Revision Log for *Introduction to Tribology for Engineers*

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The first version of the textbook (1.0) was published on August 6, 2022. The most recent version is 1.6 and was published on July 21, 2023. Since the initial version, multiple edits have been made to improve clarity as well as correct errors. This document first summarizes the major revisions to content, especially technical errors, organized by the version in which the change was made. Then, at the end, all minor edits made between the first and most recent version are compiled by chapter.

Technical Corrections

Version 1.1

Section 7.4 Grease Classification

This section originally did not contain information about the grease dropping point, which is an important metric for grease characterization. The following content was added to resolve this.

"Lastly, greases are characterized by their *dropping point*. The dropping point is the temperature at which a grease changes from semi-solid to liquid. This temperature is measured by heating the grease in a standard test cup and recording the temperature at which the grease falls or drips through a small hole at the bottom of the cup. A grease should have a dropping point above the highest expected operating temperature for the target application."

Section 8.2 Hydrodynamic Theory

The explanation of the calculation of the viscous friction force was improved and simplified. This involved removing the equation for velocity profile (Eq. 8.3 in the original version of the book). The updated text is as follows:

"The viscous friction force F_v' per unit width is the integral of the shear stress within the lubricant. For a Newtonian fluid, the shear stress is viscosity

η multiplied by shear strain rate $\partial u/\partial z$:

$$F_v' = \int_0^l \left(\eta \frac{\partial u}{\partial z}\right) dx$$

where l is the length of the lubricated contact and u is the local velocity of the fluid at vertical position z. The fluid speed u is a function of the local film thickness h and pressure gradient dp/dx."

Section 8.3 Analytical Solution for Inclined Plane

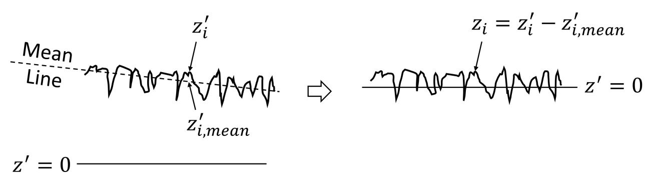
The partial derivative of velocity in the equation for viscous friction force per width for an inclined plane was changed from $\frac{\partial u}{\partial x}$ to $\frac{\partial u}{\partial z}$. The corrected Eq. 8.8 (Eq. 8.9 in the original version) is:

$$F_v' = \int_0^l \eta \frac{\partial u}{\partial z} dx = -\frac{\eta U l}{s_h}\left[4 \ln\left(\frac{h_0}{h_0 + s_h}\right) + \frac{6 s_h}{s_h + 2h_0}\right]$$

Version 1.2

Section 3.3 Roughness Quantification

The variable for reference height was originally given as $z_{i,mean}$. Since the reference height is calculated based on raw height data, the variable used should be $z^{'}_{i,mean}$. This was corrected in the text and Fig. 3.6. The updated version of Fig. 3.6 is:



Version 1.3

Section 3.3 Roughness Quantification

The use of parentheses in Eq. 3.5 was misleading as it suggested the summation should be taken before the square. This was corrected by removing the parenthesis around z_i. The updated version of Eq. 3.5 is:

$$R_q = \sqrt{\frac{1}{N}\sum_{i=1}^{N} z_i^2}$$

Section 4.5 Plasticity

The use of average as opposed to maximum pressure to estimate the onset of plasticity was corrected. In addition, the discussion of two different models for maximum shear stress at yield was found to be confusing and unnecessary, so it was removed. The latest text in this section is:

"The onset of plastic deformation is expected when $p_{ave} \approx 1.1Y$, and starts below the surface at the position of the maximum shear stress z_{max}. Under these conditions, deformation is partially elastic and partially plastic, also called elastic-plastic. As load increases, more of the shear stress within the material exceeds the yield criterion and more of the deformation is plastic instead of elastic. ... The onset of this fully plastic regime has been estimated to occur at $p_{ave} \approx 2.8Y$."

Section 6.3 Base Oils

The description of the distillation process was revised to improve clarity. The new text is:

"First, the crude oil is separated into many different "fractions" through a process called fractional distillation, which takes advantage of the different boiling points of the hydrocarbons in the crude. The process involves adding heat to vaporize the crude oil, which then rises up through a vertical column. As the vapor moves upward, it is gradually cooled. A series of trays collect the material that condenses (becomes a liquid) at each temperature, as illustrated in Fig. 6.2. Substances with higher boiling points condense near the bottom of the column and those with lower boiling points condense closer to the top."

Section 9.4 Empirical Equations

A caveat was added to clarify that the minimum film thickness equations were developed for point contact but could be used to approximate line content. The following is the new content:

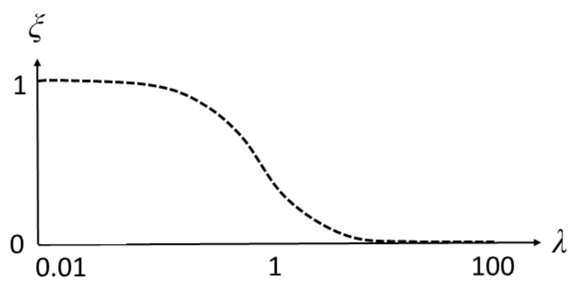
"These equations were developed from numerical solutions for elliptical contacts with k between 1 (circular contact) and 36 (elliptical contact approaching the rectangular shape of line contact)."

Version 1.4

10.5 Friction in Mixed and Boundary Lubrication

The limiting cases of the load support ratio were incorrect. This was corrected in the following text and updated Fig. 10.5:

"When λ is small, at the transition between boundary and mixed lubrication, boundary friction is dominant and $\xi = 1$. When λ is large, at the onset of full film lubrication, viscous friction is dominant and $\xi = 0$."



Version 1.5

Section 9.4 Empirical Equations

The equation for normalized minimum film thickness was missing the effective radius in the denominator. The corrected Eq. 9.5 is:

$$h_0^{'} = \frac{h_0}{R'} \left(\frac{W}{R' U \eta_0} \right)^2$$

Also, a note was added to clarify that Eq. 9.7 cannot be used for line contact:

"Note that this equation cannot be used as an estimate for line contact since film thickness is directly proportional to k."

Section 9.6 End of Chapter Evaluation

Two of the exercise problems were updated (along with their solutions in the Appendix). The following are the latest version of problems (solutions):

2. The contact between the teeth of mating gears can be approximated as contact between two cylinders of radius 10 cm. The transmitted load is 100 N and the relative speed at the tooth contact is 0.5 m/s. The gears are made of 52100 steel and they are lubricated by an oil with 30 mPa·s and pressure-viscosity coefficient of 8 GPa^{-1}. Calculate the minimum film thickness using empirical equations assuming the interface experiences piezoviscous-elastic lubrication. ($h_{0,PE} = 0.19$ µm)

3. A rolling element bearing has 2 cm radius spherical elements and a 20 cm radius ring (assume a circular contact patch), all made of 52100 steel. The bearing is subject to a radial load of 3 N and the relative speed at the ball-ring contact is 5 m/s. For an oil with a viscosity of 40 mPa·s and pressure-viscosity coefficient of 10 GPa^{-1}, determine the lubrication regime and then use the appropriate empirical equation to calculate minimum film thickness. ($h_{0,IR} = 0.73$ µm)

Section 10.4 End of Chapter Evaluation

Problem 2 (and its solution in the Appendix) was updated. The following is the latest version of problem (solution):

2. A human knee joint comprises soft, elastic articular cartilage (E'=25 MPa) lubricated by synovial fluid for which viscosity (η_0=2 mPa·s) does not increase appreciably with pressure. The knee joint can be approximated as a sphere of radius 4 cm moving with linear speed of 0.2 m/s relative to a spherical cup (socket) of radius 4.1 cm. Calculate the minimum film thickness at this joint for person who weighs 200 lbs (assume all of the weight is on the joint). (h_0 = 1.88 µm)

Version 1.6

Section 3.3 Roughness Quantification

The use of parentheses in Eqs. 3.9 and 3.10 was misleading as it suggested the summation should be taken before the third or fourth power. This was corrected by removing the parenthesis around z_i.

Section 4.3 Conformal Contact

The terminology and variable for conformal contact pressure changed from pressure p to applied pressure p_a in the text and Eq. 4.2.

Section 9.3 Numerical Solutions

Viscous friction force F_v defined and the reference to Eq. 8.3 modified to correctly identify it as being used to calculate friction force as opposed to friction coefficient.

Minor Edits or Clarifications

Chapter 1

- exaJoules are → exajoules is
- solid surfaces move → solid surfaces in direct contact move
- Although this textbook is intended for engineers, the → This textbook is intended for engineers, but
- In the description of the Stribeck curve: friction → friction coefficient
- Figure 1.1 updated to explicitly identify Total Energy Losses
- there is no wear → there is minimal wear

Chapter 2

- most common engineering ceramics → most common ceramics in tribological applications
- Although brittle materials have a yield strength, it is difficult to measure → In the case of brittle materials, the yield strength is difficult to measure
- Thermal conductivity quantifies → Thermal conductivity κ quantifies
- Specific heat quantifies → Specific heat C_p quantifies
- High Density Polyethylene → High-Density Polyethylene
- prevent corrosion → protect against corrosion
- What is a Vicker's test used to measure → What property is a Vicker's test used to measure

Chapter 3

- difference in phase between the light reflected off the mirror and the light → difference between the phase of the light reflected off the mirror and that of the light
- inteferometers → interferometers
- the first step is to identify the reference height $z'_{i,mean}$ and subtract it from the measured height → the first step is to identify the reference height $z'_{i,mean}$ and subtract it from each measured value z'_i
- In Fig. 3.6: $z_{i,mean}{}'$ → $z'_{i,mean}$
- R_q is the root-mean-square roughness → R_q is the root-mean-square roughness (Eq. 3.5)
- different levels of roughness → different average roughness
- Problem 1 and Problem 2: Units changed from mm to µm; units of solutions in the Appendix changed accordingly

Chapter 4

- Table 4.1 updated to give names of the four shapes
- most tribological analyses assume elastic behavior and use the Hertz equations. → most tribological analyses assume elastic behavior and use the Hertz equations. However, Eq. (4.5) can be consider the limiting case for contact area.
- Figure 4.6 updated to replace text axis labels with variables and the caption updated to include variable names
- conditions to do the Hertz contact → conditions do the Hertz contact

Chapter 5

- will presented → will be presented
- viscosometer → viscometer
- for non-conformal lubrication → for lubrication of non-conformal contacts
- fluid can adsorb form → fluid can absorb from
- Why is high thermal conductivity beneficial for a lubricant? → Why are thermal conductivity and specific heat important for lubricants?

Chapter 6

- fraction tapped from each tray boils at the temperature in that tray → fraction tapped from each tray condenses at the temperature in that tray
- alklyated aromatics → alkylated aromatics
- speciality ester-based synthetic lubricants → speciality ester-based synthetic lubricants
- containing flourine → containing fluorine
- Table 6.1 PAO → polyalphaolefin
- Table 6.1 Di/polyester → Diester/Polyester
- Table 6.2 high temperatures → high temperature
- Table 6.2 Hinder agglomeration of contaminants → Hinder contaminant agglomeration
- Table 6.2 from contaminant build up → from contaminants
- Table 6.2 Reduce friction in mixed and boundary lubrication → Reduce friction
- Table 6.2 Mitigate wear under moderate conditions → Reduce wear
- Table 6.2 Mitigate wear under severe conditions → Reduce wear in severe conditions
- build up of sludge → buildup of sludge
- polar head group associates with contaminants → polar head groups associate with contaminants
- non-polar tails separate → non-polar tails physically separate
- Many lubricant additives → Lubricants and the environment
- anti-wear → anti-wear (AW)
- the differences between → the difference between

Chapter 7

- relative amount of molecules → relative numbers of molecules
- Table 7.1: 100° → 100°C
- Table 7.1: 150° → 150°C
- greases further also classified → greases are further classified

Chapter 8

- The partial derivatives in Eq. 8.1 were changed to full derivatives.
- The fact that Eq. 8.1 is the 1D form of the Reynolds equation was clarified.
- in the numerator of the equation → in the denominator of the equation
- Taking the partial derivative of Eq. 8.6 and setting it to zero → Taking the partial derivative with respect to shoulder height of Eq. 8.6 and setting it to zero
- solid surfaces are not fully separated → solid surfaces may not be fully separated
- Problem 8.5: 2.5 nm → 2.5 cm

Chapter 9

- However, there is also a small "pressure spike" at the outlet of the contact (near x/a=1). This position corresponds to a local drop in film thickness as well. → However, there is also a narrow "pressure spike" at the outlet of the contact (near x/a=1). The magnitude of the pressure at the outlet of the contact can be larger than that in the middle of the contact. The position of the pressure spike corresponds to a local drop in film thickness as well.
- Figure 9.2: P/P_{max} → p/p_{max}
- A ratio of the radii of the contacting bodies → The ratio of the radii of the two contacting bodies
- use the entire load on the bearing for a single rolling element → use the load on the bearing as W in contact calculations for a single rolling element
- In multiple Concept Questions and Exercises Problems: lubrication category → lubrication type

Chapter 10

- few few sliding cycles → first few sliding cycles
- Deleted text to avoid confusion: Even without lubricant additives, boundary friction is lower than dry contact friction because high local pressures within the contact increase the viscosity of the lubricant. The resulting very thin, but highly viscous layers can provide some degree of friction reduction, particularly for boundary lubrication at light loads.
- Some materials have even exhibit → Some materials even exhibit
- ratio or friction-to-normal force → ratio of contact friction force to normal force
- r is the average radius of asperities → r is the average radius of curvature of the asperities
- $A_{0,side}$ → $A_{0,\text{side}}$
- $A_{0,top}$ → $A_{0,\text{top}}$
- small amount of the softer polymer will transfer to the surface of the harder material, called a *transfer film*, as illustrated in Fig. 10.4. → small amount of the softer polymer will transfer to the surface of the harder material, as illustrated in Fig. 10.4. The transferred material is called a *transfer film*.
- components always operate some of the time → components necessarily operate some of the time
- f_m is the sum of the contributions → f_m is due to the contributions
- boundary friction coefficient is estimated → boundary friction coefficient is estimated (Section 10.3)
- Rolling adhesion is much smaller than that during sliding → Rolling adhesion is much smaller than sliding adhesion
- friction decrease with lambda ratio → friction decrease with increasing lambda ratio

Chapter 11

- wear coefficient K that is present in these equations → wear coefficient K in these equations
- environment will bond with the metal → environment will react with the metal
- vary widely and it is a function of → vary widely since it is a function of

- Higher reliability corresponds → A higher reliability goal corresponds
- Bubbles form dissolved gas → Bubbles from dissolved gas
- adhesion is not a primary wear mechanisms for → adhesion is not a primary wear mechanism for
- However, in contrast to metals, the formation an oxide → The formation of an oxide
- ultra high molecular weight → ultra-high molecular weight

Chapter 12

- most benchtop test use → most benchtop tests use
- from other tribometer geometries → from any tribometer
- benchtop tests to measure wear and characterize wear mechanisms → benchtop tests and post-test surface characterization to measure wear and investigate wear mechanisms
- Measure the lateral force (friction) → Measure the lateral force (friction force)
- Remove duplicate phrase: also called the breakaway friction
- ball creates a circular path ball → travels along a circular path
- tests involving spheres involve non-conformal contact → tests involving spheres have non-conformal contacts
- laboratory test → benchtop test
- Wear track from a linear reciprocating ball-on-flat test measured using an interferometer → Wear track on a flat measured using an interferometer after a linear reciprocating ball-on-flat test
- Problem 1 wear track area changed from 200 μm^2 to 3500 μm^2

Chapter 13

- specialized lubricants were developed that are very thin → specialized lubricants were developed to be very thin
- minimize the head-disk spacing, but still remain on the disk despite the fast speeds → minimize the head-disk spacing while remaining on the disk at very fast speeds
- leads to graduate material loss → leads to gradual material loss

- This means that the same instrument can be used to first wear the sample and then measure the nanoscale volume of material removed. → sample wear can be measured using the AFM itself with the load reduced such that the instrument is a small profilometer.
- very high due to layering near the surface → very high near the surfaces due to layering
- synovial fluid to lubricant → synovial fluid to lubricate
- New text: Tribological considerations therefore also affect the design of dental care products.

Appendix

- 3.1 $R_a = 0.412$ µm, $R_q = 0.437$ µm, $R_{sk} = -0.707$, $R_{ku} = 1.50$
- 3.2 $R_a = 0.341$ µm, $R_q = 0.398$ µm, $R_{sk} = -0.188$, $R_{ku} = 1.73$
- 4.6 $A = 3.14$ mm^2, $A = 40.0$ mm^2
- 8.4 $h_0 = 21$ µm
- 9.2 $h_{0,PE} = 0.19$ µm
- 9.3 $h_{0,IR} = 0.73$ µm
- 12.1 $V = 0.035$ µm^3
- 12.2 $V = 2.65 \times 10^{-5}$ mm^3
- 12.3 $P_{initial}$ =613 MPa, P_{final} =141 MPa
- 13.1 a =0.96 nm
- 13.2 $h_0 = 1.88$ µm