Selection of Materials and Manufacturing Processes for Engineering Design

MAHMOUD M. FARAG BSc, MMet, PhD

Selection of Materials and Manufacturing Processes for Engineering Design

MAHMOUD M. FARAG BSc, MMet, PhD
Professor of Engineering
American University in Cairo

Prentice Hall
New York London Toronto Sydney Tokyo

First published 1989 by
Prentice Hall International (UK) Ltd,
66 Wood Lane End, Hemel Hempstead,
Hertfordshire, HP2 4RG
A division of
Simon & Schuster International Group

Printed and bound in Great Britain at
the University Press, Cambridge

Library of Congress Cataloging-in-Publication Data

Farag, Mahmoud M., 1937–
Selection of materials and processes for engineering design/by Mahmoud M. Farag.
p. cm.
Bibliography: p.
Includes index.
ISBN 0-13-802208-9
ISBN 0-13-802216-X (pbk)
1. Engineering design. 2. Materials. 3. Manufacturing processes.
I. Title.
TA174.F27 1989
620'.0042–dc20 89-8518
CIP

British Library Cataloguing in Publication Data

Farag, Mahmoud M., 1937–
Selection of materials and processes for engineering design
1. Engineering Design Optimization's
I Title
620' 00425

ISBN 0-13-802208-9
ISBN 0-13-802216-X (pbk)

---

1 2 3 4 5 93 92 91 90 89

OCR-A ISBN

ISBN 0-13-802208-9
0-13-802216-X PBK

Preface

The introduction of a new engineering product or the changing of an old model involves reaching economic decisions, making designs, selecting materials and choosing manufacturing processes. These activities are interdependent and should not be performed in isolation from each other. This is because the materials and processes used in making the product can have a large influence on its design, shape, cost and performance in service. For example, making a part from injection-molded plastics instead of formed sheet metal is expected to involve large changes in design, new production facilities and widely different economic analysis. The further the design process proceeds the more difficult it is to consider alternative materials and manufacturing processes. Thus careful consideration should be given to materials and process selection in the earliest stages of design and decision making.

With the increasing pressure to produce cheaper and more reliable components and with the greater number of new engineering materials and manufacturing processes that are now available, there is a growing need for an integrated approach to economic analysis, design and materials and process selection. The integrated approach will make it easier to achieve the optimum component that will combine the functional requirements with reliability at a competitive cost. However, this task is not easy, especially in the context of today's technical and social climate where a large number of factors, not all of which are necessarily compatible, have to be taken into consideration. These factors are usually so diverse that it is seldom possible for one individual to be thoroughly conversant with all of them. At the same time, however, the engineer cannot afford to overlook any of these factors. Above all, the engineer must know how all these considerations fit together, what interactions are possible and what sort of tradeoffs can be made. The increasing use of computers in the various stages of product development has made the integrated approach easier to attain. Computer aided design, computer aided manufacture, computer aided economic analysis and computerized materials properties data banks are among the tools that are now available to the engineer.

The objective of this book is to provide both the technical and economic backgrounds that will enable the engineer to integrate the various activities involved in product development in order to arrive at the optimum solution for a given application. The book contains 25 chapters which are divided into four parts. Part I discusses the behavior and processing of engineering materials including metals, polymers, ceramics and composite materials; a discussion of the different causes of failure of components in service is also included. Part II introduces the elements of engineering design, reviews the different methods of decision making and discusses the effects of material properties and manufacturing processes on design. A review of the concepts of computer aided design and computer aided manufacture is also included. Part III reviews the economic concepts that are involved in design, materials selection and manufacturing. Part IV reviews the different methods of selection and uses case studies to illustrate the integration of design principles, economic analysis, manufacturing methods and materials selection. In view of the breadth of the subjects covered and in order to keep the length of the text within reasonable limits, only information that has direct relation to the objective of the book is presented. Selected references are given at the end of each chapter to allow the reader to find more detailed information. Whenever possible, examples and case studies are given to illustrate the practical application of the presented material, while questions and problems are given to help in reviewing the material. Appendices which give the properties of selected engineering materials and principles of engineering statistics are also included.

This book is written at the level of senior undergraduate or graduate engineering students; however, practicing engineers will also find the subject matter interesting and useful. Although the text is mainly written in metric units, English units are also given whenever possible. Appendices are also provided to give easy conversion between the two systems of units.

Mahmoud M. Farag

Contents

Chapter 1 The Activities Involved in Developing a Concept into a Finished Product

1.1 Introduction 1
1.2 Stages of product development 1
1.3 The feasibility study 4
1.4 Developing the design and selecting materials and processes 5
1.5 Project planning and scheduling 7
1.6 Launching the product 7
1.7 The product life cycle 8
1.8 Review questions and problems 10
Bibliography and further reading 10

PART I BEHAVIOR AND PROCESSING OF ENGINEERING MATERIALS

Chapter 2 Metallic Materials

2.1 Classification and specification of metallic materials 13
2.2 Strengthening of metallic materials 16
2.3 Carbon steels 21
2.4 Alloy steels 24
2.5 Cast irons 27
2.6 Light nonferrous metals and alloys 29
2.7 Heavy nonferrous metals and alloys 32
2.8 Design and selection considerations for metallic materials 35
2.9 Review questions and problems 36
Bibliography and further reading 37

Chapter 3 Processing of Metallic Materials

3.1	Classification of manufacturing processes	38
3.2	Dimensional accuracy and surface finish	40
3.3	Manufacturing by casting	47
3.4	Powder metallurgy processes	52
3.5	Bulk forming processes	52
3.6	Sheet metal forming processes	55
3.7	Fastening and joining processes	59
3.8	Machining processes	65
3.9	Surface treatment	69
3.10	Review questions and problems	72
	Bibliography and further reading	72

Chapter 4 Polymeric Materials and their Processing

4.1	Classification of polymers	74
4.2	Parameters affecting the behavior of plastics	75
4.3	General characteristics of plastics	77
4.4	Thermoplastics	83
4.5	Thermosetting plastics	86
4.6	Elastomers	87
4.7	Adhesives	88
4.8	Processing of plastics by molding	90
4.9	Extrusion of plastics	93
4.10	Thermoforming	94
4.11	Casting of plastics	96
4.12	Fastening and joining of plastic parts	97
4.13	Finishing of plastic parts	98
4.14	Design and selection considerations for polymers	100
4.15	Review questions and problems	101
	Bibliography and further reading	101

Chapter 5 Ceramic Materials and their Processing

5.1	Classification of ceramic materials	103
5.2	General characteristics of ceramics	103
5.3	Refractory ceramics	106
5.4	Whitewares	107
5.5	Clay products	108
5.6	Glass	108
5.7	Processing of ceramic products	110
5.8	Forming of glass products	113
5.9	Design considerations for ceramic products	114

5.10 Review questions and problems 115
Bibliography and further reading 116

Chapter 6 Composite Materials and their Processing

6.1 Introduction 117
6.2 Dispersion-strengthened composites 118
6.3 Particulate-strengthened composites 120
6.4 Mechanics of fiber reinforcement 121
6.5 Materials for fiber reinforcement 125
6.6 Laminated composites 127
6.7 Manufacturing of components made of composite materials 130
6.8 Designing with composites 134
6.9 Selection and use of composite materials 136
6.10 Review questions and problems 140
Bibliography and further reading 140

Chapter 7 Failure of Components in Service

7.1 Causes of failure of engineering components 141
7.2 Types of mechanical failure 142
7.3 Fracture toughness and fracture mechanics 143
7.4 Ductile and brittle fractures 149
7.5 Fatigue fracture 153
7.6 Wear failures 159
7.7 Corrosion failures 160
7.8 Stress corrosion and corrosion fatigue 163
7.9 Elevated temperature failures 164
7.10 Failure analysis 167
7.11 Review questions and problems 170
Bibliography and further reading 170

Chapter 8 Functional Requirements of Engineering Materials

8.1 Introduction 172
8.2 Selection of materials for static strength 172
8.3 Selection of materials for stiffness 174
8.4 Selection of materials for fatigue resistance 179
8.5 Selection of materials for toughness 181
8.6 Selection of materials for corrosion resistance 185
8.7 Selection of materials for temperature resistance 191
8.8 Selection of materials for wear resistance 194
8.9 Selection of materials for protective coatings 198
8.10 Review questions and problems 202
Bibliography and further reading 202

PART II DESIGN AND MANUFACTURE OF ENGINEERING COMPONENTS

Chapter 9 Elements of Engineering Design

9.1	Introduction	207
9.2	Factors influencing design	207
9.3	Major phases of design	208
9.4	Design codes and standards	211
9.5	Probabilistic design	213
9.6	Factor of safety and derating methods	214
9.7	Modeling and simulation in design	217
9.8	General considerations in mechanical design	219
9.9	Review questions and problems	219
	Bibliography and further reading	220

Chapter 10 Decision Making

10.1	Introduction	221
10.2	Decision matrix	222
10.3	Decision trees	224
10.4	Planning and scheduling models	225
10.5	Optimization methods	229
10.6	Optimization by differential calculus	231
10.7	Search methods of optimization	231
10.8	Linear programming	234
10.9	Sensitivity analysis	236
10.10	Geometric programming	237
10.11	Review questions and problems	238
	Bibliography and further reading	239

Chapter 11 Effect of Material Properties on Design

11.1	Factors affecting the behavior of materials in components	240
11.2	Statistical variation of material properties	240
11.3	Stress concentration	242
11.4	Designing for static strength	246
11.5	Designing with high-strength low-toughness materials	250
11.6	Designing against fatigue	255
11.7	Designing under high-temperature conditions	263
11.8	Review questions and problems	268
	Bibliography and further reading	268

Chapter 12 Effect of Manufacturing Processes on Design

12.1 Introduction 269
12.2 Design considerations for cast components 269
12.3 Design considerations for molded plastic components 271
12.4 Design considerations for forged components 274
12.5 Design of powder metallurgy parts 275
12.6 Design of sheet metal parts 278
12.7 Designs involving joining processes 279
12.8 Designs involving heat treatment 285
12.9 Designs involving machining processes 287
12.10 Designing for corrosive environments 289
12.11 Designs involving automated assembly 292
12.12 Review questions and problems 293
Bibliography and further reading 293

Chapter 13 Reliability of Engineering Components

13.1 Introduction 294
13.2 Assessment of reliability 296
13.3 Service life 301
13.4 Hazard analysis 302
13.5 Fault tree analysis 302
13.6 The role of design in achieving reliability 305
13.7 The role of materials and manufacturing in achieving reliability 309
13.8 The role of the user in achieving reliability 311
13.9 Maintenance and condition monitoring 311
13.10 Product liability 312
13.11 Review questions and problems 314
Bibliography and further reading 315

Chapter 14 Computer Aided Design

14.1 Introduction 316
14.2 The components of CAD systems 317
14.3 Geometric modeling 319
14.4 Automated drafting 321
14.5 Finite element analysis 322
14.6 Design review and evaluation 325
14.7 Creating the design and manufacturing data base 325
14.8 Applications of CAD in industry 326
14.9 Benefits of CAD 327
14.10 Review questions and problems 328
Bibliography and further reading 328

Chapter 15 Elements of the Production Function

15.1 Introduction 329
15.2 Types of manufacturing system 331
15.3 Production planning and control 332
15.4 The manufacturing shop 335
15.5 Modeling of production systems 336
15.6 Improving productivity in manufacturing 337
15.7 Review questions and problems 339
Bibliography and further reading 340

Chapter 16 Computer Aided Manufacture

16.1 Fundamentals and applications of CAM 341
16.2 Numerical control 341
16.3 Computer aided process planning 343
16.4 Computer aided quality control 345
16.5 Group technology 346
16.6 Industrial robots 351
16.7 Flexible manufacturing systems 353
16.8 The automated factory 355
16.9 Review questions and problems 356
Bibliography and further reading 356

PART III ECONOMIC CONSIDERATIONS

Chapter 17 Concepts of Economic Analysis

17.1 Types of costs in manufacturing 361
17.2 Break-even analysis 362
17.3 Time value of money 365
17.4 Comparing alternatives on cost basis 367
17.5 Depreciation and tax considerations 370
17.6 Benefit-cost analysis 373
17.7 Cost-effectiveness analysis 375
17.8 Minimum cost analysis 377
17.9 Value analysis 380
17.10 Review questions and problems 381
Bibliography and further reading 381

Chapter 18 Economics of Manufacturing Processes

18.1 Introduction 382
18.2 Methods of cost estimation in the process industries 382
18.3 Methods of cost estimation in manufacturing industries 384

18.4 Manufacturing time 385
18.5 Manufacturing costs 388
18.6 Economic justification of jigs and fixtures 390
18.7 Economics of metal cutting 391
18.8 Standard costs 394
18.9 Learning curve 395
18.10 Selling price of a product 396
18.11 Life cycle costing 399
18.12 Review questions and problems 399
Bibliography and further reading 400

Chapter 19 Economics of Materials

19.1 Introduction 401
19.2 Elements of the cost of materials 402
19.3 Factors affecting material prices 404
19.4 Comparison of materials on cost basis 407
19.5 Value analysis of material properties 407
19.6 Economics of material utilization 410
19.7 Competition in the materials field 412
19.8 Review questions and problems 413
Bibliography and further reading 413

PART IV INTEGRATION OF DESIGN AND ECONOMIC ANALYSIS WITH MATERIALS AND PROCESS SELECTION

Chapter 20 The Selection Process

20.1 Introduction 417
20.2 The nature of the selection process 418
20.3 Analysis of the material performance requirements 419
20.4 Development and evaluation of alternative solutions 421
20.5 Cost per unit property method 422
20.6 Weighted properties method 424
20.7 Incremental return method 429
20.8 Limits on properties method 430
20.9 Computer aided materials and process selection 433
20.10 Materials data bases 435
20.11 Sources of information on materials properties 437
20.12 Review questions and problems 438
Bibliography and further reading 443

Chapter 21 Design and Selection of Materials for a Turnbuckle

21.1 Introduction 445
21.2 Design of the turnbuckle 446

21.3 Candidate materials and manufacturing processes 450
21.4 Sample calculations 451
21.5 Selection of optimum materials 453
Bibliography and further reading 456

Chapter 22 Design and Selection of Structural Parts of a Cargo Trailer

22.1 Introduction 457
22.2 Design of the cargo trailer 457
22.3 Candidate materials and manufacturing processes 459
22.4 Evaluation of candidate materials 461
22.5 Selection of optimum materials 463
Bibliography and further reading 466

Chapter 23 Design and Materials Selection for Lubricated Journal Bearings

23.1 Introduction 467
23.2 Design of the journal bearing 468
23.3 Analysis of bearing material requirements 470
23.4 Classification of bearing materials 473
23.5 Selection of the optimum bearing alloy 474
Bibliography and further reading 475

Chapter 24 Analysis of the Requirements and Selection of Materials for Tennis Rackets

24.1 Introduction 477
24.2 Analysis of the functional requirements of the tennis racket 477
24.3 Design considerations 478
24.4 Analysis of the racket material requirements 481
24.5 Classification of racket materials 482
24.6 Evaluation of racket materials 484
Bibliography and further reading 485

Chapter 25 Design and Selection of Materials for a Surgical Implant

25.1 Introduction 486
25.2 Design considerations 486
25.3 Analysis of implant material requirements 489
25.4 Classification of materials for the prosthesis pin 491
25.5 Evaluation of candidate materials 492
Bibliography and further reading 493

PART V APPENDICES

Appendix A Properties and composition of selected engineering materials 497
Appendix B Conversion of units and hardness values 513
Appendix C Principles of engineering statistics 516

Index 528

Chapter 1

The Activities Involved in Developing a Concept into a Finished Product

1.1 INTRODUCTION

The introduction of a new product or changing an old model involves carrying out a feasibility study, making designs, reaching economic decisions, selecting optimum materials, choosing appropriate manufacturing processes, planning and scheduling of various activities, developing the market, selling the product and arranging for after-sales service. These diverse activities are interdependent and should not be performed in isolation from each other. This is because it is not sufficient that the design of the product should satisfy the technical requirements, it must also be possible to manufacture it with the available facilities and to sell it at a competitive price.

The main objective of this chapter is to outline the spectrum of activities that are involved in developing a new product, starting from the conception of the idea and ending with the marketable product. This chapter will also help in showing how the different topics that are discussed in this book fit into the total picture of the industrial enterprise.

1.2 STAGES OF PRODUCT DEVELOPMENT

An industrial product is normally expected to satisfy a certain demand and to give satisfaction to the user. A product usually starts as a concept which, if feasible, develops into a design, then into a finished product. While each engineering product has its own individual character and its own sequence of development events, there is a general pattern for the various stages that accompany the introduction of a new product, as shown in Fig. 1.1. To illustrate how the various stages could apply in practice, let us take a hypothetical case of a motor car company considering the introduction of an inexpensive fuel-efficient two-passenger (two-seater) model. This is based on the statistics that on about 80 percent of all trips American cars carry no more than two people and that in a little more than 50 percent of all trips the driver is alone. Such a car will be predominantly driven in city traffic, where the average vehicle speed is about 55 km/h (30 mph). Based on this concept and function, a feasibility study could be started. As a first phase of the project, assume it is decided to select a design concept which is based on the present traditional internal combustion engine technology. The company expects, however, that

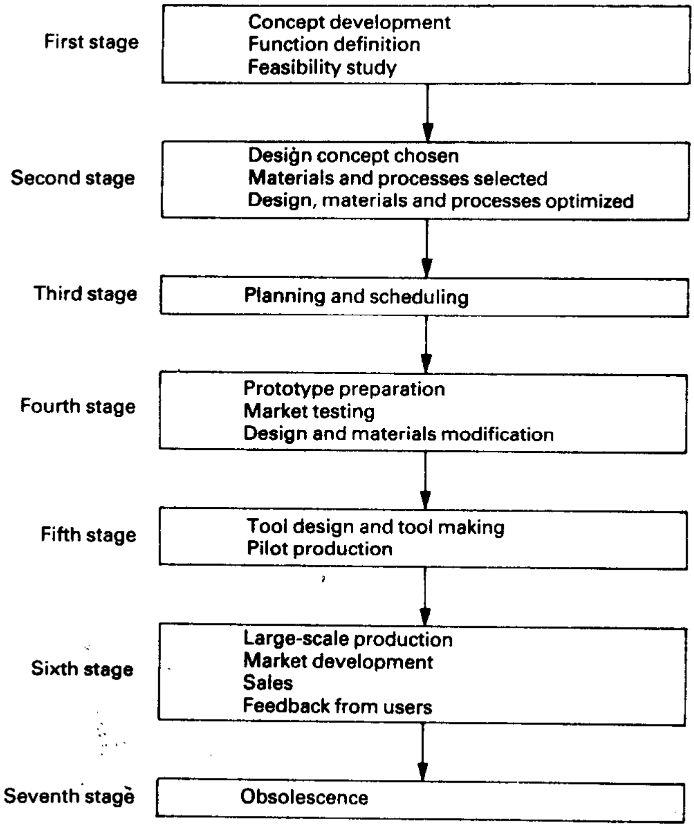

Figure 1.1 Stages of product development.

in view of the growing pressure to reduce pollution in large cities, a battery/solar cell-driven car could be in demand in the future. This concept is adopted as a second phase.

Having defined the overall concept and product function, the second step is the feasibility study where social, economic and legal issues related to the nature and functions of the new model are analyzed and questions related to the market and competition are posed. Important design features as well as the main manufacturing processes and materials requirements should be broadly outlined at this stage. More details about the feasibility study will be given in Section 1.3.

With such a new product (which has no precedent, since at present the only two-passenger models available are the relatively expensive and energy-inefficient sports cars) the first stage involves a large amount of creative work and innovation. In many cases of product development, however, an existing product is modified to suit other applications, to take advantage of new processes and materials or to improve its service performance. In the latter cases, the innovative part of the first stage may not constitute an important phase in product development, although economic analysis would still be required.

As a result of the feasibility study and the comparisons between the various design concepts, a final design concept is selected (Fig. 1.1, second stage). For the hypothetical case of the two-passenger car, let us assume that for the first phase of the project it was decided to select a design concept which would not require a major break with traditional automotive technology. The design limits that were imposed on the design for the first phase are shown in Table 1.1. The relevant figures for a four-passenger car which is produced by the same company are included for comparison. Based on the imposed limits, a workable design will be developed and used as a basis for a more accurate estimation of the development costs. Optimization techniques are then performed to refine the design and to select the optimum material and processing route. Other related departments within the company, e.g. purchasing, quality control, industrial engineering, production and marketing, should be consulted to determine the optimum material procurement, manufacturing methods and sales of the product. The design of engineering components will be discussed in detail in Part II of this book while the selection process will be discussed in Part IV.

The third stage of product development is planning and scheduling in preparation for production. Planning consists of identifying the key activities and ordering them in the sequence in which they should be performed; scheduling consists of putting the plan on a calendar timetable, as will be discussed in Section 1.5.

Table 1.1 Comparison of design parameters for the proposed two-passenger car and an average four-passenger model

Design parameter	Range for 4-passenger car[a]	2-passenger car
Fuel consumption	10.4–25 km/l (25–60 mile/gal)	35 km/l (84 mile/gal)
Mass	900–1600 kg (2000–3600 lb)	500 kg (1100 lb)
Acceleration time from 0–90 km/h (0–50 mile/h)	10–15 s	15 s
Speed maintained on 5% gradient	100 km/h (55 mile/h)	90 km/h (50 mile/h)
Cost of the car	\$5000–12 000	\$4000
Safety requirement in US	30 mile/h crash test	same
Engine emission	EPA test limits	same

[a]Based on figures given by Gray and Hippel (see bibliography).

The fourth stage involves preparation of prototypes, preliminary production and market tests. In the case of our two-passenger car, the prototype is used for measuring aerodynamic drag forces, crash tests and consumer reaction. As a result of this development work, some design or materials modifications may have to be made. The fifth stage consists of tool design and tool making as well as pilot production. Even at this stage, some design and materials modifications may have to be made in order to suit large-scale production.

The sixth stage is commercial or large-scale production of the product, which is carried out concurrently with market development. The activities involved in launching the product will be discussed in Section 1.6. Feedback from users to evaluate the reliability of the product and its effectiveness in performing the intended function is useful in determining future modifications or developments. The availability of spare parts and maintenance facilities are also important factors that could influence the final level of product use. The factors affecting the reliability of engineering components will be discussed in Chapter 13.