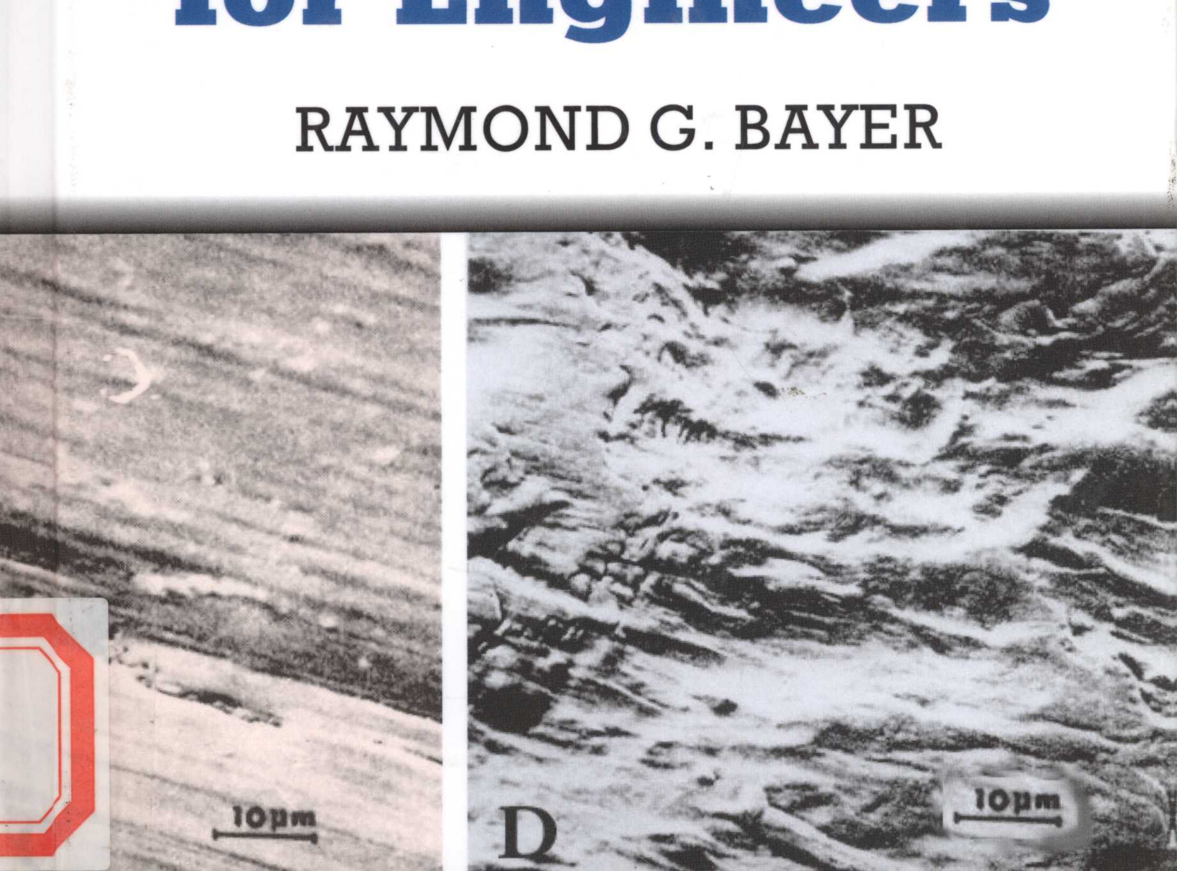


Wear Analysis for Engineers

RAYMOND G. BAYER



Wear Analysis for Engineers

RAYMOND G. BAYER

Tribology Consultant
Vestal, New York

HNB Publishing • New York

To my wife, Barbara

Library of Congress Control Number: 2001097043

ISBN: 0-9664286-5-X

The publisher offers discounts on this book when ordered in bulk quantities.

HNB Publishing
250 W. 78th St., #3FF
New York, NY 10024
www.hnbpub.com

Current printing (last digit):

10 9 8 7 6 5 4 3 2

PRINTED IN THE UNITED STATES OF AMERICA

Preface

Like other types of analysis commonly used in engineering, wear analysis is fundamentally the use of equations and models to evaluate wear behavior. However, for it to be effective, wear analysis must incorporate certain elements and considerations beyond the evaluation of equations. In this book I describe a wear analysis methodology that incorporates these elements and considerations. While wear behavior is complex, useful wear analyses often are not. Generally, the complexity and rigor of the analysis depend primarily on the engineering needs and secondarily on the wear situation. It has been my experience that simple and basic wear analyses, conducted in the proper manner, are often adequate in many engineering situations. Integral and fundamental to the wear analysis approach is the treatment of wear and wear behavior as a system property. As a consequence wear analysis is not limited to the evaluation of the effects of materials on wear behavior. Wear analysis often enables the identification of nonmaterial solutions or nonmaterial elements in a solution to wear problems. For example, changes in or recommendations for contact geometry, roughness, tolerance, and so on are often the results of a wear analysis.

The wear analysis process and the trends in tribological behavior described in this book are based on experienced gathered over 40 years of utilizing this method to resolve and avoid wear problems in a wide range of machines. Based on personal experience, this wear analysis method has been successfully applied to wear situations as diverse as those in modules containing computer chips to wear problems in engines and agricultural equipment. It has been used for devices sensitive to small amounts of wear but expected to withstand hundreds of millions of operations, as well as mechanisms less sensitive to wear or expected to withstand only a few hundred or so operations. Some of these applications are described in Chapter 8, as well as in my previous book, *Mechanical Wear Prediction and Prevention* (Marcel Dekker).

This book is intended to explain the wear analysis method and its implementation and to provide sufficient information for the performance of most wear analyses. It is intended primarily for engineers. The wear analysis process and the implementation of its various elements are described in the first chapter. Case study examples of wear analyses are presented in the final chapter. Basic information generally needed for the proper conduction of a wear analysis is provided in the intervening chapters. Chapter 2 contains a summary of general tribological behavior and generic descriptions of the significant phenomena involved. The general influence of operational conditions and design parameters on wear behavior and phenomena are also described in this chapter. Chapter 3 covers methods used in the examination phase of a wear analysis. Chapter 4 treats two methods of classification of wear situations that are useful in conducting wear analyses, particularly in identifying significant parameters and relevant models. General analytical relationships for wear and wear models, which are applicable to most wear situations, are discussed in Chapter 6. Chapters 5 and 7 contain a variety of additional information that is often significant in the conduction of a wear analysis. Chapter 5 focuses on phenomenological aspects. Chapter 7 focuses on specific wear situations that are frequently encountered in practice, such as galling and fretting.

Several appendixes are provided to facilitate the application of the wear analysis method. Appendix I contains contact stress equations for various geometries. The remaining appendices contain tables of experimental wear coefficients gathered from various sources.

The detail of tribological information provided in this book is intended to be adequate for typical wear analysis. There are situations where more detailed or more extensive information is required for the analysis. Numerous references are provided for this purpose. I have found the following to be good sources of additional information for wear analysis. *Handbook of Tribology*, B. Bhushan & B.K. Gupta, McGraw-Hill, is a good source of material data; *Friction, Wear, and Lubrication Technology, Vol. 18, ASM Handbook*, P. Blau Ed., ASM International, is a good source for data and for a description of tribological behavior in different applications. *Mechanical Wear Prediction and Prevention*, R. G.

Bayer, Marcel Dekker, is a good source for general tribology, detailed cases studies, testing, and modeling.

I am grateful to all of those organizations (cited by Reference number in the figure legends and table footnotes) that granted permission for reproduction of numerous figures and tables.

Raymond G. Bayer

Contents

Preface *iii*

Chapter 1 THE WEAR ANALYSIS METHOD **1**

1.1 WEAR ANALYSIS OVERVIEW **1**
1.2 THE WEAR ANALYSIS PROCESS **3**
1.2.1 Examination 4
1.2.2 Characterization 5
1.2.3 Modeling and Evaluation 7
1.2.4 Testing 11
1.3 PROCESS IMPLEMENTATION **13**
1.3.1 Problem-Solving Situation 13
1.3.2 Design Situation 16

Chapter 2 BASIC TRIBOLOGY **19**

2.1 SYSTEM CONCEPT **24**
2.2 WEAR MECHANISMS **29**
2.2.1. Adhesive Mechanisms 32
2.2.2 Single-Cycle Deformation Mechanisms 37
2.2.3 Repeated-Cycle Deformation Mechanisms 41
2.2.4 Chemical Mechanisms 44

2.2.5 Thermal Mechanisms 48
2.2.6 Tribofilm Mechanisms 48
2.2.7 Coexistence and Interaction of Mechanisms 52
2.2.8 Mild and Severe Wear 54
2.3 FRICTION 57
2.4 LUBRICATION 62
2.5 WEAR SITUATIONS 72
2.5.1 Sliding 72
2.5.2 Rolling 76
2.5.3 Impact 80
2.5.4 Abrasive Situations 85
2.6 DESIGN FACTORS 92
2.6.1 Mechanical 93
2.6.2 Material 104
2.6.3 Lubrication 117
2.6.4 Environmental Considerations 119

Chapter 3 EXAMINATION METHODS 126

3.1 TRIBOSYSTEMS 126
3.1.1 Macrotribosystems 128
3.1.2 Microtribosystems 130
3.2 WEAR 133
3.2.1 Wear Scar Features 134
3.2.2 Examination Techniques 139
3.3 OPERATING AND DESIGN CONDITIONS 146
3.3.1 Analysis Without Worn Parts 147
3.3.2 Analysis With Worn Parts 149
3.4 SUPPLEMENTARY EXAMINATIONS AND COMPARISONS 150

Chapter 4 CHARACTERIZATION METHODS 152

4.1 OPERATIONAL CLASSIFICATION 156
4.2 MECHANISTIC CLASSIFICATION 158

Chapter 5 PHENOMENOLOGICAL CONSIDERATIONS 164

5.1 TRIBOLOGICAL TRENDS 165
5.2 PIVOTAL FEATURES 168
5.3 LUBRICATION 170
5.4 MATERIALS 172
5.5 DATABASE USE AND TESTING 173
5.6 WEAR SEVERITY 174

Chapter 6 ANALYTICAL METHODS **181**

6.1 WEAR RELATIONSHIPS 181
6.1.1 Sliding 182
6.1.2 Rolling 204
6.1.3 Impact 211
6.1.4 Abrasion 224
6.2 DATA ANALYSIS 226
6.3 ALTERNATIVE MODELS 229

Chapter 7 SPECIAL CONSIDERATIONS **232**

7.1 CONTACT CONDITIONS 233
7.2 FLUID LUBRICATION 235
7.3 COATINGS AND SURFACE TREATMENTS 238
7.4 JOURNAL BEARINGS 239
7.5 FRETTING 244
7.6 GALLING 247

Chapter 8 WEAR ANALYSIS EXAMPLES **253**

8.1 DESIGN TRIAGE FOR SLIDING WEAR 253
8.2 ELECTRO-EROSION PRINT HEAD 256
8.3 FLUID TRANSFER SYSTEM LUGS 267
8.4 INJECTION VALVE 276
8.5 DISK DRIVE BEARING 285

Appendixes **295**

A.I EQUATIONS FOR CONTACT STRESS AND AREA . . . 295
A.II NOMINAL K-FACTORS AND FRICTION COEFFICIENTS 300
A.III ZERO-WEAR FACTORS AND COEFFICIENTS OF FRICTION FOR SLIDING 312
A.IV K-FACTORS AND P-V LIMITS FOR PLASTICS 322
A.V GALLING THRESHOLD STRESS 325

References *333*

Glossary of Wear Mechanisms *344*

Index *351*

1 The Wear Analysis Method

1.1 WEAR ANALYSIS OVERVIEW 1
1.2 THE WEAR ANALYSIS PROCESS 3
1.2.1 Examination 4
1.2.2 Characterization 5
1.2.3 Modeling and Evaluation 7
1.2.4 Testing 11
1.3 PROCESS IMPLEMENTATION 13
1.3.1 Problem-Solving Situation 13
1.3.2 Design Situation 16

1.1 WEAR ANALYSIS OVERVIEW

Wear analysis is an engineering method that can be used to resolve wear problems with existing equipment and wear concerns with new designs. The method can be applied to any type of wear and can be used in a variety of engineering situations. Several types of situations where the method has been found to be useful are given in Table 1.1.1. The basic concept of the method is to develop a model for the wear situation and use that model to select design parameters to obtain satisfactory wear performance. Models of varying degrees of completeness and approximation are used, depending on the purpose for which the analysis is done and the complexity of the wear situation.

Table 1.1.1 Engineering Situations for the Use of Wear Analysis

- Occurrence of reduced wear life in established hardware
- Wear life differences in different installations
- Poor or unacceptable wear life with prototype or development hardware
- Evaluation of the effect of design change
- Evaluation of the effect of new or extended applications
- Design of new equipment
- Design enhancement

A wear analysis process is comprised of a blend of theoretical and experimental techniques that involve the consideration of both qualitative and quantitative aspects of wear behavior. While a wear analysis may include the use of wear tests to evaluate materials for an application, such tests are not intrinsic to the methodology. Effective wear analyses may often be performed using only available material data without the need for materials evaluations, which is a desirable feature in many engineering situations. Further, the method does not simply focused on material replacement as a means of resolving wear problems. Wear analysis involves the consideration of all the factors that can affect wear behavior in a given situation, including material selection. As a consequence the method can be used to identify and evaluate non-material factors, which may be changed to resolve or avoid a wear problem. For example, the wear analysis may lead to a change in contact geometry, assembly procedures, or lubricant supply method, or the elimination of extraneous motions to obtain adequate wear performance. In cases of erosion wear analysis might include changes to eliminate undesirable features of the fluid flow.

While material wear tests are not an essential element of a wear analysis approach, it is essential to use quantitative wear data and mathematical relationships. These are used to aid in obtaining an understanding of the wear situation and the identification of a resolution, as well as providing a basis for the model. In typical engineering situations very rudimentary and approximate wear relationships and data analysis techniques are generally adequate for these purposes. The use of these is emphasized in the approach. However, the method does allow the use of more complex and specific relationships and more sophisticated data analysis techniques when required by the nature of the wear situation or the goals of the analysis.

1.2 THE WEAR ANALYSIS PROCESS

Conceptually, the wear analysis method consists of developing an engineering model for the wear behavior and using that model to identify design parameters, which will ensure acceptable wear performance. The general steps involved in doing this are shown in Figure 1.2.1. The process starts with examinations of the wear situation and ends with verification of the proposed solution. As indicated in that figure, the process may be iterative. This is particularly true of the core element, modeling. Theoretical considerations and modeling alternatives often lead to the need for additional examinations and more refined characterization of the wear situation.

The examination and characterization steps are needed to select the basic wear relationships that are used as the basic building block of the engineering

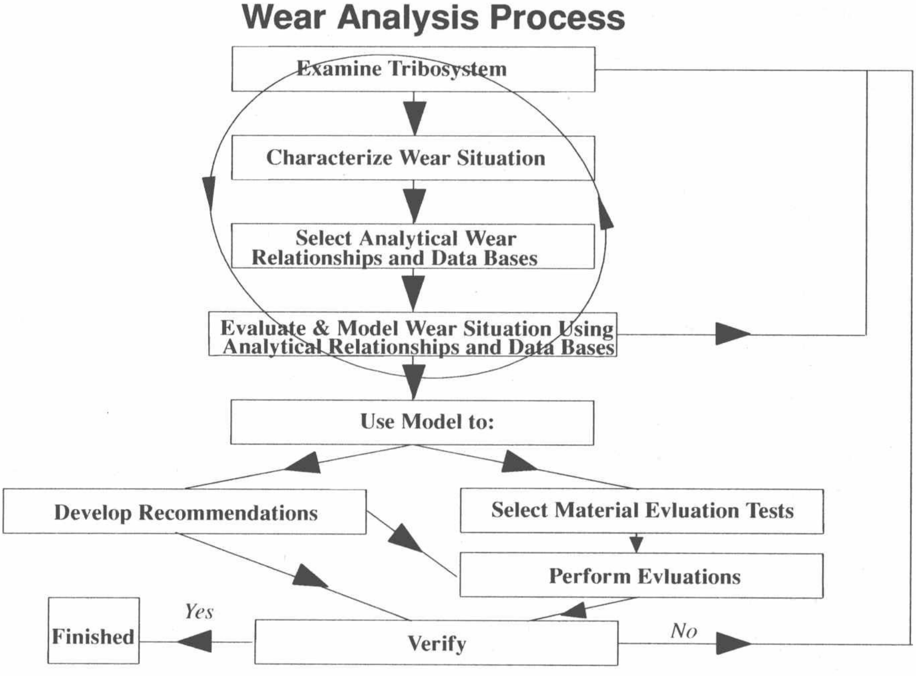


Figure 1.2.1 Flow diagram illustrating the elements involved in a wear analysis.

model. They also provide the additional information that is needed in the development of a model. Once a model is developed, recommendations for solutions to the wear problem can be identified, as well as the need for material wear tests. Because of the complex and varied nature of wear behavior and the incomplete nature of wear theory, verification is a necessary element of the overall method.

1.2.1 Examination

Basically, the examination element of a wear analysis is the data-gathering portion. Data gathering is not limited to the examination of the worn part or component. It includes gathering information about the entire tribosystem, that

Table 1.2.1.1 Data Required for Wear Analysis

1. **Component Information**
   a. Geometry
   b. Dimensions
   c. Materials
2. **Contact Condition Information**
   a. Orientation
   b. Location
   c. Loading
   d. Motion
3. **Lubrication Information**
   a. Type of lubrication
   b. Lubricant
   c. Conditions
4. **Environmental Information**
   a. Temperature
   b. Humidity
   c. Atmosphere
   d. Contamination
5. **Wear Information**
   a. Amount of wear
   b. Usage
   c. Appearance
   d. Location of wear

is, all those elements that can affect wear. Generally, this means obtaining information about the contacting member, the history of the part, environmental conditions, operating conditions, and factors that affect them, as well as about the nature of the wear and the properties of the worn part. The data that is gathered during the examination process is both qualitative and quantitative. As a minimum the magnitude of the wear and the amount of usage need to be quantified. Also, some of the operating and environmental conditions should be quantified, such as, load, speed, temperature, and humidity. During the course of the analysis it may be necessary to quantify other parameters, as well as refine the accuracy to which they are known.

The variety of techniques and instruments used to obtain the necessary data range from the very simple and common to the very sophisticated and specialized. Examples of the former include visual and low-power optical examination, measurement of wear using scales or dial gauges, reviewing the operation of the device, tracing the history of the parts, and simple mechanical analysis techniques to determine loads and motions. Examples of the latter include the use of state-of-the-art analytical equipment, finite element methods, and dynamic modeling. While the more sophisticated techniques are often helpful and sometimes necessary, the simpler and more commonly available ones are often adequate for performing useful wear analyses.

The information that needs to be developed in this step of the wear analysis procedure is listed in Table 1.2.1.1. Examination methods and techniques that can be used to obtain this data are discussed in Chapter 3.

1.2.2 Characterization

Since wear behavior is complex and many different relationships may be used to describe wear behavior, characterization is an essential element of a wear analysis. Characterization of the wear situation is the basis for selecting appropriate relationships for wear behavior and identifying relevant databases. It also aids in the application of these to the wear situation under analysis. Basically it involves synthesizing the data gathered into a useful description of the wear situation. The characterization should contain the following elements:

- Description of the motion causing the wear
- Description of the geometry of the contact
- Nature of the loading
- Description of the materials

- Type of lubrication
- Predominate wear features
- Surface roughness
- Description of the operating environment
- Wear magnitude
- Associated usage

Generally, these elements need to be described only nominally to initiate the modeling and evaluation activity. In general it is important to include any additional features that can significantly alter the wear situation.

It is not necessary for the characterization to contain all the information needed to perform a wear analysis. To complete the wear analysis more specific and quantitative information is generally required than that contained in the characterization. However, this is not necessary for all the elements. For example, nominal descriptions of the state of lubrication and the environment that are contained in the characterization are often adequate for the entire analysis. On the other hand, more specific information, which is beyond that necessarily contained in the characterization, is typically required for dimensions, loads, amount of motion, and amount of wear.

Primarily, characterization serves to limit the number of possibilities that need to be considered in performing the wear analysis. Less specific characterization results in the need to consider more relationships and databases in the analysis, while more specific characterization reduces the number that need to be considered. When an initial characterization is too broad, incomplete, or inaccurate, the modeling and evaluation process, as well as additional examinations, will generally lead to a better characterization. Examples of the type of characterizations that have been found to be useful are shown in Table 1.2.2.1. These examples illustrate the nominal nature of such characterization. They also illustrate the need to focus on attributes that can alter wear behavior and to include them in the characterization. Examples of this are the qualification of the type of sliding—for instance, unidirectional versus reciprocating—and the comments on alignment contained in the characterizations. Another example is the notation that intermittent contact is possible in the one situation.

There are two general ways that the characterization of a wear situation can be used to select wear relationships and databases. One is based on the operational conditions—for example, type of motion and loading—and the other is based on wear mechanisms, such as abrasion, galling, and fretting. These two approaches are treated in Chapter 4. Many times a blend of both approaches is beneficial in the characterization process.

Table 1.2.2.1 Examples of Initial Characterizations of Wear Situations

	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 load	Smaller member spring loaded against flat; nominally constant
Materials	Soft metal (larger flat) contacting harder metal (smaller flat)	Both members are case-hardened steel
Lubrication	Thin oil film	None
Wear features	(a) Morphology typical of mild sliding wear; (b) non-uniform wear track, suggestive of misalignment	(a) Intermittent wear track on larger surface, suggestive of separation and impact during sliding; (b) morphological features typical of impact and sliding motions
Roughness	Ground finish on both, 0.25–1 μm CLA	Polished finish on both, 0.2–0.5 μm CLA
Environment	Room	Room
Wear and usage	Wear track on larger flat, 250–1000 μm deep after 6 months of operation; no observable wear on harder part; device operates at 10 rpm, 16 hr/day	200-μm float on cylindrical surface after approximately 10^4 cycles of operation

1.2.3 Modeling and Evaluation

Modeling and evaluation, which constitute the core of wear analysis, use mathematical relationships to describe the wear of a component or device and to select design parameters. The development and use of these relationships are a distinguishing feature of this method, when compared with other engineering approaches that may be used to resolve wear problems. For example, a testing approach to resolve a wear problem or optimize performance may involve examination and characterization elements but not the use of mathematical expression for wear behavior.

Conceptually, the modeling and evaluation process typically involve a sequence of four, sometimes five, different activities. The first is determining what general relationships for wear behavior might be used to describe the wear in the situation that is being analyzed. The second activity is to use those relationships to develop a mathematical model, which relates either wear life or wear to design parameters. The third activity is to verify that the model provides a satisfactory explanation for the observed wear. If it does not, it is then necessary either to modify the model or develop an alternative model. Once an acceptable model is obtained, the final step is to use that model to evaluate the effect that different design changes will have on wear performance.

The characterization statement is use to select the appropriate general relationship. General relationships that can be used for wear analysis come

Linear Wear Relationship for Sliding

$$V = K\,P\,S$$

V: wear volume P: normal force S: sliding distance K: empirical wear coefficient

Energy Relationship for Sliding Wear

$$d\left(\frac{Q}{(\tau_{max}\,W)^{9/2}}\right) = C\,dN$$

Q: cross-sectional area of wear scar τ_{max}: maximum shear stress W: width of contact in sliding direction N: number of sliding passes C: empirical coefficient

Palmgren Equation for Rolling

$$P_1^3\,N_1 = P_2^3\,N_2$$

N_1: number of revolutions to failure with a load of P_1; N_2: number of revolutions to failure with a load of P_2

Percussive Equation for Impact

$$V = K\,v^n\,N$$

V: wear volume v: impact velocity N: number of impacts K & n empirical coefficients

Zero-Wear Relationship for Compound Impact

$$N_o = \frac{2000}{1+\beta}\left(\Gamma_r'\,\frac{\sigma_y}{\sigma_m}\right)^9$$

N_o: number of impact to exceed zero-wear σ_y: yield stress in tension σ_m: maximum contact stress Γ_r' & β empirical coefficients

Figure 1.2.3.1 Examples of mode equations. (From Ref. 67.)