

Contents

List of Contributors V

Foreword XXXI

A word of thanks XXXIII

List of Abbreviations XXXV

1	Lubricants and their Market	1
1.1	Preface	1
1.2	Lubricant Sales	2
1.3	The Lubricants Industry	3
1.4	Lubricant Systems	5
2	Lubricants in the Tribological System	7
2.1	Lubricants as Part of Tribological Research	7
2.2	The Tribological System	8
2.3	Friction	8
2.3.1	Types of Friction	9
2.3.1.1	Sliding Friction	9
2.3.1.2	Rolling Friction	10
2.3.1.3	Static Friction	10
2.3.1.4	Kinetic Friction	10
2.3.1.5	Stick-Slip	10
2.3.2	Friction and Lubrication Conditions	12
2.3.2.1	Solid Friction (Dry Friction)	12
2.3.2.2	Boundary Friction	12
2.3.2.3	Fluid Friction	13
2.3.2.4	Mixed Friction	13
2.3.2.5	Solid Lubricant Friction	13
2.3.2.6	Stribeck Diagram	13
2.3.2.7	Hydrodynamic Lubrication	14
2.3.2.8	Elasto-Hydrodynamic Lubrication (EHD Regime)	14

2.4	Wear	15
2.4.1	Wear Mechanisms	15
2.4.1.1	Abrasion	15
2.4.1.2	Adhesion	17
2.4.1.3	Tribochemical Reactions	17
2.4.1.4	Surface Fatigue	17
2.4.1.5	Erosion	17
2.4.1.6	Fretting	17
2.4.1.7	Cavitation	18
2.4.2	Types of Wear	18
2.4.3	The Wear Process	18
2.4.4	Tribomutation	18
3	Rheology of Lubricants	21
3.1	Viscosity	21
3.2	Influence of Temperature on Viscosity (V–T Behavior)	23
3.2.1	Viscosity Index	24
3.3	Viscosity–Pressure Dependency	25
3.4	The Effect of Shear Rate on Viscosity	26
3.5	Special Rheological Effects	28
3.5.1	Greases	29
3.6	Viscosity Grades	29
3.6.1	ISO Viscosity Grades	29
3.6.2	Other Viscosity Grades	30
3.6.2.1	Engine Oils	30
3.6.2.2	Automotive Gear Oils	30
3.6.2.3	Industrial Gear Oils	30
3.6.2.4	Viscosity Grades for Base Oils	30
3.6.2.5	Comparison of Viscosity Grades	30
4	Base Oils	32
4.1	Base Oils—A Historical Review and Outlook	32
4.2	Chemical Characterization of Mineral Base Oils	33
4.2.1	Rough Chemical Characterization	33
4.2.1.1	Viscosity–Gravity Constant (VGC)	33
4.2.1.2	Aniline Point	33
4.2.2	Carbon Distribution	34
4.2.3	Hydrocarbon Composition	34
4.2.4	Polycyclic Aromatics in Base Oils	34
4.2.4.1	Aromatics in White Mineral Oils	35
4.3	Refining	36
4.3.1	Distillation	37
4.3.2	De-asphalting	37
4.3.3	Traditional Refining Processes	38
4.3.3.1	Acid Refining	39

4.3.3.2	Solvent Extraction	39
4.3.4	Solvent Dewaxing	41
4.3.5	Finishing	42
4.3.5.1	Lube Crudes	42
4.4	Base Oil Manufacturing by Hydrogenation and Hydrocracking	43
4.4.1	Manufacturing Naphthenic Base Oils by Hydrogenation	44
4.4.2	Production of White Oils	46
4.4.3	Lube Hydrocracking	47
4.4.4	Catalytic Dewaxing	48
4.4.5	Wax Isomerization	50
4.4.6	Hybrid Lube Oil Processing	50
4.4.7	All-Hydrogen Route	51
4.4.8	Gas-to-Liquids Conversion Technology	53
4.5	Boiling and Evaporation Behavior of Base Oils	53
4.6	Base Oil Categories and Evaluation of Various Petroleum Base Oils	56

5	Synthetic Base Oils	61
5.1	Synthetic Hydrocarbons	62
5.1.1	Polyalphaolefins	63
5.1.2	Polyinternalolefins	65
5.1.3	Polybutenes	66
5.1.4	Alkylated Aromatics	67
5.1.5	Other Hydrocarbons	68
5.2	Halogenated Hydrocarbons	69
5.3	Synthetic Esters	69
5.3.1	Esters of carboxylic acids	69
5.3.1.1	Dicarboxylic Acid Esters	70
5.3.1.2	Polyol Esters	71
5.3.1.3	Other Carboxylic Esters	72
5.3.1.4	Complex Esters	73
5.3.1.5	Fluorinated Carboxylic Acid Esters	73
5.3.2	Phosphate Esters	74
5.4	Polyalkylene Glycols	75
5.5	Other Polyethers	77
5.5.1	Perfluorinated Polyethers	77
5.5.2	Polyphenyl Ethers	78
5.5.3	Polysiloxanes (Silicone Oils)	79
5.6	Other Synthetic Base Oils	81
5.7	Mixtures of Synthetic Lubricants	84

6	Additives	85
6.1	Antioxidants	86
6.1.1	Mechanism of Oxidation and Antioxidants	86
6.1.2	Compounds	88
6.1.2.1	Phenolic Antioxidants	88

6.1.2.2	Aromatic Amines	88
6.1.2.3	Compounds Containing Sulfur and Phosphorus	89
6.1.2.4	Organosulfur Compounds	89
6.1.2.5	Organophosphorus Compounds	89
6.1.2.6	Other Compounds	90
6.1.2.7	Synergistic Mixtures	90
6.1.3	Testing of the Oxidation Stability	90
6.2	Viscosity Modifiers	91
6.2.1	Physical Description of Viscosity Index	91
6.2.2	VI Improvement Mechanisms	91
6.2.3	Structure and Chemistry of Viscosity Modifiers	93
6.3	Pourpoint Depressants (PPD)	94
6.4	Detergents and Dispersants	96
6.4.1	Mechanism of DD Additives	96
6.4.2	Metal-containing Compounds (Detergents)	97
6.4.2.1	Phenates	97
6.4.2.2	Salicylates	98
6.4.2.3	Thiophosphonates	98
6.4.2.4	Sulfonates	98
6.4.3	Ashless Dispersants (AD)	99
6.5	Antifoam Agents	100
6.5.1	Silicon Defoamers	101
6.5.2	Silicone-free Defoamers	102
6.6	Demulsifiers and Emulsifiers	102
6.6.1	Demulsifiers	102
6.6.2	Emulsifiers	102
6.7	Dyes	102
6.8	Antiwear (AW) and Extreme Pressure (EP) Additives	103
6.8.1	Function of AW/EP Additives	103
6.8.2	Compounds	104
6.8.2.1	Phosphorus compounds	104
6.8.2.2	Compounds Containing Sulfur and Phosphorus	104
6.8.2.3	Compounds Containing Sulfur and Nitrogen	106
6.8.2.4	Sulfur Compounds	106
6.8.2.5	PEP Additives	108
6.8.2.6	Chlorine Compounds	108
6.8.2.7	Solid Lubricating Compounds	109
6.9	Friction Modifiers (FM)	109
6.10	Corrosion Inhibitors	110
6.10.1	Mechanism of Corrosion Inhibitors	110
6.10.2	Antirust Additives (Ferrous Metals)	111
6.10.2.1	Sulfonates	111
6.10.2.2	Carboxylic Acid Derivatives	111
6.10.2.3	Amine Neutralized Alkylphosphoric Acid Partial Esters	112
6.10.2.4	Vapor Phase Corrosion Inhibitors	112

6.10.3	Metal Passivators (Non-ferrous Metals)	113
7	Lubricants in the Environment	115
7.1	Definition of 'Environmentally Friendly Lubricants'	115
7.2	Current Situation	116
7.2.1	Statistical Data	116
7.2.2	Economic Consequences and Substitution Potential	117
7.2.3	Agriculture, Economy, and Politics	119
7.2.4	Political Initiatives	120
7.3	Tests to Evaluate Biotic Potential	121
7.3.1	Biodegradation	121
7.3.2	Ecotoxicity	122
7.3.3	Emission Thresholds	123
7.3.4	Water Pollution	123
7.3.4.1	The German Water Hazardous Classes	123
7.3.4.2	German Regulations for Using Water-endangering Lubricants (VAWS)	124
7.4	Environmental Legislation 1: Regular use	126
7.4.1	Environmental Liability Law	126
7.4.2	The Chemicals Law, Hazardous Substances Law	127
7.4.3	Transport Regulations	128
7.4.4	Disposal (Waste and Recycling Laws)	128
7.4.5	Disposal Options for 'Not water pollutant' Vegetable Oils	129
7.5	Environmental Legislation 2: Emissions	130
7.5.1	Air Pollution	130
7.5.2	Water Pollution	130
7.5.3	German Law for Soil Protection	131
7.5.4	German Water Law	131
7.5.5	Waste Water Charges	132
7.5.6	Clean Air: German Emissions Law	133
7.5.7	Drinking Water Directive	133
7.6	Standardization of Environmentally Friendly Hydraulic Fluids	133
7.6.1	The German Regulation VDMA 24568	134
7.6.2	ISO Regulation	136
7.7	Environmental Seal	136
7.7.1	Global Eco-labeling Network	136
7.7.2	European Eco-labels	137
7.7.3	The German 'Blue Angel'	137
7.7.4	Nordic countries (Norway, Sweden, Finland, Iceland) – 'White Swan'	139
7.7.4.1	Requirements Concerning Renewable Resources	140
7.7.4.2	Requirements Concerning Re-refined Oil	141
7.7.4.3	Requirements Concerning Environmentally Harmful Components	141
7.7.4.4	Requirements for Hydraulic Fluids, Mold Oil, Metalworking Fluids	141
7.7.5	The Canadian 'Environmental Choice' (Maple Leaf)	141

7.7.6	Other Eco-labels	143
7.7.6.1	Austria	143
7.7.6.2	Brazil	143
7.7.6.3	China	143
7.7.6.4	France	143
7.7.6.5	Japan	144
7.7.6.6	Spain	144
7.7.6.7	Thailand	144
7.7.6.8	United Kingdom	144
7.7.6.9	USA	145
7.7.7	The Netherlands	145
7.8	Base Fluids	146
7.8.1	Biodegradable Base Oils for Lubricants	146
7.8.2	Synthetic Esters	148
7.8.3	Polyglycols	148
7.8.4	Polyalphaolefins	149
7.8.5	Relevant Properties of Ester Oils	149
7.8.5.1	Evaporation Loss	149
7.8.5.2	Viscosity–Temperature Behavior	149
7.8.5.3	Boundary Lubrication	150
7.9	Additives	150
7.9.1	Extreme Pressure/Antiwear Additives	151
7.9.2	Corrosion Protection	151
7.9.3	Antioxidants	151
7.10	Products (Examples)	151
7.10.1	Hydraulic Fluids	151
7.10.2	Metal Working Oil	152
7.10.3	Oil-refreshing System	152
7.11	Safety Aspects of Handling Lubricants (Working Materials)	153
7.11.1	Toxicological Terminology and Hazard Indicators	154
7.11.1.1	Acute Toxicity	154
7.11.1.2	Subchronic and Chronic Toxicity	154
7.11.1.3	Poison Categories	154
7.11.1.4	Corrosive, Caustic	155
7.11.1.5	Explosion and Flammability	155
7.11.1.6	Carcinogenic	155
7.11.1.7	Teratogens, Mutagens	155
7.11.2	MAK (Maximum Workplace Concentration) Values	155
7.11.3	Polycyclic Aromatic Hydrocarbons (PAK, PAH, PCA)	156
7.11.4	Nitrosamines in Cutting Fluids	157
7.11.5	Law on Flammable Fluids	158
7.12	Skin Problems Caused by Lubricants	158
7.12.1	Structure and Function of the Skin	159
7.12.2	Skin Damage	159
7.12.2.1	Oil Acne (Particle Acne)	160

7.12.2.2	Oil Eczema	160
7.12.3	Testing Skin Compatibility	161
7.12.4	Skin Function Tests	163
7.12.5	Skin Care and Skin Protection	164
8	Disposal of Used Lubricating Oils	165
8.1	Possible Uses of Waste Oil	166
8.2	Legislative Influences on Waste Oil Collection and Reconditioning	166
8.3	Re-refining	167
8.3.1	Sulfuric Acid Refining (Meinken)	167
8.3.2	Propane Extraction Process (IFP, Snamprogetti)	168
8.3.3	Mohawk Technology (CEP–Mohawk)	169
8.3.4	KTI Process	169
8.3.5	PROP Process	169
8.3.6	Safety Kleen Process	170
8.3.7	DEA Technology	171
8.3.8	Other Re-refining Technologies	172
9	Lubricants for Internal Combustion Engines	173
9.1	Four-stroke Engine Oils	173
9.1.1	General Overview	173
9.1.1.1	Fundamental Principles	174
9.1.1.2	Viscosity Grades	175
9.1.1.3	Performance Specifications	177
9.1.1.4	Formulation of Engine Oils	178
9.1.1.5	Additives	178
9.1.1.6	Performance Additives	178
9.1.1.7	Viscosity Improvers	179
9.1.2	Characterization and Testing	179
9.1.2.1	Physical and Chemical Testing	180
9.1.2.2	Engine Testing	180
9.1.2.3	Passenger Car Engine Oils	182
9.1.2.4	Engine Oil for Commercial Vehicles	183
9.1.3	Classification by Specification	184
9.1.3.1	MIL Specifications	184
9.1.3.2	API and ILSAC Classification	184
9.1.3.3	CCMC Specifications	186
9.1.3.4	ACEA Specifications	188
9.1.3.5	Manufacturers' Approvals	189
9.1.3.6	Future Trends	191
9.1.3.7	Fuel Efficiency	192
9.1.3.8	Long Drain Intervals	192
9.1.3.9	Low Emission	195
9.2	Two-stroke Oils	195
9.2.1	Application and Characteristics of Two-stroke Oils [9.25–9.27]	195

9.2.2	Classification of Two-stroke Oils	197
9.2.2.1	API Service Groups	197
9.2.2.2	JASO Classification	197
9.2.2.3	ISO Classification	198
9.2.3	Oils for Two-stroke Outboard Engines	199
9.2.4	Environmentally Friendly Two-stroke Oils [9.31]	200
9.3	Tractor Oils	201
9.4	Gas Engine Oils [9.32–9.34]	202
9.4.1	Use of Gas Engines—Gas as a Fuel	203
9.4.2	Lubricants for Gas Engines	203
9.5	Marine Diesel Engine Oils [9.35]	204
9.5.1	Low-speed Crosshead Engines	204
9.5.2	Medium-speed Engines	205
9.5.3	Lubricants	206
10	Gear Lubrication Oils	207
10.1	Introduction	207
10.2	Requirements of Gear Lubrication Oils	208
10.3	Tribology of Gears	210
10.3.1	Friction Conditions of Gear Types	211
10.3.1.1	Toothed Wheels	211
10.3.1.2	Load and Speed Conditions During Tooth Engagement	211
10.3.1.3	Static and Dynamic Load Distribution in Tooth Engagement	213
10.3.1.4	Lubrication Film Generation in Tooth Contact	214
10.3.1.5	Lubrication Conditions	215
10.3.2	Specific Gear and Transmission Failure	217
10.3.2.1	Wear	218
10.3.2.2	Scuffing and Scoring	218
10.3.2.3	Micro-pitting	219
10.3.2.4	Pitting	221
10.3.2.5	Tooth Fracture	222
10.4	Gear Lubrication Oils for Motor Vehicles	222
10.4.1	Lubricants for Gear Drives in Commercial Vehicles	224
10.4.2	Lubricants for Gear Drives in Passenger Cars	227
10.4.3	Lubricants for Automatic Transmissions and CVTs	231
10.4.3.1	ATF Lubricant Requirements for Hydrodynamic Transmissions	232
10.4.3.2	ATF Lubricant Requirements for Wet Clutches and Brakes	233
10.4.3.3	Gear Lubrication Oils for CVT Applications	236
10.4.3.4	B-CVT Belt Drives	237
10.4.3.5	T-CVT Traction Drives	238
10.4.3.6	Hydrostatic Dynamic Powershift Drives	239
10.5	Multipurpose Lubricants in Vehicle Gears	240
10.6	Gear Lubricants for Industrial Gears	241
10.6.1	Viscosity–Temperature Behavior and Viscosity Index	243
10.6.2	Corrosion and Rust Protection	243

10.6.3	Oxidation Stability	243
10.6.4	Flash Point and Pour Point	244
10.6.5	Demulsibility and Water Separation	244
10.6.6	Air Separation	244
10.6.7	Paint Compatibility	244
10.6.8	Seal Compatibility	244
10.6.9	Foaming	245
10.6.10	Miscibility with Mineral Oils	245
10.6.11	Environmental and Skin Compatibility	245
10.6.12	Open gear drives	245
11	Hydraulic Oils	246
11.1	Introduction	246
11.2	Hydraulic Principle–Pascal’s Law	247
11.3	Hydraulic Systems, Circuits, Components	248
11.3.1	Elements of a Hydraulic System	248
11.3.1.1	Pumps and Motors	248
11.3.1.2	Hydraulic Cylinders	249
11.3.1.3	Valves	251
11.3.1.4	Circuit Components	251
11.3.1.5	Seals, Gaskets and Elastomers	251
11.4	Hydraulic Fluids	253
11.4.1	Composition of Hydraulic Fluids (Base fluids, additives)	253
11.4.1.1	Base Oil, Base Fluid	253
11.4.1.2	Hydraulic Fluid Additives	253
11.4.2	Primary, Secondary and Tertiary Characteristics of a Hydraulic Fluid	254
11.4.3	Selection Criteria for Hydraulic Fluids	254
11.4.4	Classification of Hydraulic Fluids–Standardization of Hydraulic Fluids	257
11.4.5	Mineral Oil-Based Hydraulic Fluids	258
11.4.5.1	H Hydraulic Oils	259
11.4.5.2	HL Hydraulic Oils	259
11.4.5.3	HLP Hydraulic Oils	261
11.4.5.4	HVLP Hydraulic Oils	261
11.4.5.5	HLPD Hydraulic Oils	261
11.4.6	Fire-Resistant Hydraulic Fluids	265
11.4.6.1	HFA Fluids	265
11.4.6.2	HFB Fluids	266
11.4.6.3	HFC Fluids	266
11.4.6.4	HFD Fluids	266
11.4.7	Biodegradable Hydraulic Fluids	267
11.4.7.1	HETG: Triglyceride, Vegetable-Oil Types	268
11.4.7.2	HEES: Synthetic Ester Types	269
11.4.7.3	HEPG: Polyglycol Types	270

11.4.7.4	HEPR: Polyalphaolefin and Related Hydrocarbon Products	273
11.4.8	Food-Grade Hydraulic Fluids	273
11.4.8.1	USDA H2 Lubricants	273
11.4.8.2	USDA H1 Lubricants	273
11.4.9	Automatic Transmission Fluids (ATF)	274
11.4.10	Fluids in Tractors and Agricultural Machinery	274
11.4.11	Hydraulic Fluids for Aircraft	274
11.4.12	International Requirements on Hydraulic Oils	275
11.4.13	Physical Properties of Hydraulic Oils and Their Effect on Performance	275
11.4.13.1	Viscosity, V-T Behavior	275
11.4.13.2	Viscosity-Pressure Behavior	279
11.4.13.3	Density	280
11.4.13.4	Compressibility	282
11.4.13.5	Gas Solubility, Cavitation	282
11.4.13.6	Air Release	284
11.4.13.7	Foaming	285
11.4.13.8	Demulsification	285
11.4.13.9	Pour-point	286
11.4.13.10	Copper Corrosion Behavior (Copper-Strip Test)	286
11.4.13.11	Water Content (Karl Fischer method)	287
11.4.13.12	Aging Stability (Baader method)	287
11.4.13.13	Aging Stability (TOST test)	287
11.4.13.14	Neutralization Number	287
11.4.13.15	Steel/Ferrous Corrosion Protection Properties	288
11.4.13.16	Wear Protection (SHELL four-ball apparatus; VKA, DIN 51 350)	288
11.4.13.17	Shear Stability of Polymer-containing Lubricants	288
11.4.13.18	Mechanical Testing of Hydraulic Fluids in Rotary Vane Pumps (DIN 51 389-2)	288
11.4.13.19	Wear Protection (FZG Gear Rig Test; DIN 51 354-1 and -2)	289
11.5	Hydraulic System Filters	289
11.5.1	Contaminants in Hydraulic Fluids	290
11.5.2	Oil Cleanliness Grades	291
11.5.3	Filtration	291
11.5.4	Requirements of Hydraulic Fluids	292
11.6	Machine Tool Lubrication	293
11.6.1	The Role of Machine Tools	293
11.6.2	Machine Tool Lubrication	293
11.6.3	Machine Tool Components-Lubricants	295
11.6.3.1	Hydraulic Unit	295
11.6.3.2	Slideways	296
11.6.3.3	Spindles (Main and Working Spindles)	297
11.6.3.4	Gearboxes and Bearings	298
11.6.4	Machine Tool Lubrication Problems	298
11.7	Summary	299

12	Compressor oils	301
12.1	Air Compressor Oils	301
12.1.1	Displacement Compressors	303
12.1.1.1	Reciprocating Piston Compressors	303
12.1.1.2	Lubrication of Reciprocating Piston Compressors	303
12.1.1.3	Rotary Piston Compressors, Single Shaft, Rotary Vane Compressors	304
12.1.1.4	Lubrication of rotary piston compressors	304
12.1.1.5	Screw Compressors	305
12.1.1.6	Lubrication of Screw Compressors	305
12.1.1.7	Roots Compressors	306
12.1.1.8	Lubrication of Roots Compressors	306
12.1.2	Dynamic Compressors	306
12.1.2.1	Turbo Compressors	306
12.1.2.2	Lubrication of Turbo Compressors	307
12.1.3	Preparation of Compressed Air	307
12.1.4	Lubrication of Gas Compressors	307
12.1.4.1	Oxygen Compressors	307
12.1.4.2	Acid Gas Compressors	307
12.1.4.3	Inert Gas Compressors	307
12.1.4.4	Hydrocarbon Compressors	307
12.1.4.5	Vacuum Pump Lubrication	308
12.1.5	Characteristics of Compressor Oils	308
12.1.6	Standards and Specifications of Compressor Oils	308
12.2	Refrigerator Oils	316
12.2.1	Introduction	316
12.2.2	Minimum Requirements of Refrigerator Oils	317
12.2.2.1	DIN 51 503-1: Refrigerator oils, Minimum requirements (1997)	317
12.2.3	Classifications of Refrigerator Oils	318
12.2.3.1	Mineral Oils (MO)–Dewaxed Naphthenic Refrigerator Oils	318
12.2.3.2	Mineral Oils (MO)–Paraffinic Refrigerator Oils	318
12.2.3.3	Semi-Synthetic Refrigerator Oils–Mixtures of alkylbenzenes and mineral oils (MO/AB)	319
12.2.3.4	Fully Synthetic Refrigerator Oils–Alkylbenzenes (AB)	320
12.2.3.5	Fully Synthetic Refrigerator Oils–Polyalphaolefins (PAO)	320
12.2.3.6	Fully Synthetic Refrigerator Oils–Polyol esters (POE)	320
12.2.3.7	Fully Synthetic Refrigerator Oils–Polyglycols (PAG) for R 134a	322
12.2.3.8	Fully Synthetic Refrigerator Oils–Polyglycols for NH ₃	322
12.2.3.9	Other Synthetic Fluids	322
12.2.3.10	Refrigerator Oils for CO ₂	322
12.2.3.11	Copper Plating	323
12.2.4	Types of Compressor	323
12.2.5	Viscosity Selection	323
12.2.5.1	General Overview	323

12.2.5.2	Mixture Concentration in Relationship to Temperature and Pressure (RENISO Triton SE 55–R 134a)	325
12.2.5.3	Mixture Viscosity in Relationship to Temperature, Pressure and Refrigerant Concentration (RENISO Triton SE 55–R 134a)	326
12.2.5.4	Mixture Density in Relationship to Temperature and Refrigerant Concentration (RENISO Triton SE 55–R 134a; Fig. 12.9)	328
12.2.5.5	Miscibility Gap, Solubility Threshold (RENISO Triton Series with R 134a, Fig. 12.10)	328
12.2.6	Summary	329
13	Turbine Oils	330
13.1	Introduction	330
13.2	Demands on Turbine Oils–Characteristics	330
13.3	Formulation of Turbine Oils	331
13.4	Turbine Lubricants–Specifications	332
13.5	Turbine Oil Circuits	337
13.6	Flushing Turbine Oil Circuits	342
13.7	Monitoring and Maintenance of Turbine Oils	343
13.8	Life of (Steam) Turbine Oils	343
13.9	Gas Turbine Oils–Application and Requirements	344
13.10	Fire-resistant, Water-free Fluids for Power Station Applications	345
13.11	Lubricants for Water Turbines and Hydroelectric Plants	346
14	Metalworking Fluids	347
14.1	Action Mechanism and Cutting Fluid Selection	348
14.1.1	Lubrication	349
14.1.2	Cooling	350
14.1.3	Significance of Cutting Fluid with Various Cutting Materials	352
14.1.3.1	High-speed Steels	352
14.1.3.2	Cemented Carbide Metals	353
14.1.3.3	Coated Carbide Metals	353
14.1.3.4	Ceramic Materials	353
14.1.3.5	Cubic Boron Nitride (CBN)	353
14.1.3.6	Polycrystalline Diamond (PCD)	354
14.1.3.7	Coatings	354
14.1.4	Cutting Fluid Selection for Various Cutting Methods and Cutting Conditions	354
14.2	Friction and Wear Assessment Method for the Use of Cutting Fluids	356
14.2.1	Tool Life and Number of Parts Produced by the Tool as Practical Assessment Parameters	357
14.2.2	Measuring Cutting Forces in Screening Tests	357
14.2.3	Feed Rates at Constant Feed Force	358
14.2.4	Measuring Tool Life by Fast-screening Methods	358
14.2.5	Cutting Geometry and Chip Flow	359

14.2.6	Other Fast Testing Methods	360
14.2.6.1	Temperature Measurement	360
14.2.6.2	Radioactive Tools	360
14.2.6.3	Surface Finish	360
14.3	Water-miscible Cutting Fluids	360
14.3.1	Nomenclature and Breakdown	361
14.3.2	Composition	363
14.3.2.1	Emulsifiers	363
14.3.2.2	Viscosity of Emulsions	369
14.3.2.3	Phase Reversal, Determination of the Type of Emulsion	370
14.3.2.4	Degree of Dispersion	371
14.3.2.5	Stability	372
14.3.2.6	Corrosion Inhibitors and other Additives	374
14.3.2.7	Cutting Fluids Containing Emulsifiers	376
14.3.2.8	Coolants Containing Polyglycols	378
14.3.2.9	Salt Solutions	378
14.3.3	Corrosion Protection and Corrosion Test Methods	379
14.3.4	Concentration of Water-mixed Cutting Fluids	380
14.3.4.1	Determination of Concentration by DIN 51 368 (IP 137)	380
14.3.4.2	Concentration Measurement Using Hand-held Refractometers	381
14.3.4.3	Concentration Measurement Through Individual Components	381
14.3.4.4	Determination of Concentration by Titration of Anionic Components	381
14.3.4.5	Determination of Concentration Through Alkali Reserve	382
14.3.4.6	Concentration after Centrifuging	382
14.3.5	Stability of Coolants	382
14.3.5.1	Determination of Physical Emulsion Stability	382
14.3.5.2	Electrolyte Stability	383
14.3.5.3	Thermal Stability	384
14.3.5.4	Stability to Metal Chips	385
14.3.6	Foaming Properties	385
14.3.6.1	Definition and Origin of Foam	386
14.3.6.2	Foam Prevention	387
14.3.6.3	Methods of Determining Foam Behavior	387
14.3.7	Metalworking Fluid Microbiology	388
14.3.7.1	Hygienic and Toxicological Aspects of Microorganisms	389
14.3.7.2	Methods of Determining Microbial Count	390
14.3.7.3	Determination of the Resistance of Water-miscible Coolants Towards Microorganisms	391
14.3.7.4	Reducing or Avoiding Microbial Growth in Coolants	391
14.3.8	Preservation of Coolants with Biocides	393
14.3.8.1	Aldehydes	396
14.3.8.2	Formaldehyde Release Compounds	396
14.3.8.3	Phenol Derivatives	397
14.3.8.4	Compounds Derived from Carbon Disulfide	397

14.3.8.5	Isothiazoles	397
14.3.8.6	Fungicides	398
14.3.8.7	Hypochlorites	398
14.3.8.8	Hydrogen Peroxide, H_2O_2	398
14.3.8.9	Quaternary Ammonium Compounds	398
14.4	Neat Cutting Fluids	398
14.4.1	Classification of Neat Metalworking Oils According to Specifications	399
14.4.2	Composition of Neat Metalworking Fluids	399
14.4.2.1	Base Oils and Additives	399
14.4.2.2	Significance of Viscosity on the Selection of Neat Products	401
14.4.3	Oil Mist and Oil Evaporation Behavior	401
14.4.3.1	Evaporation Behavior	402
14.4.3.2	Low-Misting Oils	402
14.4.3.3	The Creation of Oil Mist	402
14.4.3.4	Sedimentation and Separation of Oil Mists	403
14.4.3.5	Toxicity of Oil Mist	403
14.4.3.6	Oil Mist Measurement	404
14.4.3.7	Oil Mist Index	405
14.4.3.8	Oil Mist Concentration in Practice	406
14.5	Machining with Geometrically Defined Cutting Edges	407
14.5.1	Turning	407
14.5.2	Drilling	409
14.5.3	Milling	409
14.5.4	Gear Cutting	410
14.5.5	Deep Hole Drilling	411
14.5.5.1	Deep Hole Drilling Methods	412
14.5.5.2	Tasks to be Fulfilled by the Cutting Fluid	413
14.5.6	Threading and Tapping	414
14.5.7	Broaching	415
14.6	Machining with Geometric Non-defined Cutting Edges	416
14.6.1	Grinding	416
14.6.1.1	High-speed Grinding	416
14.6.1.2	Grinding Wheel Abrasive Materials and Bondings	417
14.6.1.3	Requirements for Grinding Fluids	418
14.6.1.4	Special Workpiece Material Considerations	418
14.6.1.5	CBN High-speed Grinding	419
14.6.1.6	Honing	420
14.6.1.7	Honing Oils	422
14.6.1.8	Lapping	422
14.6.1.9	Lapping Powder and Carrier Media	423
14.7	Specific Material Requirements for Machining Operations	423
14.7.1	Ferrous Metals	423
14.7.1.1	Steel	423
14.7.1.2	Tool Steels	424

14.7.1.3	High-speed Steels (HSS)	424
14.7.1.4	Stainless Steels	424
14.7.1.5	Cast Iron	425
14.7.2	Aluminum	425
14.7.2.1	Influence of the Type of Aluminum Alloy	425
14.7.2.2	The Behavior of Aluminum During Machining	426
14.7.2.3	Tool Materials	428
14.7.3	Magnesium and its Alloys	429
14.7.4	Cobalt	430
14.7.4.1	The Health and Safety Aspects of Carbides	430
14.7.4.2	Use of Cutting Oils in Carbide Machining Processes	431
14.7.5	Titanium	431
14.8	Metalworking Fluid Circulation System	432
14.8.1	Metalworking Fluid Supply	432
14.8.1.1	Grinding	435
14.8.2	Individually-filled Machines and Central Systems	436
14.8.3	Tramp Oil in Coolants	437
14.8.4	Separation of Solid Particles	437
14.8.4.1	Swarf Concentration and Filter Fineness	437
14.8.4.2	Full, Partial or Main Flow Solids Separation	438
14.8.4.3	Filtration Processes	439
14.8.4.4	Solids Separation Equipment	442
14.8.5	Plastics and Sealing Materials in Machine Tools—Compatibility with Cutting Fluids	446
14.8.6	Monitoring and Maintenance of Neat and Water-miscible Cutting Fluids	448
14.8.6.1	Storage of Cutting Fluids	448
14.8.6.2	Mixing Water-miscible Cutting Fluids	448
14.8.6.3	Monitoring Cutting Fluids	449
14.8.6.4	Cutting Fluid Maintenance	451
14.8.6.5	Corrective Maintenance for Neat and Water-miscible Cutting Fluids	452
14.8.7	Splitting and Disposal	455
14.8.7.1	Disposal of Cutting Fluids	455
14.8.7.2	Evaluation Criteria for Cutting Fluid Water Phases	455
14.8.7.3	Electrolyte Separation	457
14.8.7.4	Emulsion Separation by Flotation	458
14.8.7.5	Splitting of Emulsions with Adsorbents	458
14.8.7.6	Separating Water-miscible Cutting Fluids by Thermal Methods	459
14.8.7.7	Ultrafiltration	461
14.8.7.8	Evaluation of Disposal Methods	462
14.9	Coolant Costs	462
14.9.1	Coolant Application Costs	462
14.9.1.1	Investment Costs (Depreciation, Financing Costs, Maintenance Costs)	462
14.9.1.2	Energy Costs	463

14.9.1.3	Coolant and Coolant Additives	463
14.9.1.4	Coolant Monitoring	463
14.9.1.5	Other Auxiliaries	463
14.9.1.6	Coolant Separation and Disposal	463
14.9.2	Coolant Application Costs with Constant System	463
14.9.2.1	Specific Coolant Costs	463
14.9.2.2	Optimization of Coolant use by Computer	467
14.10	New Trends in Coolant Technology	469
14.10.1	Oil Instead of Emulsion	469
14.10.1.1	Fluid Families and Multifunctional Fluids for Machine Tools	470
14.10.1.2	Washing Lines	471
14.10.1.3	De-oiling of Chips and Machined Components	471
14.10.1.4	Future Perspectives – Unifluid	472
14.10.2	Minimum Quantity Lubrication	472
14.10.2.1	Considerations When Dispensing with Coolants	473
14.10.2.2	Minimum Quantity Lubrication Systems	474
14.10.2.3	Coolants for Minimum Quantity Lubrication	475
14.10.2.4	Oil Mist Tests with Minimum Quantity Lubrication	477
14.10.2.5	Product Optimization of a Minimum Quantity Coolant Medium for Drilling	479
15	Forming Lubricants	481
15.1	Sheet Metal Working Lubricants	481
15.1.1	Processes	482
15.1.2	Basic Terms in Forming Processes	482
15.1.2.1	Lattice Structure of Metals	482
15.1.2.2	Yield Strength	483
15.1.2.3	Strain	483
15.1.2.4	Flow Curve	483
15.1.2.5	Efficiency of Deformation, Resistance to Forming, Surface Pressure	485
15.1.2.6	Strain Rate	485
15.1.2.7	Anisotropy, Texture, R value	485
15.1.3	Deep drawing	486
15.1.3.1	Friction and Lubrication in the Different Areas of a Deep Drawing Operation	486
15.1.3.2	Significance of Lubrication Dependent upon Sheet Metal Thickness, Drawn-part Size and the Efficiency of Deformation	490
15.1.3.3	Assessment of the Suitability of Lubricants for Deep Drawing	492
15.1.4	Stretch Drawing and a Combination of Stretch and Deep Drawing	493
15.1.5	Shear Cutting	494
15.1.5.1	Stamping	495
15.1.5.2	Fineblanking	498
15.1.6	Material and Surface Microstructure	500
15.1.6.1	Material	500
15.1.6.2	Surface Microstructure [15.17–15.19]	501

15.1.7	Tools Used in Sheet Metal Forming Operations	502
15.1.8	Lubricants for Sheet Metal Forming	504
15.1.8.1	Before Forming	504
15.1.8.2	Lubricant Behavior During Forming	507
15.1.8.3	After Forming	507
15.1.8.4	Trends in Sheet Metal Forming Lubricants	508
15.1.9	Corrosion Protection	509
15.1.9.1	Corrosion Mechanisms	509
15.1.9.2	Temporary Corrosion Protection	510
15.1.9.3	Corrosion Tests	512
15.1.10	Removal of Forming Lubricants—Industrial Cleaners	512
15.1.10.1	Intermediate Cleaning in Mechanical Manufacture	513
15.1.10.2	Cleaning Before Heat Treatment and Surface Coating	513
15.1.10.3	Cleaning During Maintenance	514
15.1.10.4	Cleaning Methods and Agents	514
15.1.10.5	Systematization of Cleaners	515
15.1.11	Testing Tribological Characteristics	522
15.1.12	Sheet Metal Forming in Automobile Manufacturing	524
15.1.12.1	Prelubes	524
15.1.12.2	Skin Passing	526
15.1.12.3	Coil Oiling	526
15.1.12.4	Transport and Storage of Sheet Metal	526
15.1.12.5	Washing of Steel Strips and Blanks	526
15.1.12.6	Additional Lubrication	527
15.1.12.7	Pressing	527
15.1.12.8	Transport and Storage of Pressed Parts	529
15.1.12.9	Welding and Bonding [15.33]	529
15.1.12.10	Cleaning and Phosphating	529
15.1.12.11	Cataphoretic Painting	530
15.1.12.12	Savings Potential using Prelubes	530
15.2	Lubricants for Wire, Tube, and Profile Drawing	530
15.2.1	Friction and Lubrication, Tools, and Machines	530
15.2.1.1	Forming Classification	530
15.2.1.2	Friction and Lubrication, Machines and Tools when Wire Drawing	531
15.2.1.3	Drawing Force and Tension	532
15.2.1.4	Drawing Tool and Wear	534
15.2.1.5	Wire Cracks	536
15.2.1.6	Hydrodynamic Drawing	536
15.2.1.7	Wire Friction on Cone	537
15.2.1.8	Lubricant Feed in Wet Drawing	539
15.2.1.9	Dry Drawing	539
15.2.1.10	Applying Lubricant as Pastes or High-viscosity Products	540
15.2.2	Drawing Copper Wire	540
15.2.2.1	Lubricants	541
15.2.2.2	Lubricant Concentration	543

15.2.2.3	Solubility of Copper Reaction Products	543
15.2.2.4	Water Quality and Electrolyte Stability	543
15.2.2.5	Laboratory Testing Methods	544
15.2.2.6	Lubricant Temperature	545
15.2.2.7	Influence of the Lubricant on Wire Enameling	545
15.2.2.8	Circulation Systems, Cleaning and Disposal of Drawing Emulsions	545
15.2.3	Drawing of Steel Wire	546
15.2.3.1	Requirements	546
15.2.3.2	Lubricant Carrier Layers	547
15.2.3.3	Lime as a Lubricant Carrier	547
15.2.3.4	Borax as Lubricant Carrier	547
15.2.3.5	Phosphate as Lubricant Carrier	547
15.2.3.6	Oxalate Coatings and Silicates	548
15.2.3.7	Lubricants for Steel Wire Drawing	548
15.2.4	Drawing Aluminum Wire	550
15.2.4.1	Drawing Machines and Lubrication	550
15.2.4.2	Lubricants for Aluminum Wire Drawing	550
15.2.5	Wire from Other Materials	551
15.2.5.1	Stainless Steel	551
15.2.5.2	Nickel	551
15.2.5.3	Tungsten	552
15.2.6	Profile Drawing	552
15.2.6.1	Lubricating Tasks in Profile Drawing	553
15.2.6.2	Pretreatment and the Use of Lubricant when Profile Drawing Steel	553
15.2.7	Tube Drawing	553
15.2.7.1	Pipe Drawing Methods	554
15.2.7.2	Tools and Tool Coatings	554
15.2.7.3	Lubricants and Surface Pretreatment for Tube Drawing	556
15.2.8	Hydroforming	558
15.2.8.1	Process Principle	559
15.2.8.2	Process Configuration	560
15.2.8.3	Tribological Aspects of Hydroforming	560
15.2.8.4	Lubricants for Hydroforming	562
15.3	Lubricants for Rolling	563
15.3.1	General	563
15.3.1.1	Rolling Speed	564
15.3.1.2	Rationalization	564
15.3.1.3	Surface and Material Quality	564
15.3.1.4	Hygienic Commercial Requirements	564
15.3.2	Friction and Lubrication when Rolling	565
15.3.3	Rolling Steel Sheet	568
15.3.3.1	Hot Rolling	568
15.3.3.2	Sheet Cold Rolling	570
15.3.3.3	Finest Sheet Cold Rolling	574
15.3.3.4	Cold Rolling of High Alloy Steel Sheet	575

15.3.4	Rolling Aluminum Sheet	577
15.3.5	Aluminum Hot Rolling	577
15.3.6	Aluminum Cold Rolling	578
15.3.7	Rolling Other Materials	579
15.4	Solid Metal Forming Lubricants (Solid Forming, Forging and Extrusion)	580
15.4.1	Processes	580
15.4.1.1	Upsetting	580
15.4.1.2	Extrusion	581
15.4.1.3	Impression Die Forging	581
15.4.1.4	Open Die Forging	581
15.4.2	Forming Temperatures	581
15.4.2.1	Cold	581
15.4.2.2	Warm	582
15.4.2.3	Hot	582
15.4.3	Friction and Lubrication with Cold Extrusion and Cold Forging	582
15.4.3.1	Friction and Lubricant Testing Methods	583
15.4.3.2	Selection Criteria for Lubricants and Lubrication Technology	585
15.4.3.3	Lubricating Oils for Cold Extrusion of Steel (Extrusion Oils)	586
15.4.3.4	Phosphate Coatings and Soap Lubricants for Cold Extrusion of Steel	588
15.4.3.5	Solid Lubricants for Cold Extrusion of Steel	591
15.4.4	Warm Extrusion and Forging	593
15.4.4.1	Temperature Range up to 350 °C	595
15.4.4.2	Temperature Range 350 to 500 °C	595
15.4.4.3	Temperature Range 500 to 600 °C	595
15.4.4.4	Temperature Range > 600 °C	595
15.4.5	Lubrication when Hot Forging	596
15.4.5.1	Demands on Hot Forging Lubricants	597
15.4.5.2	Lubricant Testing Methods	598
15.4.6	Hot Forging of Steel	598
15.4.6.1	Lubricants	599
15.4.7	Aluminum Forging	600
15.4.8	Isothermal and Hot Die Forging	601
15.4.9	Application and Selection of Lubricant	601
16	Lubricating Greases	603
16.1	Introduction	603
16.1.1	Definition	603
16.1.2	History	603
16.1.3	Advantages over Lubricating Oils	604
16.1.4	Disadvantages	604
16.1.5	Classification	605
16.2	Thickeners	606
16.2.1	Simple Soaps	606

16.2.1.1	Soap Anions	606
16.2.1.2	Soap Cations	606
16.2.1.3	Lithium Soaps	607
16.2.1.4	Calcium Soaps	609
16.2.1.5	Sodium Soaps	609
16.2.1.6	Other Soaps	610
16.2.1.7	Cation Mixed Soaps M_1X/M_2X	610
16.2.1.8	Anion Mixed Soaps MX_1/MX_2	611
16.2.2	Complex Soaps	611
16.2.2.1	Lithium Complex Soaps	611
16.2.2.2	Calcium Complex Soaps	613
16.2.2.3	Calcium Sulfonate Complex Soaps	613
16.2.2.4	Aluminum Complex Soaps	614
16.2.2.5	Other Complex Soaps	614
16.2.3	Other Ionic Organic Thickeners	615
16.2.4	Non-ionic Organic Thickeners	615
16.2.4.1	Diureas and Tetraureas	615
16.2.4.2	Other Non-ionic Organic Thickeners	617
16.2.5	Inorganic Thickeners	617
16.2.5.1	Clays	617
16.2.5.2	Highly Dispersed Silicic Acid	617
16.2.6	Miscellaneous Thickeners	617
16.2.7	Temporarily Thickened Fluids	618
16.3	Base Oils	619
16.3.1	Mineral Oils	619
16.3.2	Synthetic Base Oils	620
16.3.2.1	Synthetic Hydrocarbons	620
16.3.2.2	Other Synthetic Base Oils	620
16.3.2.3	Immiscible Base Oil Mixtures	621
16.4	Grease Structure	621
16.5	Additives	622
16.5.1	Structure Modifiers	622
16.5.2	Antirust Additives (Corrosion Inhibitors)	623
16.5.3	Extreme Pressure and Anti-Wear Additives	623
16.5.4	Solid Lubricants	623
16.5.5	Friction Modifiers	624
16.6	Manufacture of Greases	624
16.6.1	Metal Soap-Based Greases	624
16.6.1.1	Batch Production with Preformed Metal Soaps	624
16.6.1.2	Batch Production with Metal Soaps Prepared In-situ	625
16.6.1.3	Continuous Production	626
16.6.2	Oligourea Greases	627
16.6.3	Gel Greases	627
16.7	Grease Rheology	627
16.8	Grease Performance	628

16.8.1	Test Methods	630
16.8.2	Analytical Methods	632
16.9	Applications of Greases	632
16.9.1	Roller Bearings	633
16.9.1.1	Re-lubrication Intervals	634
16.9.2	Cars, Trucks, Construction Vehicles	636
16.9.3	Steel Mills	639
16.9.4	Mining	640
16.9.5	Railroad, Railway	640
16.9.6	Gears	641
16.9.7	Food-Grade Applications	641
16.9.8	Textile Machines	641
16.9.9	Application Techniques	642
16.9.10	Special and Lifetime Applications	642
16.9.11	Applications with Polymeric Materials	642
16.10	Grease Market	643
16.11	Ecology and the Environment	645
16.12	Grease Tribology	646
17	Solid Lubrication	647
17.1	Classification of Solid Lubricants	647
17.1.1	Class 1: Structural Lubricants	648
17.1.2	Class 2: Mechanical Lubricants	649
17.1.2.1	Self-Lubricating Substances	649
17.1.2.2	Substances with Lubricating Properties that Need a Supporting Medium	651
17.1.2.3	Substances with Indirect Lubricating Properties Based on their Hardness (Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), and Diamond-like Carbon (DLC) layers)	652
17.1.3	Class 3: Soaps	652
17.1.4	Class 4: Chemically Active Lubricants	652
17.2	Characteristics	653
17.2.1	The Crystal Structures of Lamellar Solid Lubricants	653
17.2.1.1	Graphite	653
17.2.1.2	Molybdenum Disulfide	653
17.2.2	Heat Stability	654
17.2.3	Melting Point	654
17.2.4	Thermal Conductivity	654
17.2.5	Adsorbed Films	655
17.2.6	Mechanical Properties	655
17.2.7	Chemical Stability	655
17.2.8	Purity	655
17.2.9	Particle Size	656
17.3	Products Containing Solid Lubricants	656

17.3.1	Powders	656
17.3.1.1	Solid Lubricants in Carrying Media	657
17.3.2	Dispersions and Suspensions	657
17.3.3	Greases and Grease Pastes	657
17.3.4	Pastes	659
17.3.5	Dry-Film Lubricants	659
17.4	Industrial Uses of Products Containing Solid Lubricants	663
17.4.1	Screw Lubrication	664
17.4.2	Roller-Bearing Lubrication	665
17.4.3	Slide Bearing, Slide Guideway, and Slide Surface Lubrication	666
17.4.4	Chain Lubrication	666
17.4.5	Plastic and Elastomer Lubrication	666
18	Laboratory Methods for Testing Lubricants	668
18.1	Introduction	668
18.2	Density	668
18.3	Viscosity	668
18.3.1	Capillary Viscometers	669
18.3.2	Rotary Viscometers	669
18.4	Refractive Index	670
18.5	Structural Analyses	670
18.6	Flash Point	670
18.7	Surface Phenomena	671
18.7.1	Air Release	671
18.7.2	Demulsibility	671
18.7.3	Foaming Characteristics	671
18.8	Cloud Point, Pour Point	672
18.9	Aniline Point	672
18.10	Water Content	672
18.11	Ash Content	672
18.12	Acidity, Alkalinity	673
18.13	Aging Tests	673
18.14	Hydrolytic Stability	674
18.15	Corrosion Tests	674
18.16	Oil Compatibility of Seals and Insulating Materials	675
18.17	Evaporation Loss	675
18.18	Analysis of Grease	675
18.19	List of Equivalent Standardized Methods for Testing Lubricants	675
19	Mechanical–Dynamic Testing Methods for Lubricants	683
19.1	Tribological System Categories within Lubricant Tests	683
19.2	Standardized and Non-standardized Test Methods for Lubricants	684
19.3	Common Mechanical–Dynamic Testers	692
19.3.1	Four-Ball Apparatus	692
19.3.2	Reichert Friction Wear Tester	693

19.3.3	The Falex Tester	694
19.3.4	Timken Tester	695
19.3.5	Translatory Oscillation Apparatus (SRV)	696
19.3.6	FZG Gear Test Rig	697
19.3.6.1	Load Stage Test	698
19.3.6.2	Micro-Pitting-Test	699
19.3.6.3	Pitting Load Capacity Test	699
19.3.6.4	Wear Load Capacity Test	700
19.3.6.5	Gear Efficiency Test	701
19.3.7	FAG FE9 Roller Bearing Grease Tester	702
19.3.8	FAG FE8 Roller Bearing Grease Tester	703
19.3.9	Synchronizer Rig SSP 180	704
19.3.10	Diesel Injection Nozzle	705
19.3.11	Vane Pump	705
19.4	Interpretation and Precision of Lubricant Tests	706

References	707
-------------------	-----

Subject Index	749
----------------------	-----