



ENERGY EFFICIENT MANUFACTURING

THEORY AND APPLICATIONS

Edited by
John W. Sutherland,
David A. Dornfeld
and **Barbara S. Linke**

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Dedication

In March 2016, our good friend and mentor Professor David A. Dornfeld passed away. Dave was a constant source of inspiration and was always ready with a kind word and helpful suggestions. He was a passionate teacher and innovative researcher who made pioneering contributions to the fields of precision and sustainable manufacturing. Dave's good natured personality, irrepressible humor, and intelligence elevated every meeting and conference he attended. He was active in many societies and received numerous honors. Dave was very inclusive and promoted talent where he saw it. His legacy is the many students, post-docs, and colleagues who benefitted from his excellent support, guidance, and advice.

We will miss you Dave!

John W. Sutherland
West Lafayette, IN

Barbara S. Linke
Davis, CA

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Contents

1	Introduction to Energy Efficient Manufacturing	1
	<i>Barbara S. Linke and John W. Sutherland</i>	
1.1	Energy Use Implications	2
1.2	Drivers and Solutions for Energy Efficiency	3
	References	9
2	Operation Planning & Monitoring	11
	<i>Y.B. Guo</i>	
2.1	Unit Manufacturing Processes	11
2.2	Life Cycle Inventory (LCI) of Unit Manufacturing Process	13
2.3	Energy Consumption in Unit Manufacturing Process	16
	2.3.1 Basic Concepts of Energy, Power, and Work	16
	2.3.2 Framework of Energy Consumption	17
2.4	Operation Plan Relevance to Energy Consumption	19
2.5	Energy Accounting in Unit Manufacturing Processes	20
2.6	Processing Energy in Unit Manufacturing Process	21
	2.6.1 Cases of Processing Energy Modeling	21
	2.6.1.1 Forging	21
	2.6.1.2 Orthogonal Cutting	22
	2.6.1.3 Grinding	24
	2.6.1.4 Specific Energy vs. MRR	25
	2.6.2 Energy Measurement	26
2.7	Energy Reduction Opportunities	26
	2.7.1 Shortening Process Chain by Hard Machining	28
	2.7.2 Substitution of Process Steps	28
	2.7.3 Hybrid processes	29
	2.7.4 Adaptation of Cooling and Flushing Strategies	29
	2.7.5 Remanufacturing	30
	References	30

3	Materials Processing	33
	<i>Karl R. Haapala, Sundar V. Atre, Ravi Enneti, Ian C. Garretson and Hao Zhang</i>	
3.1	Steel	34
3.1.1	Steelmaking Technology	35
3.2	Aluminum	36
3.2.1	Aluminum Alloying	37
3.2.2	History of Aluminum Processing	37
3.2.3	Aluminum in Commerce	38
3.2.4	Aluminum Processing	41
3.2.5	Bayer Process	42
3.2.6	Preparation of Carbon	44
3.2.7	Hall-Heroult Electrolytic Process	44
3.3	Titanium	45
3.3.1	Titanium Alloying	46
3.3.2	History of Titanium Processing	47
3.3.3	Titanium in Commerce	48
3.3.4	Titanium Processing Methods	49
3.3.5	Sulfate Process	50
3.3.6	Chloride Process	51
3.3.7	Hunter Process and Kroll Process	51
3.3.8	Remelting Processes	52
3.3.9	Emerging Titanium Processing Technologies	52
3.4	Polymers	54
3.4.1	Life Cycle Environmental and Cost Assessment	59
3.4.2	An Application of Polymer-Powder Processes	59
	References	61
4	Energy Reduction in Manufacturing via Incremental Forming and Surface Microtexturing	65
	<i>Jian Cao and Rajiv Malhotra</i>	
4.1	Incremental Forming	66
4.1.1	Conventional Forming Processes	66
4.1.2	Energy Reduction via Incremental Forming	72
4.1.3	Challenges in Incremental Forming	75
4.1.3.1	Toolpath Planning for Enhanced Geometric Accuracy and Process Flexibility	76
4.1.3.2	Formability Prediction and Deformation Mechanics	85
4.1.3.3	Process Innovation and Materials Capability in DSIF	92
4.1.3.4	Future Challenges in Incremental Forming	95

4.2	Surface Microtexturing	97
4.2.1	Energy Based Applications of Surface Microtexturing	97
4.2.1.1	Microtexturing for Friction Reduction	97
4.2.1.2	Microtexturing Methods	101
4.2.1.3	Future Work in Microtexturing	114
4.3	Summary	115
4.4	Acknowledgement	116
	References	116
5	An Analysis of Energy Consumption and Energy Efficiency in Material Removal Processes	123
	<i>Tao Lu and I.S. Jawahir</i>	
5.1	Overview	123
5.2	Plant and Workstation Levels	126
5.3	Operation Level	129
5.4	Process Optimization for Energy Consumption	134
5.4.1	Plant Level and Workstation Level	134
5.4.2	Operation Level	137
5.4.2.1	Turning Operation	137
5.4.2.2	Milling Operation	145
5.4.2.3	Drilling Operation	148
5.4.2.4	Grinding Operation	150
5.5	Conclusions	152
	Reference	154
6	Nontraditional Removal Processes	159
	<i>Murali Sundaram and K.P. Rajurkar</i>	
6.1	Introduction	159
6.1.2	Working Principle	160
6.1.2.1	Electrical Discharge Machining	160
6.1.2.2	Electrochemical Machining	161
6.1.2.3	Electrochemical Discharge Machining	163
6.1.2.4	Electrochemical Grinding	164
6.2	Energy Efficiency	165
	Acknowledgments	167
	References	167
7	Surface Treatment and Tribological Considerations	169
	<i>S.R. Schmid and J. Jeswiet</i>	
7.1	Introduction	170
7.2	Surface Treatment Techniques	173
7.2.1	Surface Geometry Modification	174

7.2.2	Microstructural Modification	175
7.2.3	Chemical Approaches	179
7.3	Coating Operations	179
7.3.1	Hard Facing	179
7.3.2	Vapor Deposition	183
7.3.3	Miscellaneous Coating Operations	185
7.4	Tribology	189
7.5	Evolving Technologies	191
7.5.1	Biomimetics – Biologically Inspired Design	191
7.6	Micro Manufacturing	192
7.7	Conclusions	194
	References	194
8	Joining Processes	197
	<i>Amber Shrivastava, Manuela Krones and Frank E. Pfefferkorn</i>	
8.1	Introduction	198
8.2	Sustainability in Joining	200
8.3	Taxonomy	203
8.4	Data Sources	205
8.5	Efficiency of Joining Equipment	208
8.6	Efficiency of Joining Processes	210
8.6.1	Fusion Welding	211
8.6.2	Chemical Joining Methods	214
8.6.3	Solid-State Welding	216
8.6.4	Mechanical Joining Methods	218
8.6.4.1	Mechanical Fastening	218
8.6.4.2	Adhesive Bonding	219
8.7	Process Selection	220
8.8	Efficiency of Joining Facilities	221
8.9	Case Studies	224
8.9.1	Submerged Arc Welding (SAW)	224
8.9.2	Friction Stir Welding (FSW)	228
	Reference	235
9	Manufacturing Equipment	239
	<i>M. Helu, N. Diaz-Elsayed and D. Dornfeld</i>	
9.1	Introduction	239
9.2	Power Measurement	240
9.3	Characterizing the Power Demand	242
9.3.1	Constant Power	242
9.3.2	Variable Power	244
9.3.3	Processing Power	244

9.4	Energy Model	244
9.5	Life Cycle Energy Analysis of Production Equipment	246
9.6	Energy Reduction Strategies	247
9.6.1	Strategies for Equipment with High Processing Power	248
9.6.2	Strategies for Equipment with High Tare Power	249
9.6.2.1	Process Time	249
9.6.2.2	Machine Design	251
9.7	Additional Life Cycle Impacts of Energy Reduction Strategies	252
9.8	Summary	254
	References	256
10	Energy Considerations in Assembly Operations	261
	<i>Camelio, J.A., McCullough, D., Prosch, S. and Rickli, J.L.</i>	
10.1	Introduction to Assembly Systems & Operations	262
10.2	Fundamentals of Assembly Operations	263
10.3	Characterizing Assembly System Energy Consumption	264
10.3.1	Indirect Energy	265
10.3.2	Direct Energy	266
10.4	Direct Energy Considerations of Assembly Joining Processes	268
10.4.1	Mechanical Assembly	268
10.4.2	Adhesive Bonding	269
10.4.3	Welding, Brazing, and Soldering	272
10.5	Assembly System Energy Metrics	275
10.6	Case Study: Heavy Duty Truck Assembly	280
10.6.1	Case Study Energy Consumption Analysis Approach	280
10.6.2	Assembly Process Categorization	281
10.6.3	Case Study Energy Analysis Results	285
10.6.4	Discussion and Recommendations	292
10.7	Future of Energy Efficient Assembly Operations	293
	References	294
	Appendix 10.A	296
11	Manufacturing Facility Energy Improvement	299
	<i>Chris Yuan, Junling Xie and John Nicol</i>	
11.1	Introduction	300
11.2	Auxiliary Industrial Energy Consumptions	303
11.2.1	Lighting	303
11.2.1.1	Lighting Technologies	304

11.2.1.2	Opportunities for Improving Energy Efficiency of Industrial Lighting	305
11.2.2	HVAC	307
11.2.2.1	HVAC Systems	308
11.2.2.2	HVAC Energy Efficiency Opportunities	310
11.2.3	Compressed Air	315
11.2.3.1	Compressed Air Technologies	316
11.2.3.2	Improving Energy Efficiency of Air Compressors	317
11.3	Industrial Practices on Energy Assessment and Energy Efficiency Improvement	321
11.3.1	Types of Energy Assessments	321
11.3.2	Energy Assessment Procedures	322
11.4	Energy Management and Its Enhancement Approaches	323
11.4.1	Energy Management Description and Benefits	324
11.4.2	Establishing an Energy Management Approach	326
11.4.2.1	ISO 50001	336
11.5	Conclusions	337
	References	338
12	Energy Efficient Manufacturing Process Planning	339
	<i>RuixueYin, Fu Zhao and John W. Sutherland</i>	
12.1	Introduction	339
12.2	The Basics of Process Planning	341
12.2.1	Types of Production	342
12.2.2	Process Planning Procedure	344
12.2.3	Process Planning Methods	346
12.3	Energy Efficient Process Planning	350
12.3.1	Energy Consumption and Carbon Footprint Models of Manufacturing Processes	350
12.3.2	A Semi-Generative Process Planning Approach for Energy Efficiency	351
12.4	Case Study	353
12.5	Conclusions	357
	Reference	358
13	Scheduling for Energy Efficient Manufacturing	359
	<i>Nelson A. Uhan, Andrew Liu and Fu Zhao</i>	
13.1	Introduction	359
13.2	A Brief Introduction to Scheduling	360
13.2.1	Machine Environments	360
13.2.2	Job Characteristics	362

13.3.3	Feasible Schedules and Gantt Charts	362
13.2.4	Objective Functions: Classic Time-Based Objectives	364
13.3	Machine Environments	365
13.4	Job Characteristics	367
13.4.1	A Very Brief Introduction to Mathematical Optimization	368
13.4.2	A Time-Indexed Integer Linear Program for the Energy-Efficient Flow Shop Problem	370
13.4.3	Algorithms for Solving Integer Linear Programs	376
13.5	Conclusion and Additional Reading	377
	References	379
14	Energy Efficiency in the Supply Chain	381
	<i>Thomas J. Goldsby and Fazleena Badurdeen</i>	
14.1	Supply Chain Management	381
14.2	Supply Chain Structure	382
14.3	Supply Chain Processes	385
14.3.1	Customer Relationship Management	387
14.3.2	Supplier Relationship Management	388
14.3.3	Customer Service Management	389
14.3.4	Demand Management	390
14.3.5	Manufacturing Flow Management	391
14.3.6	Order Fulfillment	392
14.3.7	Product Development and Commercialization	393
14.3.8	Returns Management	394
14.4	Supply Chain Management Components	395
14.5	Conclusion	396
	References	396
	Endnotes	400
15	Business Models and Organizational Strategies	401
	<i>Omar Romero-Hernandez, David Hirsch, Sergio Romero and Sara Beckman</i>	
15.1	Introduction	402
15.2	Reference Framework for Selection of Energy Efficiency Projects	404
15.2.1	Mission and Drivers	405
15.2.2	Set Level of Assessment	405
15.2.3	Recognize Opportunities and Risk	406
15.2.4	Select Projects	406

15.2.5	Implementation and Communication	407
15.3	Common Energy Efficiency Opportunities	408
15.3.1	Building Envelope	408
15.3.2	Heating, Ventilation and Air Conditioning (HVAC)	409
15.3.3	Efficient Lighting	410
15.3.4	Efficient Motors and Systems	411
15.3.5	Building Management Systems	412
15.4	Stakeholders	413
15.4.1	Tenants and Owners	413
15.4.2	Regulators	414
15.4.3	Banks/Lenders	414
15.4.4	Energy Service Companies (ESCOs)	415
15.4.5	Business Models	415
15.5	Conclusions	417
	References	417
16	Energy Efficient or Energy Effective Manufacturing?	421
	<i>S. A. Shade and J. W. Sutherland</i>	
16.1	Energy Efficiency: A Macro Perspective	422
16.1.1	Government Perspective	422
16.1.2	Company Perspective	423
16.2	The Basics of Energy Efficiency	425
16.3	Limitations of Energy Efficiency	433
16.4	Energy Effectiveness	436
16.4.1	Effectiveness – It’s Up to the Decision Maker	438
16.4.2	Effectiveness – A Choice on Where to Invest	439
16.4.3	Effectiveness – Is An Action Really Worthwhile?	439
16.5	Summary	442
16.6	Acknowledgments	443
	References	443
Index		445

Introduction to Energy Efficient Manufacturing

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Abstract

Over the last decade, manufacturers around the world have expressed increasing interest in reducing their energy consumption. It appears that there are at least two principal motivations for this interest: i) the emergence of policies and legislation related to carbon emissions due to energy generation, and ii) the rising cost of energy relative to other production costs. Thus, manufacturers have begun to search for opportunities to reduce their energy usage.

A recent study by Johnson Controls shows that the demand for facility projects that promote and introduce renewable energy have dramatically increased over the last ten years [1]. Cost reduction remains the primary driver, but energy security, customer and employee attraction, greenhouse gas reduction, enhanced reputation, government policy, and investor expectations are increasingly important for investment in renewable energy [1].

In this book, the authors explore a variety of opportunities to reduce the energy footprint of manufacturing; these opportunities cover the entire spatial scale of the manufacturing enterprise: from unit process-oriented approaches to enterprise-level strategies. Each chapter examines some aspect of this spatial scale, and discusses and describes the opportunities that exist at each point on the scale. Each chapter uses one or more case studies to demonstrate how the opportunity may be acted on. Our goal is to inform students, practicing engineers, and business leaders of energy reduction approaches that exist across the manufacturing enterprise and provide some guidance on how to respond to these opportunities.

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Keywords: Introduction, energy consumption, energy efficiency, overview

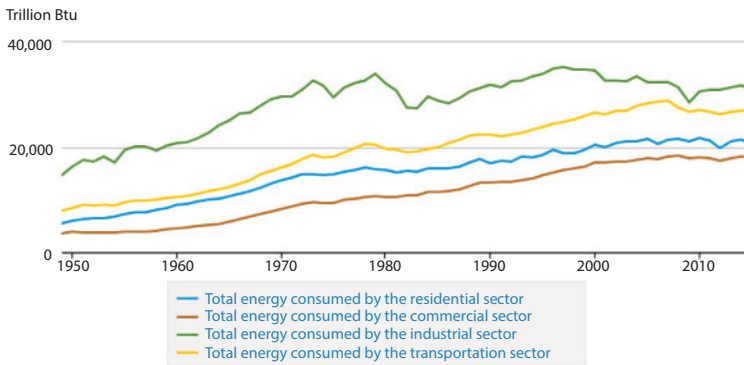
1.1 Energy Use Implications

Energy is defined as the ability to do work. It can be neither created nor destroyed but can be changed from one form to another (First Law of Thermodynamics). The different forms of energy include kinetic, potential, heat, electric, light, chemical and nuclear. The different forms have different relevance in our daily life. The different forms of energy are such so that some conversions from one form to another are easier than others (e.g., chemical energy in oil is readily converted into heat and light through combustion, but it is difficult to convert electricity into nuclear energy, for example with particle accelerators) [2].

Worldwide we use about 500 EJ of energy per year [3]. Although energy cannot be destroyed, the useful energy decreases in most systems. In addition, theory-based energy requirements often significantly underestimate actual energy requirements. For example, reduction of iron oxide to iron theoretically requires 7.35 MJ/kg of energy, but generally consumes 20 MJ/kg in industrial practice [2]. Theoretical energy and the actual energy consumed by industry differ because of energy losses at various steps in every process. A recent DOE bandwidth study estimated the potential energy savings opportunities for the U.S. Iron and Steel Manufacturing Sector as 240 TBtu (or 256 PJ) [4]. These savings could occur if the best technologies and practices available today were used to upgrade production. The savings would be 39% of the thermodynamic minimum or the minimum amount of energy theoretically required for these processes assuming ideal conditions.

Energy use may be attributed to four principal end-uses: transportation, residential, commercial, and industrial consumption, with each end-use roughly representing one-quarter of the total U.S. consumption (please refer to Figure 1.1). Manufacturing accounts for about 90% of industrial energy consumption and 84% of energy-related CO₂ emissions (construction, mining, and agricultural activities account for the remaining industry sector contributions).

Manufacturing sector activities generate carbon dioxide and other greenhouse gas (GHG) emissions directly through onsite energy consumption (onsite generation and process energy), as well as indirectly through energy consumption to support non-process operations (e.g., facility HVAC – Heating, Ventilation and Air Conditioning, lighting, and onsite transportation). On a global scale, industry accounts for 21% of the




 Source: U.S. energy information administration

Figure 1.1 Energy consumption in the USA by sector [5].

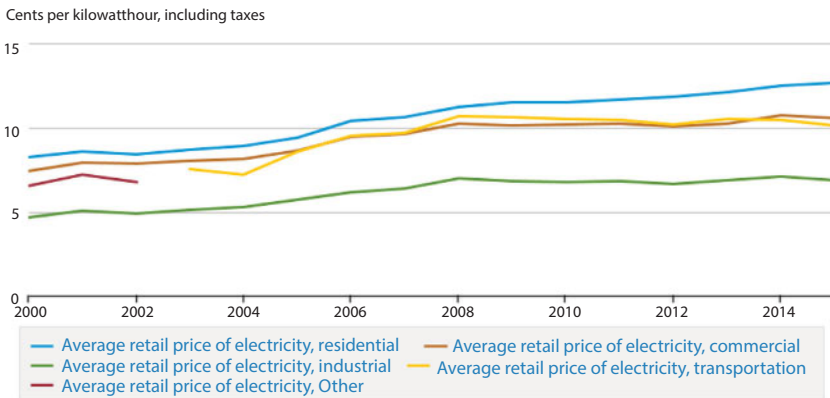
total emissions generated [6]. Climate scientists report that these emissions upset the natural carbon balance of earth's systems [7]. As actions are demanded to reduce GHG, it should be noted that such emissions are largely proportional to energy consumption. Further, environmental impacts from electricity generation and transmission include the physical footprint of the power plant, carbon dioxide and monoxide, sulfur dioxide, nitrogen oxides, particulate matter, heavy metals, and liquid and solid wastes.

1.2 Drivers and Solutions for Energy Efficiency

Around the globe industry is facing pressure from governments in the form of regulations, penalties, or tax benefits to reduce GHG emissions. For example, the Global Warming Solutions Act of 2006 (AB32) is a California State Law to reduce GHG emissions throughout California by 2020 [8]. It applies to 6 GHG contributors: CO_2 , CH_4 , NO_x , hydrofluorocarbons, perfluorocarbons, and SF_6 . The European Union Emissions Trading System (EU ETS) has set a cap on GHG emissions and allows trading of 'allowances' [9].

Energy prices are increasing (Figure 1.2) and using energy more efficiently is therefore in the best interest of companies and part of their continuous improvement efforts. Furthermore, depending upon an acquired resource always involves a financial risk. This includes electricity, gasoline, and natural gas. Electricity at peak hours of demand costs more than at off-peak times. In addition, companies pay a cost penalty for low power

4 ENERGY EFFICIENT MANUFACTURING




 Source: U.S. energy information administration

Figure 1.2 Average retail prices of electricity [5].

factors. The power factor describes the ratio between real power (“consumed” power that does useful work) and apparent power (includes added load from capacitors or inductors) in an AC electrical circuit. Since power plants have to generate enough electricity to satisfy the apparent power, industrial consumers must pay additional costs for low power factors.

In addition to pressure from governmental regulations and energy prices, companies are always striving to increase their competitiveness and enhance their market share. Growing pressure from society, consumers, and customers to become greener and more environmentally-friendly also drives manufacturers to reduce energy usage.

The U.S. Department of Energy has initiated many initiatives to help American companies become leaders in the use and production of clean energy technologies like electric vehicles, LED bulbs, and solar panels and to increase their energy productivity (output per unit of energy input) by implementing energy efficiency measures. Manufacturing data is key to achieving higher energy efficiency. For example, smart manufacturing, which is receiving increasing attention, seeks to use data from ubiquitous sensors across the manufacturing enterprise to increase throughput, improve quality, and reduce environmental impacts.

Dornfeld and Wright suggested that rather than implementing one solution, that “technology wedges” should be adopted to offer a better framework for addressing the manufacturing energy challenge [10]. “Technology wedges” are the manufacturing equivalent of the “stabilization wedges” concept introduced by Pacala and Socolow [11]. Stabilization

wedges can reduce GHG through efficient cars, efficient buildings, wind power instead of coal power, reinventing land use rather than deforesting, etc. – in short, employing alternative technologies to reduce fossil fuel consumption through demand-side (consumptive) technology and supply-side (generative) technology changes. Both concepts highlight the gap between the current trends in consumption rate with respect to fossil fuel consumption/emission and movement towards a sustainable rate with respect to the atmosphere's capability to accommodate emissions [10]. Instead of seeking a single solution to fill this gap, smaller wedges, such as simpler, single technologies should be introduced to reduce consumption rates. Manufacturing engineers have the power to embed technology wedges in their processes, manufacturing equipment, factories, business operations, and supply chains. This book explores some technology wedges for energy reduction.

Overview of the Book Contents

This book presents a variety of opportunities to reduce the energy footprint of manufacturing, mainly for discrete product manufacturing. These opportunities cover the entire spatial scale of the manufacturing enterprise: from unit process-oriented approaches to enterprise-level strategies. Each chapter examines some aspect of this spatial scale, and discusses and describes the opportunities that exist at that level (Figure 1.3). The book is therefore divided into three sections:

Section I. Manufacturing Processes

In order to identify, analyze, and improve energy efficiencies, an enterprise must have a clear understanding of the performance of its manufacturing processes and the effect of process parameters on the energy consumption of unit processes. The primary focus of this section is therefore on the energy consumed by unit processes, explained by the physical principles associated with each process. Each chapter in this section will describe the physics of the manufacturing process and how energy is utilized, discuss energy reduction opportunities, and present a case study.

Chapter 2 lays the ground work for explaining the terminology for this book, in particular power, energy, and work. The energy for a unit manufacturing process is classified into four parts: processing, machine tool, process peripherals, and background. Processing energy can be modeled using a first principles approach, which will be demonstrated with examples from forging, orthogonal cutting, and grinding.

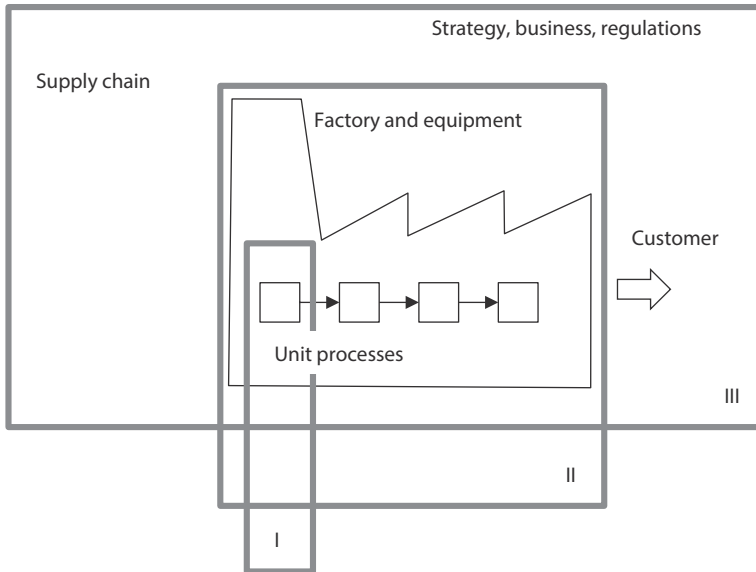


Figure 1.3 Structure of the book.

Chapter 3 focuses on raw material processing, which remains one of the most energy intensive phases in the product life cycle. This chapter provides an overview of the steel, aluminum, titanium, and polymer industries and describes the related materials processing technologies.

Chapter 4 discusses deformation processes, in particular the general concept, geometric accuracy, surface finish, formability prediction, and energy consumption of incremental forming in comparison with conventional forming. Surface texturing is introduced as a strategy to save energy by reducing friction at moving interfaces.

Chapter 5 reviews machining processes and the energy for machine tools and machining lines, discusses how energy depends on the material removal rate, and gives strategies for process optimization with regard to energy consumption. A detailed case study illustrates the optimization for minimal energy consumption in a turning process. Further studies address power consumption in turning, milling, drilling and grinding processes.

Chapter 6 concentrates on nontraditional machining processes, in particular electro-discharge machining (EDM), electrochemical machining (ECM), electrochemical discharge machining (ECDM), and electrochemical grinding (ECG). The electrical energy requirements herein are of significant importance as electrical energy is controlling the material removal in these processes.

Chapter 7 describes the principles and energy requirements for many of the most important surface treatment and coating processes. The surface treatment processes include hardening and heat treatment with furnaces, as well as laser and electron beam operations. Coating principles are discussed for thermal spraying, hard facing, physical and chemical vapor deposition, as well as certain electroplating operations. In addition, texturing with energy beams and through surface replication and machining are introduced, as are the stress-inducing operations of peening, burnishing, and explosive hardening.

Chapter 8 focuses on joining processes, which play a prominent role in manufacturing since almost all products are fabricated from multiple parts. Fusion welding processes, solid state welding, chemical joining, and mechanical joining methods are discussed. For the equipment and processes, models for energy efficiency and example data are given. Furthermore, the efficiency of joining facilities such as welding shops is analyzed and applied to case studies.

Section II. Manufacturing Systems and Enterprises

Careful consideration must be given not only to the energy consumed by manufacturing operations but also to the energy consumed by the auxiliary equipment of a manufacturing system as well as the other system elements that may influence the technical and economic performance of the system. The focus of this section is on reducing energy consumption at the facilities level, and improving the collective energy efficiency of the equipment in a facility.

Chapter 9 characterizes the energy consumption of production equipment. For this, power measurement is described, followed by the power breakdown of common manufacturing equipment. A life cycle energy analysis of equipment with the example of two milling machines is presented. Multiple energy reduction strategies and their additional life cycle impacts are discussed.

Chapter 10 introduces assembly processes and methods and their energy consumption. Energy consumption analyses have the potential to influence assembly workstation design, material handling, and part location, as well as upstream fastener design or selection decisions.

Chapter 11 investigates supporting facilities such as lighting, HVAC, compressed air, pumps, process heating, cooling, and cleaning with regard to their electricity use and energy efficiency. Several strategies for industrial lighting are presented including more efficient lamp technologies, occupancy sensors, and reduced lighting levels. Furthermore, strategies for higher efficiency HVAC and air compressors are introduced, followed by energy management benefits and approaches.

Chapter 12 focuses on process planning, which determines the specific and sequence of manufacturing operations needed to produce a given part with the design specifications. The basic concepts and procedures of process planning and an energy efficient approach are introduced that is based on energy and carbon footprint models, feature-based technology, and genetic algorithms. For a case study, the energy efficient process plan is compared with a cost-driven process plan.

Chapter 13 explores scheduling, the act of allocating limited resources to tasks over time. Traditionally, scheduling is addressed with time-based objectives, such as minimizing the total waiting time. This chapter presents an approach that also addresses energy. The mathematics are explained and optimization models demonstrated.

Section III. Beyond the Factory

Manufacturing is often considered to consist of the processes and systems used to produce products. Other business organizational elements can, however, either impede or promote efforts directed at reducing the energy consumption of manufacturing, and more generally, the energy consumed by the enterprise and society. With this in mind, this section examines a variety of system-oriented opportunities for reducing energy consumption.

In Chapter 14, supply chain management is used to explore energy consumption along the supply chain. The supply chain can be described as the network of companies working together to provide goods or services to an end-use customer. The supply chain structure in horizontal and vertical dimensions, business relationships, and main activities (customer and supplier relationship management, customer service management, order fulfillment, etc.) are explored with regard to energy use.

Drivers and barriers for companies for implementing energy efficient projects are tackled in Chapter 15. They provide the reference for a proposed framework for project selection. Different efficiency opportunities ranging from lighting, efficient HVAC systems, improved motor systems, and building envelope projects are presented.

Chapter 16 explores the imperatives of efficiency (doing things right) and effectiveness (doing the right thing) with regard to energy. The strategies for higher energy efficiency explained in this book often have well delineated objectives. Energy effectiveness, however, depends highly on the decision-maker's viewpoint. One strategy for considering both imperatives is to constantly pursue energy efficiency improvements, and to periodically adopt a course correction with energy effectiveness in mind.

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Operation Planning & Monitoring

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Abstract

Manufacturing industry is energy intensive. Due to the increasing energy cost and upcoming energy and environmental regulations, manufacturing faces the challenge of improving energy efficiency. This chapter gives an overall review of energy consumption in various manufacturing processes. The basic concepts of power, energy, and work are introduced. The scope and boundary of energy accounting are also discussed. The energy for a unit manufacturing process is classified into four parts: processing energy, machine tool energy, process periphery energy, and background energy. Case studies on processing energy modeling in forging, orthogonal cutting, grinding has been provided. The relationship between specific energy and material removal rate has been investigated. In addition, the measurement of power and energy consumption in manufacturing is discussed. Furthermore, possible energy reduction strategies are discussed.

Keywords: Manufacturing, energy consumption, energy efficiency, sustainability

2.1 Unit Manufacturing Processes

Manufacturing involves the controlled application of energy to convert raw materials into finished products with defined shape, structure, and properties that satisfy given functions. The energy applied during processing may be mechanical, thermal, electrical, or chemical in nature. Usually manufacturing entails a process chain through the sequencing of different processes. The terminology “process” is equivalent to “operation.” They are

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the individual steps required to produce finished goods by transforming raw material and adding value to the workpiece as it becomes a finished product. Each individual process is known as a “unit operation/process.” These unit processes can be considered as the fundamental building blocks of a nation’s manufacturing capability. For example, a modern process chain to manufacture bearings is shown in Figure 2.1. The individual process such as forming, hardening, hard turning, and polishing is referred as unit process [1].

From the viewpoint of input and output, a unit process may be defined as an area of the process or a piece of equipment where materials are input, a function occurs and materials are output, possibly in a different form, state or composition [2–4]. All manufacturing processes take material inputs, including working materials and auxiliary materials, and transform them into products and wastes. Similarly, the energy inputs into these processes (primarily from electricity) are transformed into useful work, some of which is embodied into the form and composition of the products and wastes, and waste heat. In addition, the energy inputs usually require fuels and produce emissions. For electrical energy inputs, this occurs at the power station. A manufacturing process, along with material and energy flows to and from the process, is diagrammed in Figure 2.2.

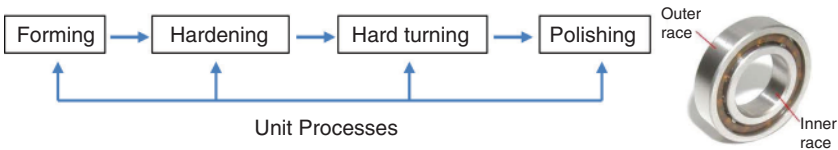


Figure 2.1 Process chain of unit processes to manufacture bearing race.

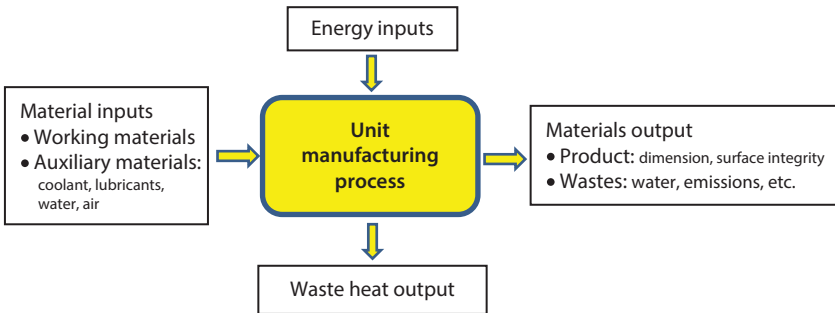


Figure 2.2 Energy and material inputs and outputs for unit manufacturing process.

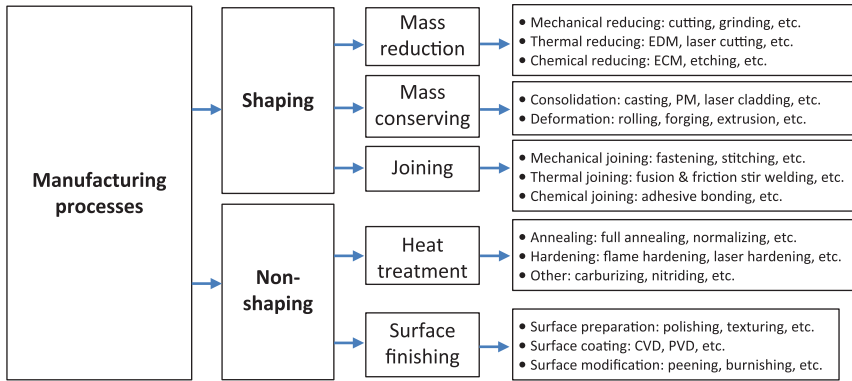


Figure 2.3 Taxonomy of manufacturing processes.

An extensive and continuously expanding variety of manufacturing processes are used to produce parts and there is usually more than one method of manufacturing a part from a given material. The taxonomy of manufacturing processes is illustrated by several versions [2, 5–7], Figure 2.3. These taxonomies have a first level classification of 5 to 6 groups and then these groups are populated by the actual different 120 unit processes.

Even though these unit manufacturing processes are very diverse, they all possess four key operation elements: the work material, the applied energy (mechanical, thermal, or chemical), a localized interaction zone between applied energy/work material, and the process equipment that provides the controlled application of energy. Advances in unit processes can be targeted at any one, or all, of these elements, although usually all four are affected to some extent by a change in any one of the elements. Furthermore, the emerging hybrid manufacturing processes may combine different unit processes working simultaneously on the same work zone within the material to improve manufacturing flexibility and efficiency. Thus, a systems approach is required for improving existing unit processes for developing new ones.

2.2 Life Cycle Inventory (LCI) of Unit Manufacturing Process

Based on a systematic taxonomy of manufacturing unit processes, a world-wide data collection effort is proposed within the CO₂PE! UPLCI-initiative. The CO₂PE!-Initiative [8] has as an objective to coordinate international

efforts aiming to document and analyze the environmental impacts of a wide range of current and emerging manufacturing processes, and to provide guidelines to reduce these impacts. Figure 2.4 gives an overview of the CO₂PE UPLCI—framework to collect, document and provide LCI data for a wide range of discrete manufacturing unit processes as well as to identify the potential for environmental improvements of the involved machine tools.

As shown in Figure 2.4, this data collection can be performed in two different ways and includes an energy, resource and process emission study. The screening approach relies on representative, publicly available data and engineering calculations for energy use, material loss, and identification of variables for improvement, while the in-depth approach is subdivided into four modules, including a time study, a power consumption study, a consumables study and an emissions study, in which all relevant process inputs and outputs are measured and analyzed in detail. The screening approach provides the first insight in the unit process and results in a set of approximate LCI data, which also serve to guide the more detailed and complete in-depth approach leading to more accurate LCI data as well as the identification of potential for energy and resource efficiency improvements of the manufacturing unit process.

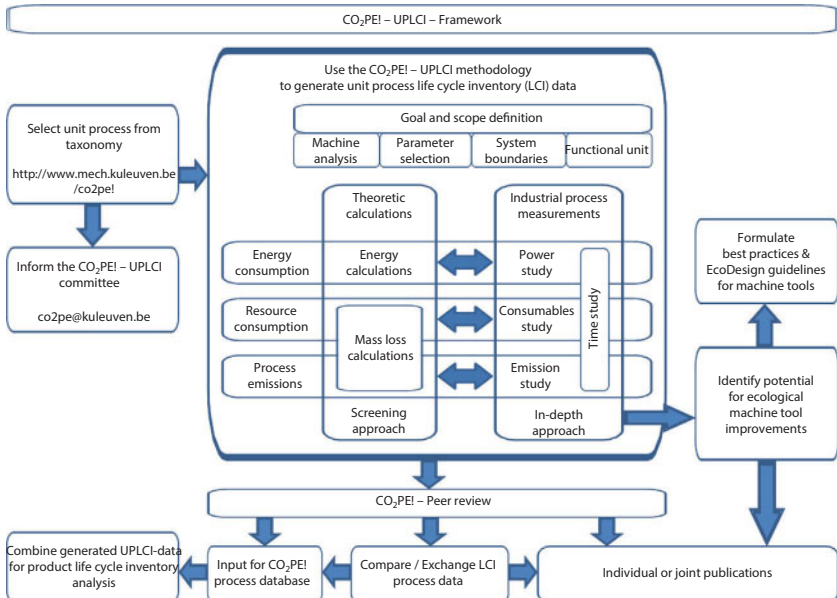


Figure 2.4 Overview of the CO₂PE! UPLCI—framework [9].