History of Tribology

Duncan Dowson
CBE, PhD, FEng, FIMechE, FCGI, Fellow ASME, Honorary Member STLE
Emeritus Professor of Engineering Fluids Mechanics and Tribology,
University of Leeds, UK
## Contents

Preface .............................................. xvii
Acknowledgements ................................. xix

### Chapter 1  Introduction
1.1  Tribology .......................... 1
1.2  History ............................ 3
1.3  Structure of the book .......... 4

### Chapter 2  Chronology
2.1  Introduction ...................... 9
2.2  A chronology of tribology .... 9
    - Geology .......................... 13
    - Evolution ....................... 13
    - History .......................... 13
    - Tribology ....................... 14

### Chapter 3  Prehistoric Times – Before c. 3500 B.C.
3.1  Introduction .................... 15
3.2  Palaeolithic period .......... 15
3.3  Mesolithic period .......... 16
3.4  Neolithic period .......... 16
3.5  Summary and chronology .... 18

### Chapter 4  The Early Civilizations
4.1  Introduction ................... 21
4.2  Mesopotamia and Egypt ..... 23
    – Drills .......................... 23
### Contents

- Potter’s wheels 26
- Wheeled vehicles 28
- Lubricants 32
- Transportation of heavy stone statues and building blocks 34

4.3 The Indus Valley 42
4.4 China 42
4.5 Central and Southern America 45
4.6 Chronology 45
4.7 Summary 46

#### Chapter 5

**The Greek and Roman Period**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>49</td>
</tr>
<tr>
<td>5.2</td>
<td>The rise of Greece</td>
<td>49</td>
</tr>
<tr>
<td>5.3</td>
<td>Philosopher, scientist and mechanicians</td>
<td>50</td>
</tr>
<tr>
<td>5.4</td>
<td>The development of machinery</td>
<td>54</td>
</tr>
<tr>
<td>5.5</td>
<td>The Romans</td>
<td>57</td>
</tr>
<tr>
<td>5.6</td>
<td>Celtic vehicles and a Chinese puzzle</td>
<td>67</td>
</tr>
<tr>
<td>5.7</td>
<td>Chronology</td>
<td>69</td>
</tr>
<tr>
<td>5.8</td>
<td>Summary</td>
<td>69</td>
</tr>
</tbody>
</table>

#### Chapter 6

**The Middle Ages**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Introduction</td>
<td>73</td>
</tr>
<tr>
<td>6.2</td>
<td>The development of machinery</td>
<td>75</td>
</tr>
</tbody>
</table>
- Bearing materials 76
- Lubricants 76
- Drills and lathes 77
| 6.3     | Roads and land transportation            | 77   |
- Wheels 78
- Footwear 79
- The wheelbarrow 79
| 6.4     | Instruments                              | 80   |
- The magnetic compass 80
- The mechanical clock 80
| 6.5     | Mechanical power generation              | 84   |
| 6.6     | Tribological stones in medieval ploughs and carts | 86 |
| 6.7     | Chronology                               | 93   |
| 6.8     | Summary                                  | 94   |

#### Chapter 7

**The Renaissance**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Introduction</td>
<td>97</td>
</tr>
</tbody>
</table>
Chapter 8  

Towards the Industrial Revolution – Early Scientific Studies of Friction

8.1  
Introduction 133

8.2  
Seventeenth-century industry 135  
– Vittorio Zonca 136  
– Water raising 140

8.3  
Bearings in the seventeenth and early eighteenth centuries 146  
– The lathe 146  
– Chronometers and navigation 147  
– The Dutch windmill 148  
– Carriage wheels and bearings 150  
– Robert Hooke 150  
– de Mondran 153  
– Jacob Rowe 154

8.4  
Early scientific studies of friction 159  
– The laws of friction and the role of asperities – the French School of Amontons, de la Hire and Parent 160  
– Germany and Leibnitz 165  
– François Joseph de Camus 165  
– The concept of cohesion – Desagulier’s work in England 165  
– Surface modelling with rigid spherical asperities by Bernard Forrest de Bélidor 170  
– Friction and applied mathematics – Leonhard Euler 171

8.5  
Viscosity and viscous flow 174

8.6  
Chronology 177
## Chapter 9

**The Industrial Revolution**

- 9.1 Introduction
- 9.2 The Industrial Revolution
  - Terminology and background
  - The textile industry
  - Agriculture
  - Communications and transportation
  - Roads
  - Canals
  - The railways
  - Steam power in industry
  - Machine tools and manufacture
  - The education and training of engineers
  - Scientific societies and professional institutions
- 9.3 Bearings in the Industrial Revolution
  - Plain bearings
  - Rolling-element bearings
- 9.4 Further studies of friction
  - Sliding friction
  - Rolling friction
- 9.5 The heyday of water-mills and windmills
  - Water-wheels
  - Windmills
- 9.6 Lubricants and lubrication
  - Fluid mechanics – viscous flow and viscosity
  - Lubricants
  - Lubrication systems
- 9.7 Wear testing
- 9.8 Tribology and the railways early in the nineteenth century
  - Wheel-rail adhesion
  - Bearings for railway wagons
- 9.9 Chronology
- 9.10 Summary

## Chapter 10

**Mineral Oil and Scientific Studies of Lubrication A.D. 1850–1925**

- 10.1 Introduction
- 10.2 Mineral oil
  - Early knowledge
- Scotland (James Young) 289
- Canada (James Miller Williams) 290
- The United States of America (Edwin L. Drake) 291

10.3 Origins of the major oil companies 294
- Exxon 298
- Socony (Mobil) 298
- Socal (Chevron) 298
- Gulf 298
- Texaco 299
- Russia 299
- Royal Dutch/Shell 300
- British Petroleum 301
- Illuminants 302
- Fuels 302
- Lubricants 303

10.4 Scientific studies of fluid-film lubrication 304
- The background 304
- France (Gustav Adolph Hirn’s studies of journal bearing friction) 305
- England (A pragmatic approach to lubricants and lubrication in the 1850s) 307
- The United States (Robert H. Thurston and the testing of lubricants) 311
- Russia (Mineral oil, the railways and the scientific work of Nikolai Pavlovich Petrov) 314
- The United Kingdom (The Institution of Mechanical Engineers’ Committee on Friction at High Velocities and the experimental work of Mr Beauchamp Tower) 321
- United Kingdom (Osborne Reynolds and the theory of fluid-film lubrication) 331
- United Kingdom (John Goodman’s estimate of film thickness) 342
- The United States (Albert Kingsbury’s experiments on air-lubricated journal bearings) 343
- Germany (Richard Striebeck’s experiments on journal friction and Ludwig Gumbel’s rationalization of the results) 344
- Germany (Arnold Johannes Wilhelm Sommerfeld) 345
- Australia (Anthony George Malden Michell) 350
- United Kingdom (W. J. Harrison’s analysis of gas bearings and dynamic loading) 351
- United States (Mayo D. Hersey’s use of dimensional analysis in the study of journal-bearing friction) 354
- England (Martin’s analysis of gear lubrication and Stanton’s approach to the experimental problem) 355
- United Kingdom (Lord Rayleigh’s early analysis of externally pressurized (hydrostatic) thrust bearings and his determination of the optimum profile of thrust bearings) 358
- Summary 359
10.5 Viscometry 360
10.6 Boundary lubrication 363
  - Sir William Bate Hardy and boundary lubrication 365
10.7 Plain bearings 370
  - Lignum-vitae 371
  - Vulcanite, glass and papier mâché 376
  - The wear of brasses 376
  - Tilting-pad bearings 377
  - Origins of specialist plain bearing manufacturers 385
10.8 The velocipede, rolling element bearings, surface contact and rolling friction 387
  - The velocipede 388
  - Materials and manufacture of steel balls 390
  - The birth of precision and ball- and roller-bearing companies 391
  - The scientific studies of Hertz, Striebeck and Goodman 400
  - Rolling friction 403
10.9 Dry friction and brakes 406
10.10 Piston rings 413
  - Early piston seals in reciprocating machinery 413
  - Metallic piston rings 415
10.11 The influence of professional institutions and government committees 419
  - The Institution of Mechanical Engineers’ Research Committee and its Sub-committee on Friction at High Velocities 420
  - The American Society of Mechanical Engineers’ Research Committee on Lubrication 420
  - The Department of Scientific and Industrial Research Advisory Council, Lubricants and Lubrication Inquiry Committee 421
10.12 Chronology 422
### Chapter 11: Towards Tribology 1925–the Present

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.1</td>
<td>Introduction</td>
<td>443</td>
</tr>
<tr>
<td>11.2</td>
<td>Surface topography</td>
<td>444</td>
</tr>
<tr>
<td>11.3</td>
<td>Friction</td>
<td>445</td>
</tr>
<tr>
<td></td>
<td>- Sliding</td>
<td>445</td>
</tr>
<tr>
<td></td>
<td>- Rolling</td>
<td>448</td>
</tr>
<tr>
<td>11.4</td>
<td>Plain bearings</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>- Materials</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>- Manufacture</td>
<td>452</td>
</tr>
<tr>
<td>11.5</td>
<td>Rolling contact bearings</td>
<td>453</td>
</tr>
<tr>
<td>11.6</td>
<td>Externally pressurized (hydrostatic) bearings</td>
<td>456</td>
</tr>
<tr>
<td>11.7</td>
<td>Gas bearings</td>
<td>457</td>
</tr>
<tr>
<td>11.8</td>
<td>Bearings selection and design (steady loading)</td>
<td>459</td>
</tr>
<tr>
<td></td>
<td>- Selection</td>
<td>459</td>
</tr>
<tr>
<td></td>
<td>- Design</td>
<td>461</td>
</tr>
<tr>
<td>11.9</td>
<td>Lubricants</td>
<td>463</td>
</tr>
<tr>
<td></td>
<td>- Additives</td>
<td>463</td>
</tr>
<tr>
<td></td>
<td>- Process fluids</td>
<td>468</td>
</tr>
<tr>
<td></td>
<td>- Synthetic lubricants</td>
<td>469</td>
</tr>
<tr>
<td></td>
<td>- Solid lubricants</td>
<td>469</td>
</tr>
<tr>
<td></td>
<td>- Summary</td>
<td>470</td>
</tr>
<tr>
<td>11.10</td>
<td>The development of fluid-film lubrication theory</td>
<td>471</td>
</tr>
<tr>
<td></td>
<td>for steadily loaded bearings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Solutions of the Reynolds equation for bearings of finite width</td>
<td>471</td>
</tr>
<tr>
<td></td>
<td>- Thermohydrodynamic lubrication</td>
<td>477</td>
</tr>
<tr>
<td></td>
<td>- Oil flow</td>
<td>481</td>
</tr>
<tr>
<td></td>
<td>- Cavitation</td>
<td>482</td>
</tr>
<tr>
<td></td>
<td>- Taylor vortices, inertia effects and turbulence</td>
<td>484</td>
</tr>
<tr>
<td></td>
<td>- Body force: gravity, magnetohydrodynamics and magnetic levitation</td>
<td>487</td>
</tr>
<tr>
<td></td>
<td>- Lubrication of real (rough) surfaces</td>
<td>488</td>
</tr>
<tr>
<td>11.11</td>
<td>Reciprocating machinery</td>
<td>489</td>
</tr>
<tr>
<td></td>
<td>- Squeeze-films</td>
<td>490</td>
</tr>
<tr>
<td></td>
<td>- Dynamically loaded bearings</td>
<td>491</td>
</tr>
<tr>
<td></td>
<td>- Piston rings</td>
<td>493</td>
</tr>
<tr>
<td>11.12</td>
<td>Bearings and rotor dynamics</td>
<td>496</td>
</tr>
<tr>
<td></td>
<td>- Rotor dynamics</td>
<td>496</td>
</tr>
<tr>
<td></td>
<td>- Bearing stiffness and damping</td>
<td>498</td>
</tr>
<tr>
<td></td>
<td>- Studies of bearing-influenced rotor dynamics</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>- Summary</td>
<td>501</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>11.13</td>
<td>Elastohydrodynamic lubrication</td>
<td>503</td>
</tr>
<tr>
<td></td>
<td>- Background</td>
<td>503</td>
</tr>
<tr>
<td></td>
<td>- Analytical</td>
<td>504</td>
</tr>
<tr>
<td></td>
<td>- Experimental</td>
<td>505</td>
</tr>
<tr>
<td></td>
<td>- Pressure</td>
<td>505</td>
</tr>
<tr>
<td></td>
<td>- Temperature</td>
<td>505</td>
</tr>
<tr>
<td></td>
<td>- Rheology and traction</td>
<td>506</td>
</tr>
<tr>
<td></td>
<td>- Gear and rolling-element bearing lubrication</td>
<td>506</td>
</tr>
<tr>
<td></td>
<td>- A mode of lubrication</td>
<td>507</td>
</tr>
<tr>
<td>11.14</td>
<td>Bio-tribology</td>
<td>507</td>
</tr>
<tr>
<td></td>
<td>- Synovial joints</td>
<td>507</td>
</tr>
<tr>
<td></td>
<td>- Total joint replacements</td>
<td>509</td>
</tr>
<tr>
<td></td>
<td>- The abrasive wear of teeth</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td>- Fluid transport in the body</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td>- The influence of micro-organisms on lubricants</td>
<td>511</td>
</tr>
<tr>
<td></td>
<td>- Summary</td>
<td>511</td>
</tr>
<tr>
<td>11.15</td>
<td>The medical analogy – machine health, diagnosis, monitoring and prognosis</td>
<td>512</td>
</tr>
<tr>
<td></td>
<td>- Health</td>
<td>512</td>
</tr>
<tr>
<td></td>
<td>- Diagnosis</td>
<td>512</td>
</tr>
<tr>
<td></td>
<td>- Monitoring</td>
<td>513</td>
</tr>
<tr>
<td></td>
<td>- Prognosis</td>
<td>514</td>
</tr>
<tr>
<td></td>
<td>- Summary</td>
<td>514</td>
</tr>
<tr>
<td>11.16</td>
<td>High-friction materials</td>
<td>515</td>
</tr>
<tr>
<td></td>
<td>- Wood, leather and fabrics</td>
<td>515</td>
</tr>
<tr>
<td></td>
<td>- Asbestos</td>
<td>515</td>
</tr>
<tr>
<td></td>
<td>- Sintered metals</td>
<td>515</td>
</tr>
<tr>
<td></td>
<td>- Ceramics</td>
<td>516</td>
</tr>
<tr>
<td></td>
<td>- Rubber</td>
<td>516</td>
</tr>
<tr>
<td></td>
<td>- Summary</td>
<td>517</td>
</tr>
<tr>
<td>11.17</td>
<td>Surface contact</td>
<td>518</td>
</tr>
<tr>
<td></td>
<td>- Plastic deformation</td>
<td>518</td>
</tr>
<tr>
<td></td>
<td>- Elastic deformation</td>
<td>518</td>
</tr>
<tr>
<td></td>
<td>- Plasticity index</td>
<td>519</td>
</tr>
<tr>
<td></td>
<td>- Recent studies of surface contact</td>
<td>520</td>
</tr>
<tr>
<td>11.18</td>
<td>Wear</td>
<td>521</td>
</tr>
<tr>
<td></td>
<td>- Definition</td>
<td>522</td>
</tr>
<tr>
<td></td>
<td>- Types of wear</td>
<td>522</td>
</tr>
<tr>
<td></td>
<td>- Relative importance of wear mechanisms</td>
<td>523</td>
</tr>
<tr>
<td></td>
<td>- History of wear studies</td>
<td>523</td>
</tr>
<tr>
<td></td>
<td>- Adhesive wear</td>
<td>524</td>
</tr>
<tr>
<td></td>
<td>- Abrasive wear</td>
<td>525</td>
</tr>
<tr>
<td></td>
<td>- The ‘zero wear’ model</td>
<td>526</td>
</tr>
<tr>
<td></td>
<td>- Delamination</td>
<td>527</td>
</tr>
</tbody>
</table>
11.19

- Non-metallic materials 528
- Summary 528

Professional bodies, meetings and the literature 529
- The Institution of Mechanical Engineers 529
- The American Society of Mechanical Engineers 532
- The American Society of Lubrication Engineers 533
- The Royal Society of London 534
- The Japan Societies of Mechanical and
  Lubrication Engineers 535
- The USSR Academy of Sciences 535
- The Gordon conferences 535
- Limits of lubrication conferences 536
- The Leeds–Lyon symposia on tribology 536
- The National Aeronautics and Space
  Administration interdisciplinary symposia 536
- The University of Southampton Gas Bearing
  Symposia 537
- European Tribology Congress (Eurotrib) 537
- Individual conferences and symposia 538
- The Literature 538

11.20

Tribology 544
- Formation of the Lubrication Engineering
  Working Group in the United Kingdom 545
- The Committee on Tribology 547
- International developments 549
- Tribology awards 550
- Summary 550

Chapter 12

Towards the Millennium, 1977–1997 553

12.1

Introduction 553

12.2

Elastohydrodynamic lubrication 555
- Friction/traction and power loss 560
- Non-steady state conditions 562
- Very thin film (VTF) elastohydrodynamic
  lubrication 563
- Micro or asperity lubrication 564
- Transition from elastohydrodynamic to
  boundary lubrication 566

12.3

Friction 568
- The surface force apparatus (SFA) and atomic
  force microscope (AFM) 569
- Molecular dynamics 569

12.4

Wear 570
12.5 Materials
12.6 Surface engineering
12.7 Condition monitoring
12.8 Bio-tribology
  - Dental tissue and restorative materials
  - Total replacement joints
12.9 Computers and magnetic storage systems
12.10 Tribologists, tribology societies, literature, and meetings
  - The Institution of Mechanical Engineers
  - The American Society of Mechanical Engineers
  - The Society of Tribologists and Lubrication Engineers
  - The Japanese Society of Tribologists
  - The Leeds–Lyon Symposia on Tribology
  - Wear of Materials Conferences
  - National and International Conferences and Symposia
12.11 Lubricant Technology
12.12 Summary

Appendix
A.1 Introduction
A.2 Leonardo da Vinci (1452–1519)
A.3 Guillaume Amontons (1663–1705)
A.4 John Theophilus Desaguliers (1683–1744)
A.5 Charles Augustin Coulomb (1736–1806)
A.6 Arthur-Jules Morin (1795–1880)
A.7 Gustav Adolph Hirn (1815–1890)
A.8 Nikola Pavlovich Petrov (1836–1920)
A.9 Robert Henry Thurston (1839–1903)
A.10 Osborne Reynolds (1842–1912)
A.11 John William Strutt, third Baron Rayleigh (1842–1919)
A.12 Beauchamp Tower (1845–1904)
A.13 Heinrich Rudolph Hertz (1857–1894)
A.14 Richard Striebeck (1861–1950)
A.15 John Goodman (1862–1935)
A.16 Albert Kingsbury (1863–1943)
A.17 William Bate Hardy (1864–1934)
A.18 Arnold Johannes Wilhelm Sommerfeld (1868–1951) 653
A.19 Anthony George Maldon Michell (1870–1959) 656
A.20 Ludwig Karl Friedrich Gümbel (1874–1923) 663
A.21 Herbert Walker Swift (1894–1960) 667
A.22 Georg Vogelpohl (1900–1975) 669
A.23 Frank Philip Bowden (1903–1968) 673
A.24 Fred William Ocvirk (1913–1967) 679
A.25 Summary 682
Introduction to 1998 supplement to Appendix – Men of Tribology 683
A.26 Mayo Dyer Hersey (1886–1978) 684
A.27 Igor Victorovich Kragelskii (1908–1989) 687
A.28 Georgi Vladimirovich Vinogradov (1910–1988) 689
A.29 Frederick Thomas Barwell (1911–1988) 691
A.30 Norimune Soda (1911–1995) 693
A.31 Dudley Dean Fuller (1913–1993) 694
A.32 Toshio Sakurai (1915–1995) 695
A.33 John Frederick Archard (1918–1989) 697
A.34 Vladimir Alexeevich Belyi (1920–1993) 699
A.35 Maurice Godet (1930–1993) 700
References and Selected Bibliography 703
Subject Index 749
Name Index 759