



# AEROSPACE INFORMATION REPORT

**AIR5433™****REV. C**Issued 2001-05  
Revised 2019-11

Superseding AIR5433B

## Lubricating Characteristics and Typical Properties of Lubricants Used in Aviation Propulsion and Drive Systems

### RATIONALE

Since issuance of AIR5433B, it was discovered that the thermal conductivity for the oils listed in Table 8 were in error. After review in the E-34C Lubricating Characteristics Subcommittee, these issues have been resolved in this revision.

### INTRODUCTION

This SAE Aerospace Information Report (AIR) is intended as a guide toward standard practice, but may be subject to change to keep pace with experience and technical advances. Hence, its use, where flexibility of revision is impractical, is not recommended.

The information contained herein is an attempt to establish guidelines for the selection of properties governing the lubricating characteristics of lubricants to be used in current and future aviation propulsion and drive systems. It is the intent of the SAE Committee E-34 on Propulsion Lubricants that this document reflects currently accepted thinking in the industry and government agencies concerned with the lubrication of components in aviation primary propulsion systems, and associated power transfer gearboxes and transmissions.

The content of this AIR is the result of communication among lubricant manufacturers, hardware manufacturers, lubricant specialists, tribologists, lubricant specifiers, and lubricant users. Continued communication will be encouraged to maintain the information contained herein as current as possible. Users are advised that they can contribute to subsequent changes and additions to this document by their comments, suggestions, and criticism.

In present standards, some properties of importance in determining lubricating ability and the methods to quantify these properties tend to be ignored; in some cases, there are no standardized test methods. Because these properties are important to designers, they are included in this document, even if methods are not specified or standardized. In these cases, typical values obtained by particular methods are presented. It is intended that by including these data, focus will be brought on the deficiencies in these areas.

It must also be recognized that the selection of properties relevant to lubricating characteristics must be made in the light of the other characteristics necessary or desirable in the lubricant. This document is not intended to specify the properties of fluids optimized for lubricating ability; instead, it is intended to provide the guidance to be considered, along with the other requirements for the application, in determining the values to be specified for each property. Trade-off in the selection of limits for various properties must be made based on the relative impact of these properties on each other and on the system.

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## 1. SCOPE

This SAE Aerospace Information Report (AIR) establishes guidance for the specification of formulated lubricant properties which contribute to the lubricating function in bearings, gears, clutches, and seals of aviation propulsion and drive systems.

## 2. REFERENCES

### 2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of the other publications shall be the issue in effect on the date of purchase. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

- [1] Anonymous, Glossary of Terms and Definitions in the Field of Friction, Wear and Lubrication; Tribology, Research Group on Wear Engineering Materials, Organisation for Economic Co-operation and Development, Paris, 1969.
- [2] Cameron, A., The Principles of Lubrication, Longmans, London, 31, 1966.
- [3] Annual Book of ASTM Standards 2000, Section 5, Petroleum Products, Lubricants, and Fossil Fuels, Volume 05.01, Petroleum Products and Lubricants (I): D56 - D2596.
- [4] Cheng, H.S., Micro-Elastohydrodynamic Lubrication, U.S. National Congress of Applied Mechanics, 161-170, June 21-25, 1982.
- [5] Hamrock, B.J., Fundamentals of Fluid Film Lubrication, McGraw-Hill, 1994, ISBN 0070259569.
- [6] Gupta, P.K., Cheng, H.S., Forster, N.H., and Schrand, J.B., "Viscoelastic Effects in MIL-L-7808 Type Lubricant, Part I: Analytical Formulation," Trib. Trans. Volume 35, 2, 269-274, 1992.

### 2.2 Definitions and Terminology

The following terms are defined according to the definitions given in reference [1] and according to the customary engineering descriptions used in the aerospace community.

**CORROSION:** Reaction at surfaces due to electrochemical or direct chemical attack resulting in discoloration and/or pitting of the surface. Can occur on functional and nonfunctional surfaces.

**CORROSIVE WEAR (TRIBOCHEMICAL WEAR):** A wear process in which chemical or electrochemical reaction with the environment predominates. (1) Usually, corrosive wear is a mild form of wear, but it may become very serious, especially at high temperatures or in moist environments. (2) In some instances, chemical reaction takes place first, followed by the removal of corrosion products by mechanical action; in other instances, mechanical action takes place first, characterized by the formation of very small debris which subsequently is chemically transformed; the phenomena may be mutually enhancing. Oxidative wear is one form of corrosive wear.

**FATIGUE:** Removal of particles detached by fatigue arising from cyclic stress variation. (1) Spalling is removal of material by fatigue resulting from the global contact stress. It can be surface or subsurface initiated. (2) Pitting is removal of material by fatigue resulting from local stress within the contact. It is surface or near surface initiated. Fatigue pits are of smaller scale than fatigue spalls. (3) Micro-pitting (peeling, frosting); this type of fatigue is characterized by surface initiated spalling in the order of 5 to 13  $\mu\text{m}$  (0.0002 to 0.0005 inch) in depth which occurs where the surface finishes have many asperities greater than the lubricant film thickness. Normally, micro-pitting is only a slight distress to the contact surface and appears to be nothing more than a frosted appearance.

**FRETTING:** A wear phenomena occurring between two surfaces having oscillatory relative motion of small, <1 mm (<0.040 inch) amplitude.

**FRETTING CORROSION:** A form of fretting in which chemical reaction predominates. (1) Fretting corrosion is often characterized by the removal of particles and subsequent formation of oxides, which are often abrasive, and so increases wear. (2) Fretting corrosion can involve other chemical reaction products, which may not be abrasive.

**GLAZING:** The formation of a glazed or polished surface due to localized plastic flow.

**SCORING (SCUFFING):** The formation of severe scratches in the direction of sliding. (1) Scoring may be due to local solid phase welding or to abrasion. (2) In the USA, the term scuffing is sometimes used as a synonym for scoring. (3) In the UK, scuffing implies local solid-phase welding only. (4) Minor damage should be called scratching rather than scoring (scuffing).

**SCRATCHING:** The formation of fine scratches in the direction of sliding. Scratching may be due to asperities on the harder surface or hard particles between the surfaces or embedded in one of the surfaces. Scratching is considered to be less damaging than scoring (scuffing).

**SMEARING:** Plastic flow and removal of material from a surface and re-deposition as a thin layer on one or both surfaces.

**WEAR:** The progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface. (1) Wear is usually detrimental, but in mild form it may be beneficial, e.g., during running in. (2) A body may become unserviceable as a result of major plastic deformation. Small-scale plastic deformation occurs in almost all wear processes.

## 2.3 Symbols and Abbreviations

|       |                                            |
|-------|--------------------------------------------|
| a     | Major axis of the Hertzian contact         |
| AIR   | Aerospace Information Report               |
| ASTM  | American Society for Testing and Materials |
| b     | Minor axis of the Hertzian contact         |
| c, C  | Constants                                  |
| d     | Diameter                                   |
| E     | Elastic modulus                            |
| EHD   | Elastohydrodynamic                         |
| EP    | Extreme pressure                           |
| f     | Regression coefficient                     |
| $F_N$ | Normal load                                |
| $F_s$ | Shear force                                |
| g     | Regression coefficient                     |
| h     | Lubricant film thickness                   |
| k     | Ellipticity of contact                     |
| K     | Thermal conductivity                       |

|                      |                                                    |
|----------------------|----------------------------------------------------|
| m                    | Slope of viscosity-temperature graph, ASTM D341-43 |
| p                    | Lubricant pressure                                 |
| $P_{\max}$           | Maximum Hertzian stress                            |
| R                    | Equivalent radius                                  |
| S                    | Slide-to-roll ratio                                |
| Subscripts 1, 2      | Refer to bodies 1 and 2                            |
| T                    | Temperature                                        |
| $T_b$                | Bulk temperature                                   |
| TCP                  | Tricresyl phosphate                                |
| $T_f$                | “Flash” temperature                                |
| $T_K$                | Absolute temperature                               |
| U                    | Velocity                                           |
| $U_e$                | Entraining velocity                                |
| $U_s$                | Sliding velocity                                   |
| VI                   | Viscosity Index                                    |
| w                    | Load per unit width                                |
| $\alpha$             | Pressure viscosity coefficient                     |
| $\beta$              | Temperature viscosity coefficient                  |
| $\lambda = h/\sigma$ | Lambda ratio                                       |
| $\eta$               | Kinematic viscosity                                |
| $\mu$                | Dynamic viscosity                                  |
| $\nu$                | Poisson's ratio                                    |
| $\rho$               | Specific gravity                                   |
| $\sigma$             | Surface roughness (Ra)                             |
| $\theta$             | Contact angle                                      |

### 3. FUNDAMENTALS OF LUBRICATION AND LUBRICANT PROPERTIES

#### 3.1 Lubricant Function

The design and formulation of aeropropulsion lubricating oils is a compromise among attributes associated with lubrication, low temperature pumping, high temperature evaporation, thermal stability, and coking. Specification requirements seek to find a balance of properties.

In any lubricated contact, the lubricant generally must perform two primary functions. These functions are: (1) lubricant film generation for the reduction of wear, and (2) heat removal to stabilize component temperatures. While the primary purpose of a lubricant is to extend component life by reduction of wear and surface distress, only a small portion of the lubricant supplied to a component is required for this purpose. In components like rolling element bearings and gears with high load Hertzian contacts, less than 10% of the lubricant supplied is required for lubrication. The remaining 90% is supplied to provide adequate cooling to control and stabilize component temperatures at an acceptable level.

Both physical and chemical properties of a lubricant affect these two functions. The primary physical properties that determine the lubricating and wear reduction performance of a lubricant include its viscosity and pressure-viscosity coefficient. These are the properties that generate hydrodynamic films, the thickness of which are determined by contact geometry, lubricant viscosity, pressure viscosity coefficient, load, surface speed, and temperature. Another inherent physical property of the lubricant is the traction (friction) coefficient. The traction of a lubricant film is a function of temperature and pressure. The traction of lubricant films under shear is directly linked to heat generation.

In addition to the above physical properties, the type and quantity of surface active boundary lubricating additives that are present play an important role in a lubricant's surface film formation to minimize adhesion and wear. Boundary lubricating additives are particularly important at low speeds, high loads, and high temperatures where the films generated by hydrodynamic or elastohydrodynamic (EHD) mechanisms may be insufficient. In this "mixed-film" lubrication regime, the oil film thickness is less than the combined surface roughness of the surfaces in contact.

The lubricant also serves to help capture and filter debris. The lubricant furthermore transports fresh chemistry to the lubricated contacts.

The primary properties, which determine a lubricant's ability to remove heat from a component, are density, heat capacity, thermal conductivity, and thermal stability. These properties determine how well the lubricant can absorb heat from the mechanical component and how well it can stand up to the thermal environment it is subjected to. Antioxidant additives are used to increase the thermal stability of a lubricant base stock to permit it to be used at elevated temperatures.

While not primarily a lubricating function in the strict sense of the word, corrosion protection is an additional performance requirement for many lubricants. Corrosion preventive additives are frequently used to improve the corrosion protection of a given lubricant. Corrosion protection can be provided by a combination of effects including chemically adherent surface film formation, acid neutralization, and moisture elimination or control. The effectiveness of anticorrosion additives is controlled by their detailed chemical properties.

Another critical property is the electrical conductivity of the lubricant. This relates to the design and function of electrical components such as rectifying diodes and estimates the susceptibility of the oil to spontaneously discharge a static electrical charge. Electrical conductivity is known to be a function of temperature. It is desirable to have the electrical conductivity measured at both 20 °C and 80 °C to determine the effect of temperature and allow for proper calibration. Electrical conductivity is used to assess the risk of generating static charges due to oil flowing past insulating materials. Electrical conductivity of an oil may increase rapidly in use.

## 3.2 Lubrication and Failure Mechanisms

### 3.2.1 Introduction

The performance of the lubricant, with its physical and chemical properties, in most cases cannot be formulated into simple and reliable equations to predict the role of lubricant properties in the failure process. Failure in the form of wear, for example, is not an intrinsic property of a bearing or gear material. Also, the performance of an oil is not an intrinsic property of the lubricant alone, but it is the result of the physical and chemical interactions within an entire lubricated contact system. Consequently, the design or selection of a lubricant is based on both science and experience. The rationale is derived from both lubrication and failure mechanisms and their interactions within a lubricated contact system.

The lubricant prevents failure through the formation of lubricating films by hydrodynamic lubrication, EHD lubrication, and boundary lubrication. The criteria for failure are judged by the user. If the deterioration of the surfaces or level of friction has progressed to the degree that it threatens the essential function of the component, it can be considered to have failed.

Through experience the engineer recognizes distinct classes of failure (see 2.2). These failures are defined without presupposing the exact mechanism by which they occur. They are defined in engineering terms based on a description of observations. The observations and their classifications reflect the remaining evidence of a complicated sequence of events involving many physical and chemical processes that preceded it. Associated with the physical and chemical interactions on the surfaces are several mechanistic wear processes, which generally fall under the basic mechanisms of:

- Adhesion
- Chemical reaction
- Plastic flow
- Fatigue

During the service life of a component, the lubricant must provide the lubrication mechanisms required to prevent or control these basic wear processes.

### 3.2.2 Types of Contacts

The geometry of contacting bodies creates the character of the contact with respect to stress and the mechanisms of lubrication. Conformal contacts are where contacting body geometries closely match one another and distribute the load over relatively large areas. Conformal contacts, like journal bearings and the cage/land interface in rolling element bearings, have clearance spaces that must be preserved during operation. Concentrated contacts are non-conformal. They concentrate the load over small areas like that found in rolling element bearings and gear mesh contacts. The lubrication of conformal contacts is primarily governed by hydrodynamic mechanisms where oil viscosity is the controlling property. The lubrication of concentrated contacts is primarily governed by EHD mechanisms where velocity, viscosity, pressure-viscosity coefficient, and traction coefficient are the controlling properties. Boundary lubrication from oil chemical attributes is associated with both conformal and concentrated contacts, when lubricant film thickness becomes less than the average combined surface roughness.

It is helpful to grasp the perspective of tribological contacts for their scale. The lubricated length of a conformal contact is generally less than a centimeter ( $10^{-2}$  m). The lubricated length of a concentrated contact is generally less than a millimeter ( $10^{-3}$  m). These load-bearing areas are on a “macro-scale” where they can be viewed with the unaided eye.

Within the world of macro-scale contacts are “micro-scale” features which control tribological behavior. Surface roughness features (asperities) and the grain sizes of metals are on the order of microns ( $10^{-6}$  m). These microscopic features are critically linked to yet a lower scale of things that control lubrication and failure phenomena. Adsorbed films of molecular size that prevent adhesion between surfaces are on the order of nanometers ( $10^{-9}$  m). Here lies a fundamental difficulty within the tribology of component hardware. Lubrication and failure mechanisms are controlled by micro-scale phenomena, but the parameters that control loads and motions of lubricated contacts are on the macro-scale engineering level. To connect lubrication and failure mechanisms, which take place on a micro-scale, surface stresses and kinematics on the engineering level should be considered as input to a tribological contact system. The role of the lubricant and its design and selection rationale can be understood by considering the structural elements of a tribological contact system.

### 3.2.3 Structural Elements of a Lubricated Contact

Engine and transmission systems have a very wide range of lubricated contacts within their basic components of bearings, gears, seals, clutches, and splines. The lubricated contacts cover a wide range of contact stresses and rolling/sliding motion.

For a concentrated contact, the performance is derived from the integrity of four general regions as shown in Figure 1. Each region performs certain functions in the lubrication and failure process. The success of the lubricant depends upon how well it handles the normal stress and accommodates the tangential shear within these regions.

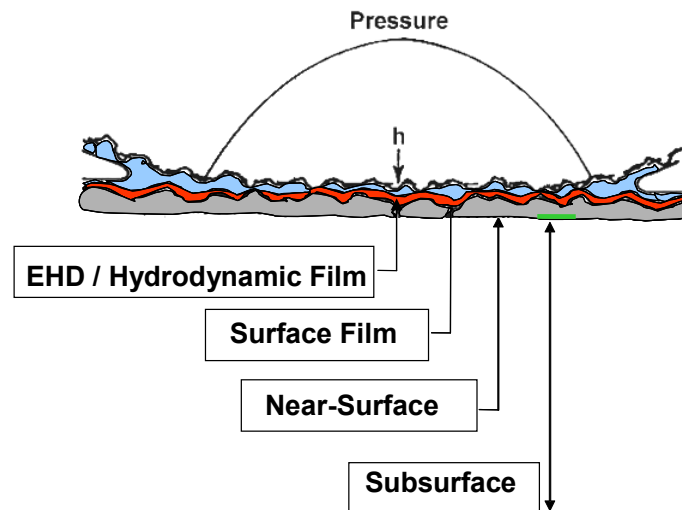


**Figure 1 - Structural elements of a lubricated contact**

The hydrodynamic/EHD lubricated region is created by the generation of an EHD lubricant film. On a global scale, the EHD film is derived from the hydrodynamic pressure generated in the inlet region of the contact. On a local scale, it is derived from the micro-EHD lubrication action associated with the local topography of the surfaces; see reference [4]. Micro-EHD is an EHD effect on an asperity scale, mostly associated with surface scratches transverse to the direction of motion. The EHD/micro-EHD region is typically less than 1  $\mu\text{m}$  thick.

The surface film region contains the thin outer layers of the surface. These consist of surface oxides, adsorbed films, and chemical reaction films derived from the lubricant and its additives. The surface films are almost always less than 1  $\mu\text{m}$  thick.

The near-surface region contains the inner layers of the surface. This region may include a finely structured and highly worked or mechanically mixed layer. The deformed layers, which are of a different microstructure than the material below them, may arise from surface preparation techniques such as grinding and honing. These may also be induced during operation; for example, during running-in. Hardness and residual stress may vary significantly in this region, and may also be substantially different from the bulk material below. The near-surface region may be on the order of 50  $\mu\text{m}$  below the surface.

For concentrated contacts, a subsurface region can be defined, which may be 50 to 1000  $\mu\text{m}$  below the surface. This region is not significantly affected by the mechanical processes that produce the surface or the asperity-induced changes that occurring during operation. Its microstructure and hardness may still be different from the bulk material below it, and significant residual stresses may be present. These stresses and microstructures, however, are the result of macro processes such as heat treatment, surface hardening and forging. For typical Hertzian contact pressures, the maximum shear stress is located within the subsurface region. After millions of stress cycles, alterations in residual stress and microstructure have been noted in the subsurface region. These alterations are attributed to the rolling contact stress field and may be the precursors for rolling contact fatigue. In other words, the detrimental global contact stresses are communicated to the subsurface region where subsurface-initiated fatigue commences.

One can also define a "quiescent zone" which is located between the near-surface region and the subsurface region. The quiescent zone resides at a depth below the surface in which the local asperity and surface defect stresses are not significant, and the stress field from the macroscopic Hertzian contact stress is not yet appreciable. This zone is quiescent from the point of view of stress and the accumulation of plastic flow and fatigue damage. The existence of the quiescent zone is important with regard to rolling contact fatigue. It inhibits the propagation of cracks between the stress field in the near-surface region and the stress field in the subsurface region.

### 3.2.4 Stress Fields of a Lubricated Contact

The performance of a lubricated contact is associated with a normal stress field and a tangential stress field. The normal stress of conformal contacts is typically in the range of mega-Pascals (MPa),  $1000000 \text{ N/m}^2$ . The normal stress of concentrated contacts is typically in the range of giga-Pascals (GPa),  $1000000000 \text{ N/m}^2$ . Concentrated contacts encounter significant elastic deformation. The elastic contact area and stress distribution can be calculated by using Hertzian theory; see reference [2].

The tangential stress is directly linked to the coefficient of friction. The tangential stress of a contact under full EHD lubrication is the shear stress in the lubricant film. Under mixed mode and boundary lubrication, friction events associated with interacting asperities between the surfaces also contribute to the tangential stress, so the resulting tangential stress is a combination of lubricant shear stress and shear stress at the asperity contact. The friction coefficient (also called traction coefficient) is determined from the ratio of the resulting tangential force to the applied normal load. The friction coefficient can also be determined from the ratio of the tangential stress to the mean Hertzian stress. The traction coefficient generally ranges from 0.002 to 0.100% for lubricated rolling contacts, while values as high as 0.500% have been recorded under adverse conditions.

Because lubrication and failure mechanisms are frequently controlled by asperity-scale phenomena, it is important to remember that normal and tangential stresses at asperities may not be that different for conformal contacts as they are for highly stressed concentrated contacts. Asperity stresses depend on how the load is momentarily distributed among the surface features. Conformal contacts, with rough surfaces and a few contacting asperities, can have stresses similar to asperities found in concentrated contacts with smoother surfaces. Because concentrated contacts tend to have finer surface finishes than conformal contacts, asperity stresses for both conformal and concentrated contacts may be on the same order of magnitude, even if their "global" or overall pressure across the contact area is substantially different. The major difference between conformal and concentrated contacts is that the stress field of the latter penetrates deeper into the material. In addition, high global pressure for concentrated contacts can dramatically change fluid viscosity.

Whether normal and tangential stresses are on a global scale or asperity scale, the objective of lubrication is to create or preserve interposing material that bears the normal stress and accommodates the tangential shear. In lubricated contact systems, lubricating mechanisms are applied to suppress failure mechanisms. The most robust contact systems are those that have boundary lubricating mechanisms preserve surface integrity to allow hydrodynamic and EHD mechanisms to maintain operative after incidental asperity contact.

### 3.2.5 Lubrication Mechanisms

The physical and chemical properties of the lubricant work within the structural elements of the contact through the mechanisms of hydrodynamic (or EHD) lubrication and boundary lubrication.

**Elastohydrodynamic Lubrication:** The formation of a hydrodynamic or EHD lubricant film contributes to lubrication by reducing the local stresses between the surfaces and by creating a lubricant film that is easy to shear. For a concentrated contact illustrated in Figure 2, the pressure and elastic deformation are similar to the Hertzian contact condition of dry contact. This Hertzian elastic deformation is critical as it creates the geometry of the surfaces to be lubricated. The Hertzian geometry creates three functional regions that the lubricant must traverse.

The formation of an EHD lubricant film is created by the hydrodynamic pressure generated in the converging space upstream of the Hertzian region. The function of the inlet region is to generate sufficient pressure to squeeze a small quantity of fluid into the high pressure Hertzian region. The success of this action is attributed to a significant rise in viscosity with pressure. The lubricant film thickness created from the inlet pressure generation can be accurately calculated from EHD theory. The required lubricant properties are its viscosity and pressure-viscosity coefficient at the temperature of the fluid in the inlet region. The inlet fluid temperature is generally close to the surface temperature of the contacting bodies. High speeds, typical of many aeropropulsion components, increase the temperature within the inlet region due to viscous shear action. In addition to the lubricant properties, the thickness of the EHD oil film is a function of the radius of curvature and the entraining (rolling) velocity of the surfaces in contact. Remarkably, the film thickness is less dependent upon the contact stress and elastic modulus of the contacting materials. EHD theory has proven to be a very useful design tool for predicting the lubrication regime for various applications. However, it is not sufficient to accurately predict wear, scuffing, and fatigue failure. This is partly because EHD lubrication is primarily an inlet phenomenon; that is, its major role occurs in a region removed from the Hertzian region where the more local events involved in failure initiation take place. The EHD lubrication process can significantly influence the severity of these local events. The nominal thickness of an EHD film determines the degree of asperity interaction between the surfaces. Failure mechanisms are associated with several less quantifiable processes that occur in the Hertzian region of the contact.

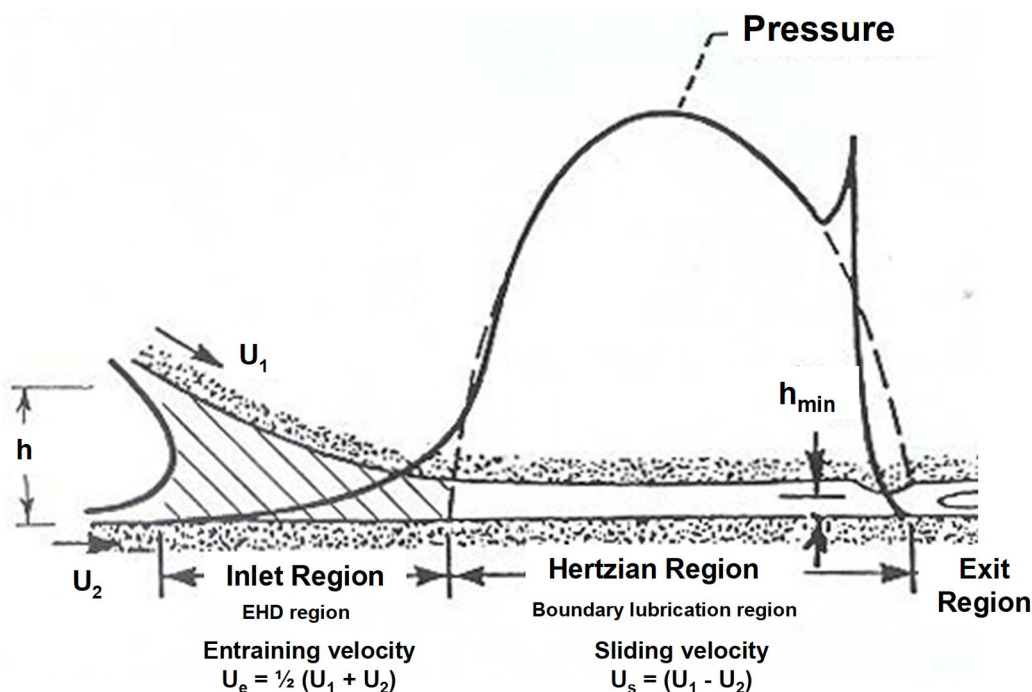


**Figure 2 - EHD lubrication**

Surface temperature is a key link between lubrication and failure. Temperature significantly influences the viscous properties of the lubricant that control the thickness of an EHD generated film. Temperature is also a major driving force in the formation of chemical reaction films. It also influences the rate of lubricant degradation. Surface temperature influences the strength of surface films, as well as the flow properties of the material in the near-surface region. Consequently, it is not surprising that the total temperature is a frequently used criterion for failure, such as scuffing (or scoring).

From a simplistic point of view, the contact temperature ( $T$ ) is the sum of a bulk temperature ( $T_b$ ) of the component and the "flash" temperature ( $T_f$ ) associated with the instantaneous temperature rise derived from the friction within the lubricated contact. Flash temperature may arise from the traction of the lubricant film as well as from the energy dissipated from the adhesion, plastic flow of surface films, and deformation of the material within the near-surface region. The magnitude of  $T_f$  can be predicted if simplifying assumptions about the coefficient of friction and conductive heat transfer are made.

**Boundary Lubrication:** It is well known that surface films are important to boundary lubrication because they prevent adhesion and provide a film that is easy to shear. These films may be in the form of oxides, adsorbed films from surfactants and chemical reaction films from other additives or the bulk fluid itself. Typical aviation oils have anti-wear additives or EP (extreme pressure) additive chemistry to create surface films to prevent adhesion. Other additives, such as anti-oxidants, can also create surface films for boundary lubrication. Boundary lubricating surface films are schematically shown in Figure 3. Boundary lubricating surface films can be formed from energy generated in localized asperity interaction. The plastic flow and removal of oxide films create sufficient surface energy for chemical reaction films to form.

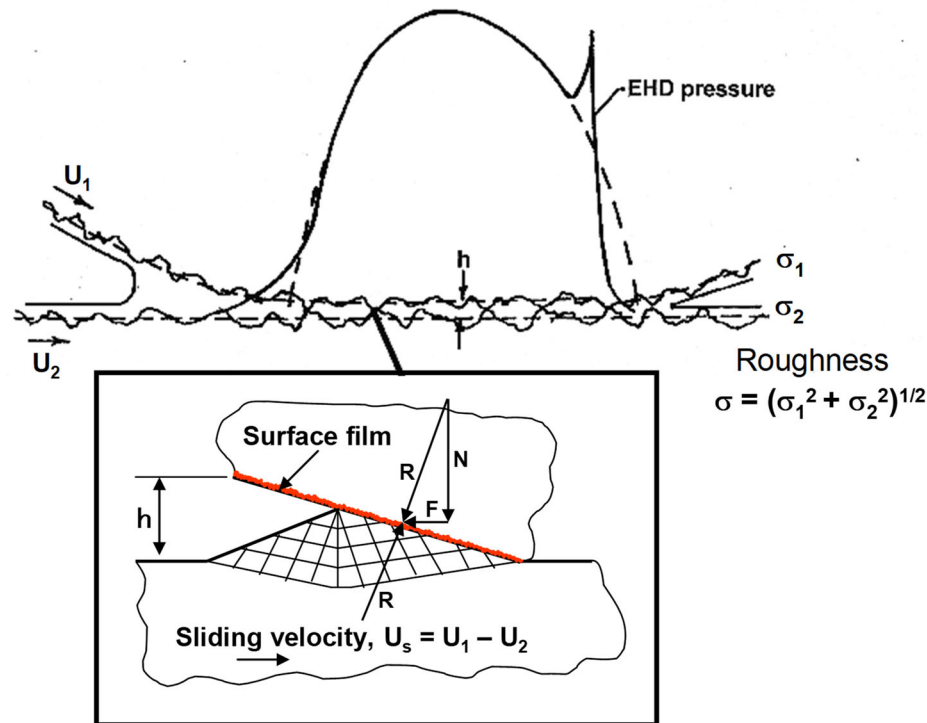


**Figure 3 - Surface films from boundary lubrication mechanisms**

The interactions of surface films are very complex. Most studies on the subject have focused on the chemical identification or phenomenological effect of surface films, but little is known about the mechanism of protection, the means of removal, or the rate of reformation. At high temperatures, the oxidation of the base fluid can contribute to surface film formation. There have been many studies of the catalytic effect of metals on the bulk oxidation of lubricants. Similar oxidative processes can occur under the thermal stress environment in the contact region where intermediate oxidation species can react with the surface or organo-metallic material that may be present. These reactions can influence boundary lubrication in several ways; such as by corrosive wear, by competition with other additives, or by forming polymeric material (friction polymer).

The contribution of surface films in preventing wear and controlling scuffing and fatigue is significant. The time and spatial distribution of the various surface films within the contact seem to be important. It is essential that active and effective boundary lubricating chemistry form surface films, and allow some degree of polishing, for lubricated contacts to operate with extremely thin EHD films.

**Mixed-Film Lubrication:** Mixed-film lubrication is a term used to describe operation with a mixture of hydrodynamic/EHD lubrication mechanisms and boundary lubrication mechanisms. Mixed-film lubrication, which can range from almost a full hydrodynamic film to almost complete boundary lubrication, is common among many aeropropulsion lubricated contacts. A transition through this range occurs during startup and shutdown. The lambda ratio ( $\lambda = h/\sigma$ ) is a useful engineering quantity to describe the ratio of the hydrodynamic or EHD lubricant film thickness ( $h$ ) to the average combined roughness height ( $\sigma$ ) of the interacting surfaces (see Figure 3). The combined roughness has been defined as the average of the Ra roughnesses of the surfaces or the square root of the sum of the squared RMS roughnesses of those surfaces; see reference [5]. When lambda is  $\lambda > 3$ , wear, scuffing, and micro-pitting (or micro-spalling) are mostly eliminated. Surface initiated fatigue and wear are controlled by  $h/\sigma$  as a result of affecting normal and tangential stress on an asperity scale. Its connection with surface-initiated fatigue seems to be more obvious than failure modes associated with wear or scuffing. The latter failure modes generally appear at low lambda, less than one, where the concept of lambda loses some of its meaning.

When the combined roughness ( $\sigma$ ) is the same order of magnitude as the film thickness ( $h$ ), the surface topography becomes intimately involved in the lubrication process itself in the form of micro-EHD lubrication. Local hydrodynamic or EHD pressures can be generated at asperity sites or topographical features to actually depress these features and boost local film formation. Micro-EHD lubrication should not be confused with boundary lubrication. Micro-EHD lubrication can also affect the friction, or traction within the contact; see reference [4].

### 3.2.6 Failure Processes

#### 3.2.6.1 Five Key Parameters

The challenges of lubricant formulation, along with bearing and gear design, are to invoke lubrication mechanisms of full-film EHD, partial-film EHD and boundary film lubrication and to avoid failure mechanisms associated with wear, scuffing, and fatigue. With the exception of hydrodynamic and EHD film thickness prediction, lubricant performance is determined by testing and service experience. Tribological testing must capture the micro-scale lubrication and failure mechanisms controlling performance and somehow link the testing results to the macro-scale design space that the design engineer can utilize. Five key tribology parameters have been found to be effective in linking tribological mechanisms in service with testing and design. The five parameters, which are derived from EHD theory, are shown in Figure 4.

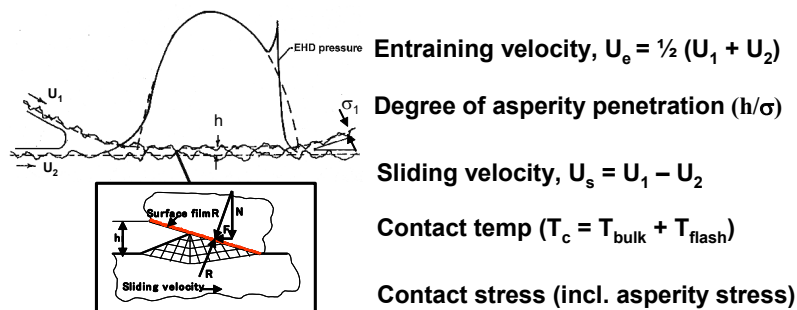


**Figure 4 - Five key tribology parameters**

The entraining velocity ( $U_e$ ) controls the formation of EHD film thickness through the generation of pressure in the inlet region. The sliding velocity ( $U_s$ ) controls the shear and heat generation within the Hertzian region. The film thickness-to-surface roughness ratio ( $h/\sigma$ ), or lambda ratio ( $\lambda$ ), controls the degree of asperity interaction. The contact stress is considered on a global Hertzian contact scale and a local asperity scale. Wear, micro-pitting, and micro-scuffing are generally initiated on a local scale and subsequently propagated to a global scale. Contact temperature ( $T_c$ ) is considered the sum of the bulk temperature ( $T_b$ ) and the friction-generated flash temperature ( $T_f$ ). The contact temperature controls reaction rates between the lubricant and surface material. It also controls the shear properties at the interface.

#### 3.2.6.2 General Failure Scenarios

The five key tribological parameters provide an engineering linkage to lubrication and failure scenarios. With little or no asperity penetration ( $\lambda \gg 1$ ), major failures of wear, scuffing, and surface initiated fatigue are avoided. It is generally recognized that the loss of an EHD film is a necessary, but not sufficient, condition for failure mechanisms. Perhaps the most important quantity in connection with failure is the deformation attributes of the near-surface region. It is unfortunate that there is little understanding of near-surface mechanical properties or the attributes needed to complement the various lubricating mechanisms to prevent failure. To maintain surface integrity, the near-surface region must prevent micro-fracture and maintain a viable surface finish even in the presence of some plastic flow.

The severity of asperity interaction is reflected in the normal load  $F_N$  (see Figure 3). The normal load on the asperity is influenced by the thickness ( $h$ ) of lubricant film that is generated. The shear force,  $F_s$ , is influenced by the various surface films and micro-EHD lubricant films, along with the flow properties in the near-surface region. The exact mechanism whereby shear stress is applied to the near-surface region is not well understood. This could come about through metal-to-metal adhesion, or possibly through shear stresses applied locally through a thin lubricant film.

The severity of interaction is important to the initiation and propagation of the events toward failure. The severity of interaction will determine whether the result is (1) a benign elastic encounter, (2) a further accumulation of plastic fracture sites that can lead to the generation of wear particles (e.g., micro-pitting, or polishing wear debris), (3) oxidative or corrosive wear, or (4) the advancing of adhesive material transfer, which can lead to adhesive wear or scuffing.