بسمه تعالی

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انتخاب مواد و فرایند در طراحی و تولید محصولات جدید

Selection of Materials and Processes in Design and Manufacturing of New Products

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عنوان درس به فارسی:	**انتخاب مواد و فرایند در طراحی و تولید محصولات جدید**			
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نوع آموزش تکمیلی عملی (در صورت نیاز): سفر علمی ☐ آزمایشگاه ☐ سمینار ☐ کارگاه ☐ موارد دیگر: ....

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در طراحی و تولید محصولات و سامانه های ساده و پیچیده انتخاب بهینه مواد و نوع فرایند تولید نقشی کلیدی خواهد داشت، کارکرد، طول عمر و قیمت تمام شده هر سامانه و اجزا آن مستقیما تحت تاثیر انتخاب مواد و فرایند قرار دارد هدف این درس آشنا شدن با مفاهیم نواوری و روندهای تکوین ایده تا ساخت محصولات جدید یا بهینه سازی آنها و افزایش مهارت دانشجویان کارشناسی ارشد شناسایی و انتخاب مواد در گزینش مواد و فرایندهای تولید برای ساخت محصولات جدید یا جایگزینی و بهینه سازی مواد سازنده اجزا سامانه های موجود است.

پ) مباحث یا سرفصل‌ها:

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- جایگاه انتخاب مواد در طراحی محصولات جدید یا بهینه سازی مواد در فرایندهای مهندسی معکوس
- طبقه‌بندی مواد و مروری بر خصوصیات مهم و کلیدی مواد برای بهره برداری در فرایند انتخاب و گزینش مواد
- آشنایی با نمودارهای نمایش خصوصیات و مشخصات مواد برای شرایط متفاوت
- ،ملاحظات مربوط به طراحی و انتخاب مواد، در شرایط بارگذاری استاتیکی و دینامیکی، انتخاب مواد بر مبنای سفتی، انتخاب مواد مقاوم به خستگی، انتخاب مواد بر مبنای چقرمگی، انتخاب مواد مقاوم به خوردگی، انتخاب مواد مقاوم به دماهای بالا، انتخاب مواد مقاوم به سایش، پوشش‌های مقاوم به خوردگی و سایش
- الکوریتم و استراتژی انتخاب مواد
- آشنایی با معیارهای انتخاب شامل محدوده های خاصیت و شاخص ماده
- فرموله کردن فرایند انتخاب برای اجزا استاندارد شامل میله، تیر، ستون و...
- مثال های کاربردی انتخاب مواد برای اجزا و قطعات سامانه های متفاوت
- مروری بر فرایندهای تولید و طبقه بندی آن ها
- روش های اصولی انتخاب فرایند و جداول انتخاب فرایند
- رتبه بندی و معیارهای انتخاب فرایند
- مثال های کاربردی انتخاب فرایند

چ) فهرست منابع پیشنهادی:

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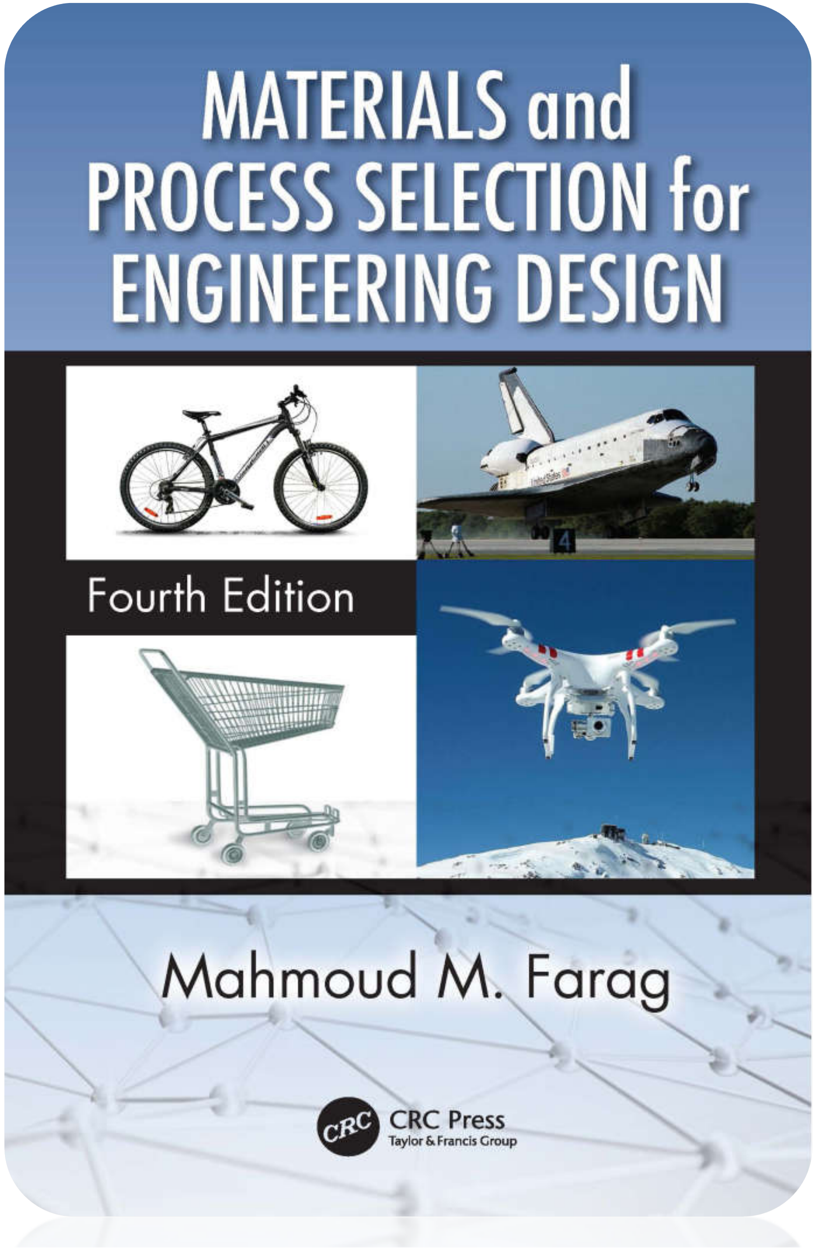
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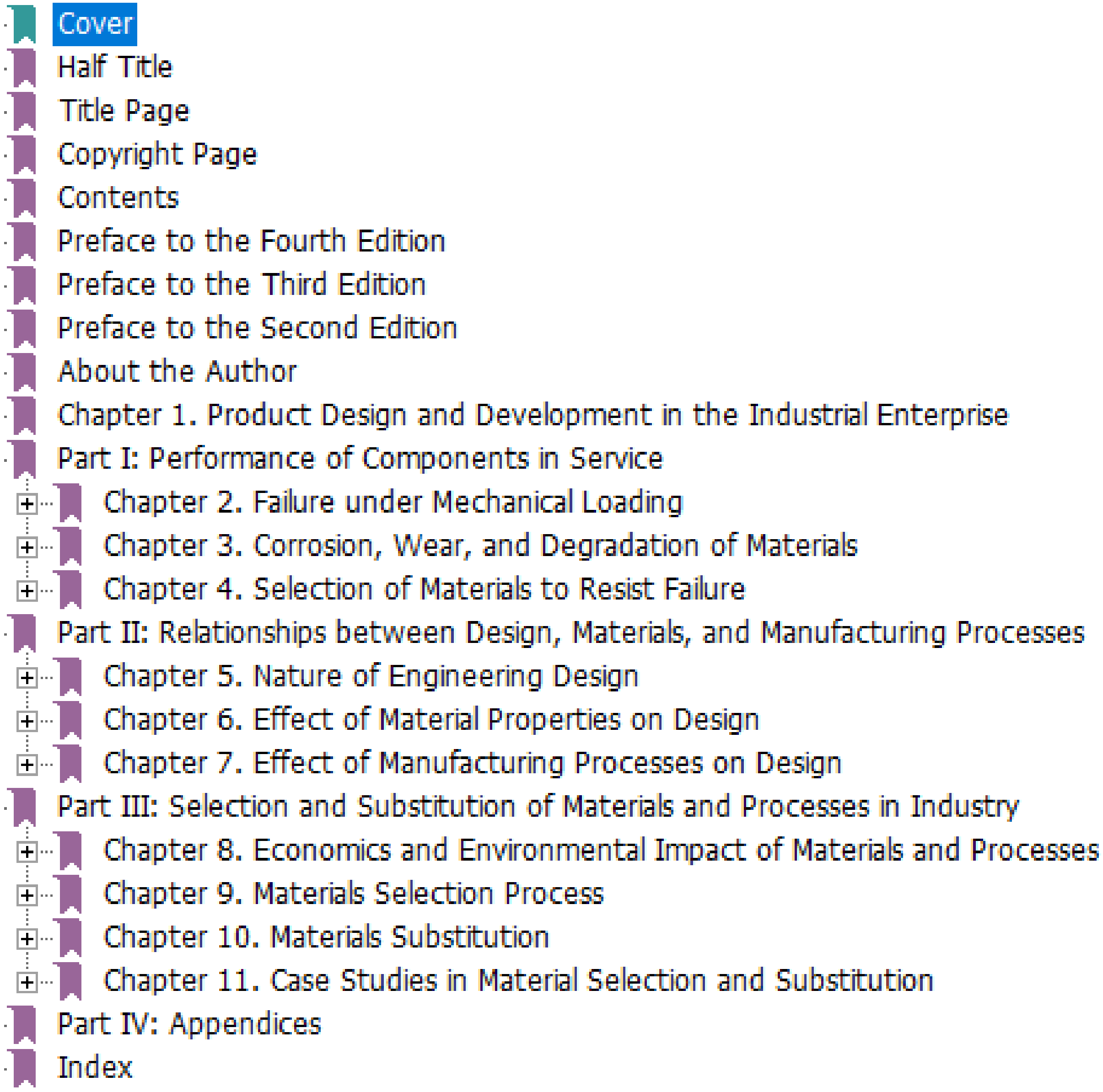
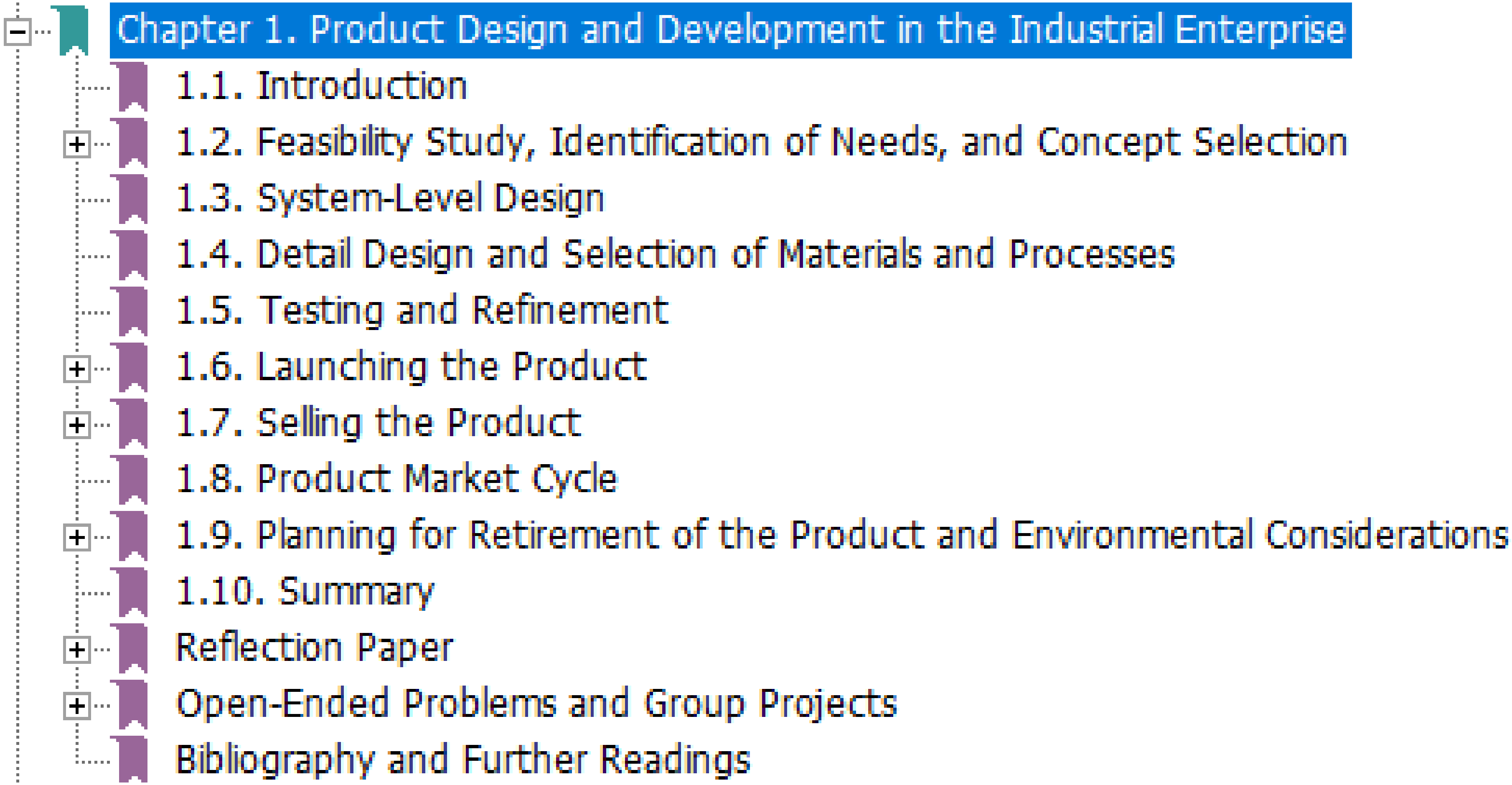


Chapter 1: Product Design and Development in the Industrial Enterprise



1.1 INTRODUCTION

Product design and development involve interdisciplinary activities with contributions from different segments of an industrial enterprise including design, materials and manufacturing, finance, legal, sales, and marketing. This is because in addition to satisfying the technical requirements, a successful product should also be esthetically pleasing, safe to use, economically competitive, and compliant with legal and environmental constraints.

A product usually starts as a concept that, if feasible, develops into a design and then a finished product. While each engineering product has its own individual character and its own sequence of development events, the following seven phases can be identified in a variety of product design and development projects:

1. Identification of needs, feasibility study, and concept selection
2. System-level design, detail design, and selection of materials and processes
3. Testing and refinement
4. Manufacturing the product
5. Launching the product
6. Selling the product
7. Planning for its retirement

1.2 FEASIBILITY STUDY, IDENTIFICATION OF NEEDS, AND CONCEPT SELECTION

A statement describing the function, main features, general shape, and essential features of the product is normally followed by a feasibility study that addresses market environment, customer views, technical specifications, economic analysis, as well as social, environmental, safety, and legal issues.

1.2.1 MARKET RESEARCH

Market research involves a survey to evaluate competing products and their main characteristics in addition to identifying the customer needs.

1.2.2 CUSTOMER NEEDS AND PRODUCT SPECIFICATIONS

Identification of needs and customer views is an important first step in the development and design of a new product. The house of quality (HOQ) is a structured process for translating customer requirements and market research into quantifiable product characteristics and specifications to be met by the product design.

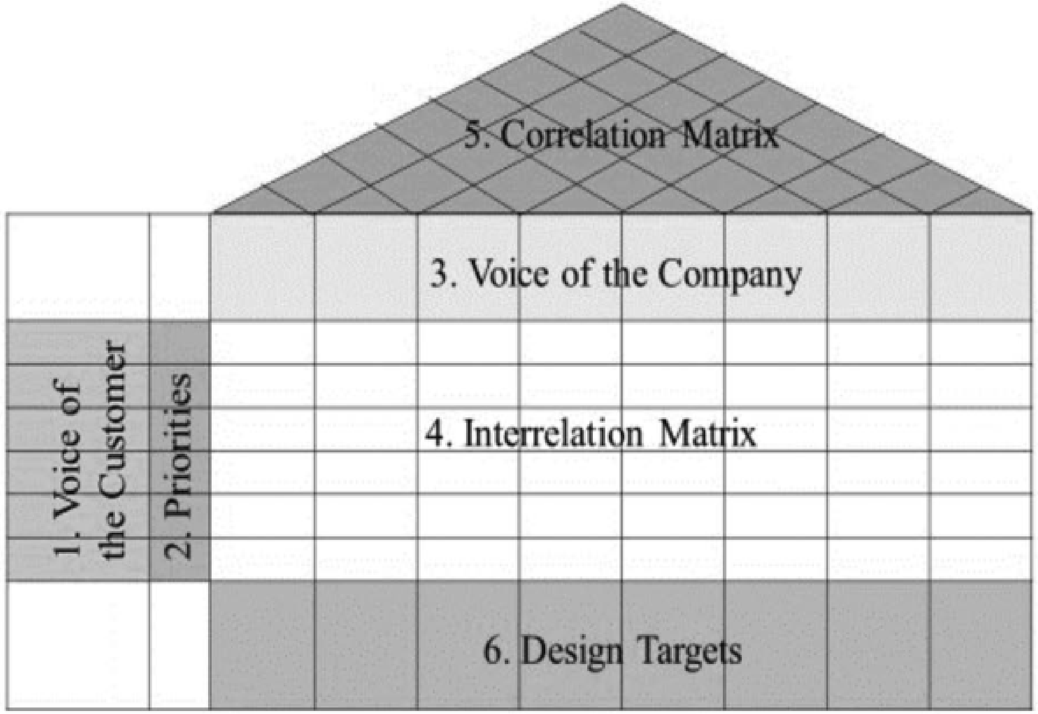


FIGURE 1.1 Simplified house of quality

The six sections of the simplified HOQ can be briefly described as follows:

1. Voice of the customer is a list of customer requirements from the product. These are usually gathered through conversations, opinion surveys, and market research. Examples of such requirements are shown in Table 1.1 for a cordless power drill for domestic use.
2. Prioritized customer requirements and the degree of customer satisfaction with various competing products relative to the different requirements are included in this section. This information is also based on opinion surveys and market research.
3. Voice of the company can be a list of the technical parameters, product characteristics, from the point of view of the manufacturer in terms of engineering specifications. These include measurable quantities such as weight, dimensions, level of noise, power consumption, and cost. For example, a specification of "the total weight of the product must be less than 5 kg" can be based on the customer need of a "lightweight product" and the observation that the lightest competing product is 5 kg. Similarly, a specification of "average time to unpack and assemble the product is less than 22 min"

TABLE 1.1

Using HOQ to Translate the Voice of the Customer into Product Specifications for a Cordless Power Drill for Domestic Use

Technical → Parameters Customer Requirements ↓	Importance to Customer	Keyless Chuck	Variable Speed, Reverse, Hammer	Variable Torque Settings	Ergonomic Design	Soft Grip	Maximum Weight	Overload Function	Light Powerful Battery	Tough Construction Material	Maximum Price
Safe to use	5	3	3	3	3	1	3	9	1	1	
Lightweight	4				1		9			3	
Rugged and long life	5							3		9	
Long life for battery charge	3								9		
Can drill holes in different materials and screw bolts	5	3	9	9			1	3	1		
Ergonomic	3	1			9	3	3				
Easy to use	4	9	3	3	3	9	3	3			
Inexpensive	3										9
Importance		69	72	72	58	50	77	87	37	62	27
Relative importance (%)		11	12	12	10	8	13	14	6	10	4
Target design parameters/ specifications		Keyless design of chuck	0–450/0–1500 rpm at no load. Drill 24 mm holes in wood and 10 mm holes in concrete and steel	Use 18 V battery and 24 torque settings. Drill 24 mm holes in wood and 10 mm holes in concrete and steel	Ergonomic design for good grip and maximum thrust of hand	Soft rubbery material on the grip	3 kg	Include overload function to avoid overheating of motor	Lithium ion technology	High toughness materials for construction of body	$120

4. Interrelation matrix correlates the customer requirements with a technical parameter based on inputs from Sections 1, 2, and 3.

5. Correlation matrix, roof of the house, shows how the technical parameters support or impede one another. When an improvement in one parameter leads to an improvement in another, a (+) sign is given to indicate support. On the other hand, when the improvement leads to deterioration in another parameter, a (–) sign is given to indicate trade-off.

6. Design targets give the conclusions drawn from the data in the other sections of the HOQ. This section gives the relative importance of the technical parameters in meeting customer needs, compares the product with the competition, and indicates the levels of performance to be achieved in the new product. Table 1.1 shows an example of the design targets for a cordless power drill for domestic use.

1.2.3 CONCEPT GENERATION, SCREENING, AND SELECTION

Product specifications are then used to develop different product concepts that satisfy customer needs. Some of the concepts may be generated by the development team as novel solutions, but others may be based on existing solutions or patents. The different concepts are then compared to select the most promising option. The Pugh method is useful as an initial concept-screening tool. In this method, a decision matrix is constructed as shown in Table 1.2. Each of the characteristics of a given concept is compared against a base/reference concept, and the result is recorded in the decision matrix as (+) if more favorable, (–) if less favorable, and (0) if the same. Concepts with more (+) than (–) are identified as serious candidates for further consideration.

The Pugh method

TABLE 1.2
Concept-Screening Matrix

Selection Criteria	Reference Concept	Concept A	Concept B	Concept C	Concept D
Criterion 1	0	–	+	+	0
Criterion 2	0	+	+	0	0
Criterion 3	0	+	+	+	–
Criterion 4	0	0	0	+	–
Criterion 5	0	0	–	–	+
Total (+)	0	2	3	3	1
Total (–)	0	1	1	1	2
Total (0)	5	2	1	1	2
Net score	0	1	2	2	–1
Decision	No	Consider	Consider	Consider	No

1.2.4 ECONOMIC ANALYSIS

The economic analysis section of the feasibility study normally provides an economic model that estimates the development costs, initial investment that will be needed, manufacturing costs, and income that will probably result for each of the selected concepts. The economic analysis also estimates sources and cost of financing based on the rate of interest and schedule of payment. The model should allow for a "what if" analysis to allow the product development team to assess the sensitivity of the product cost to changes in different elements of cost.

1.2.5 SELECTING AN OPTIMUM SOLUTION

The final stage of the feasibility study identifies an optimum solution. Selection is usually based on economics as well as technical specifications, since the product is expected to satisfy the customer needs at an acceptable price. This process involves trade-offs between a variety of diverse factors, such as

- Customer needs
- Physical characteristics of size and weight
- Expected life and reliability under service conditions
- Energy needs
- Maintenance requirements and operating costs
- Availability and cost of materials and manufacturing processes
- Environmental impact
- Quantity of production
- Expected delivery date

A quantitative method that can be used in concept selection gives weight to product specifications according to their importance to the function of the product and preference of the customer. The total score of each concept is determined by the weighted sum of the ratings of its characteristics, as shown in Table 1.3.

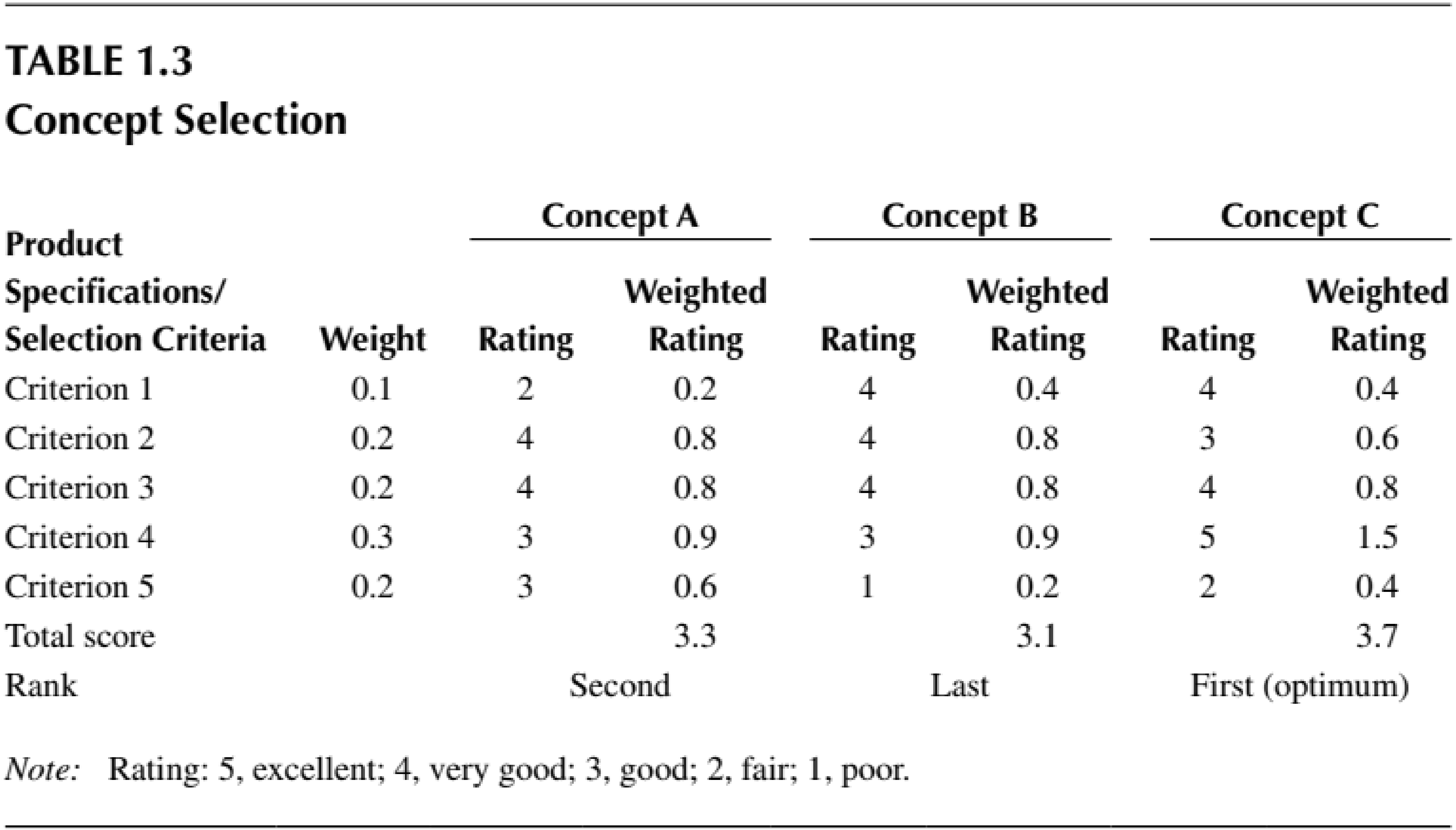


TABLE 1.3

Concept Selection

Product Specifications/ Selection Criteria	Weight	Concept A		Concept B		Concept C	
		Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Criterion 1	0.1	2	0.2	4	0.4	4	0.4
Criterion 2	0.2	4	0.8	4	0.8	3	0.6
Criterion 3	0.2	4	0.8	4	0.8	4	0.8
Criterion 4	0.3	3	0.9	3	0.9	5	1.5
Criterion 5	0.2	3	0.6	1	0.2	2	0.4
Total score			3.3		3.1		3.7
Rank		Second		Last		First (optimum)	

Note: Rating: 5, excellent; 4, very good; 3, good; 2, fair; 1, poor.

CASE STUDY 1.1: DEVELOPING THE GREENOBILE

A motorcar company is considering the introduction of an inexpensive, environment-friendly, two-passenger (two-seater) model. The idea behind this product is based on the statistics that in about 80% of all trips, American cars carry no more than two people, and in a little more than 50% of all trips, the driver is alone. Such cars will be predominantly driven in city traffic, where the average vehicle speed is about 55 km/h (30 mph).

MARKET RESEARCH

Market research is carried out through interviews and discussions with focus groups of 8–12 prospective customers. The questions discussed include the following:

1. Frequency of driving the car, how far is each journey on an average, expected distance traveled per year, and expected life of the car.
2. Esthetic qualities: main preferences for body styling and look, number of doors, number of wheels, etc.
3. Level of comfort on a bumpy road.
4. Ease of handling and parking.
5. Safety issues including stability on the road, especially when turning around sharp corners.
6. Expected cost.

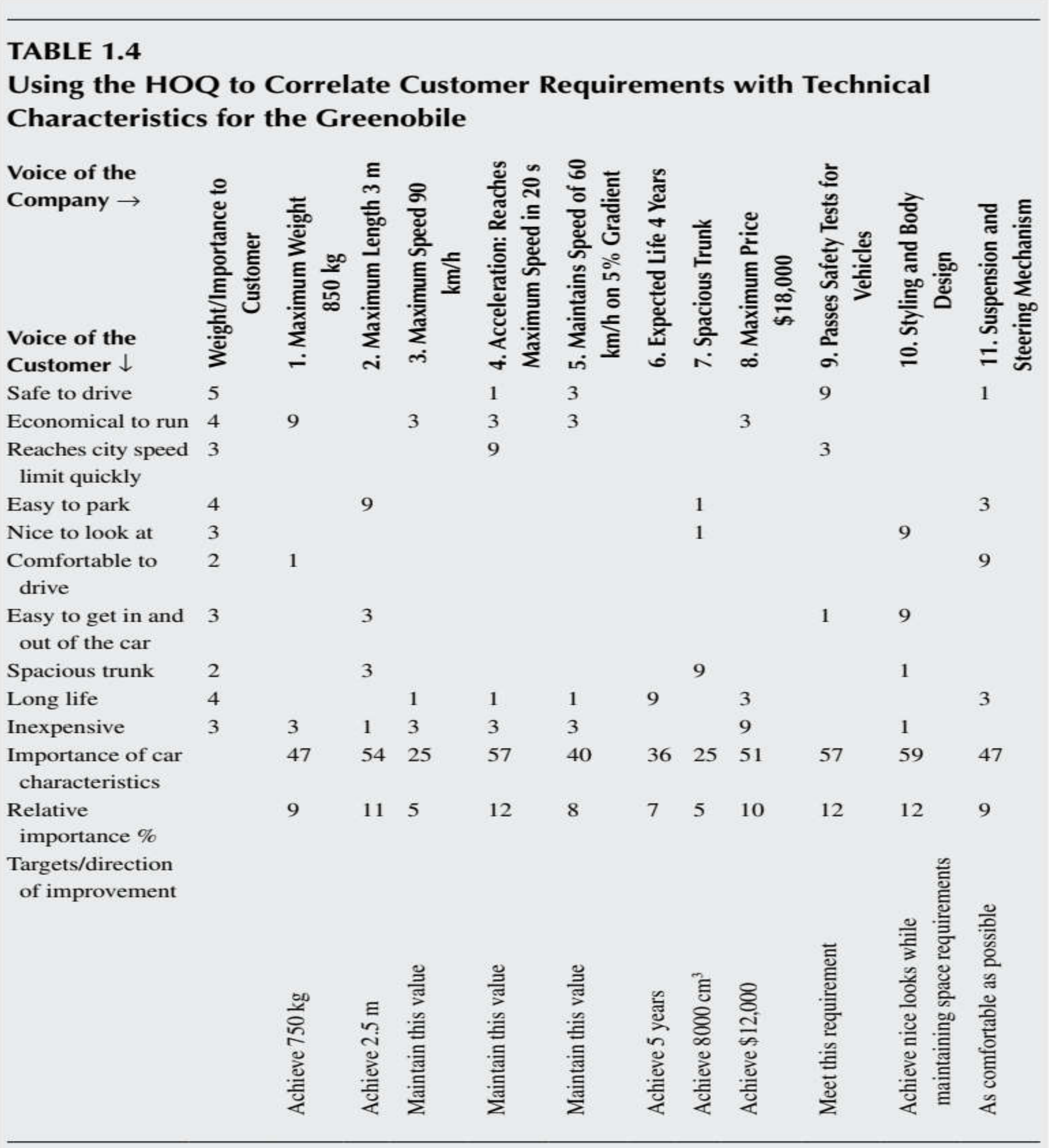


TABLE 1.4
Using the HOQ to Correlate Customer Requirements with Technical Characteristics for the Greenobile

Voice of the Company → Voice of the Customer ↓	Weight/Importance to Customer	1. Maximum Weight 850 kg	2. Maximum Length 3 m	3. Maximum Speed 90 km/h	4. Acceleration: Reaches Maximum Speed in 20 s	5. Maintains Speed of 60 km/h on 5% Gradient	6. Expected Life 4 Years	7. Spacious Trunk	8. Maximum Price $18,000	9. Passes Safety Tests for Vehicles	10. Styling and Body Design	11. Suspension and Steering Mechanism
Safe to drive	5				1	3				9		1
Economical to run	4	9		3	3	3			3			
Reaches city speed limit quickly	3				9					3		
Easy to park	4		9					1				3
Nice to look at	3							1			9	
Comfortable to drive	2	1										9
Easy to get in and out of the car	3		3							1	9	
Spacious trunk	2		3					9			1	
Long life	4			1	1	1	9		3			3
Inexpensive	3	3	1	3	3	3			9		1	
Importance of car characteristics		47	54	25	57	40	36	25	51	57	59	47
Relative importance %		9	11	5	12	8	7	5	10	12	12	9
Targets/direction of improvement		Achieve 750 kg	Achieve 2.5 m	Maintain this value	Maintain this value	Maintain this value	Achieve 5 years	Achieve 8000 cm^3	Achieve $12,000	Meet this requirement	Achieve nice looks while maintaining space requirements	As comfortable as possible

TABLE 1.5
Concept Selection for the Greenobile

Technical Requirements	Targets	Relative Importance	Concept A		Concept B		Concept C	
			Rating Relative to Target	Weighted Rating	Rating Relative to Target	Weighted Rating	Rating Relative to Target	Weighted Rating
1. Maximum weight 850 kg	Achieve 750 kg	0.09	750/850	0.079	750/800	0.084	750/750	0.09
2. Maximum length 3.0 m	Achieve 2.5 m	0.11	2.5/3.0	0.092	2.512.5	0.11	2.5/2.8	0.98
3. Maximum speed 90 km/h	Maintain this value	0.05	1	0.05	1	0.05	1	0.05
4. Acceleration: reaches maximum speed in 20 s	Maintain this value	0.12	1	0.12	1	0.12	1	0.12
5. Maintains speed of 60 km/h on 5% gradient	Maintain this value	0.08	1	0.08	1	0.08	1	0.08
6. Expected life 4 years	Achieve 5 years	0.07	5/5	0.07	4/5	0.056	4/5	0.056
7. Spacious trunk	Achieve 8000 cm³	0.05	8/8	0.05	7/8	0.044	7/8	0.044
8. Maximum price $18,000	Achieve $12,000	0.10	12/18	0.067	12/15	0.08	12/12	0.1
9. Passes safety tests for vehicles	Meet this requirement	0.12	1	0.12	1	0.12	1	0.12
10. Styling and body design	Achieve nice looks while maintaining space requirements	0.12	1	0.12	0.9	0.11	0.8	0.096
11. Suspension and steering mechanism	As comfortable as possible	0.09	1	0.09	0.9	0.08	0.9	0.08
Total score				0.938		0.934		0.934

CONCLUSION

The results of Table 1.5 indicate that concept A is the optimum solution by a small margin with concepts B and C of equal score. The points in favor of concept A are the styling, larger trunk space, longer life, the flexibility of hybrid drive, and greater comfort. With these advantages, the higher price and longer length are justified.

1.4 DETAIL DESIGN AND SELECTION OF MATERIALS AND PROCESSES

As progress is made from product specifications to system-level design and then to detail design, the tasks to be accomplished become more narrowly defined. In the detail design stage, the focus is on static and dynamic forces and their effect on the performance of the component under the expected service conditions. This latter task requires thorough knowledge of how materials behave in service and what processes are needed to achieve the final shape of the component.

Design reviews represent an important part of each phase of the design process. They provide an opportunity to identify and correct problems before they can seriously affect the successful completion of the design. The design review teams normally have representatives from the materials and manufacturing, quality control, safety, financial, and marketing areas. This ensures that the design is satisfactory not only from the performance point of view but also from the manufacturing, economic, reliability, and marketing points of view.

The behavior of materials in service is discussed in Part I, the effect of materials and processes on design is discussed in Part II, and the selection of the optimum materials and processes is discussed in Part III.

1.5 TESTING AND REFINEMENT

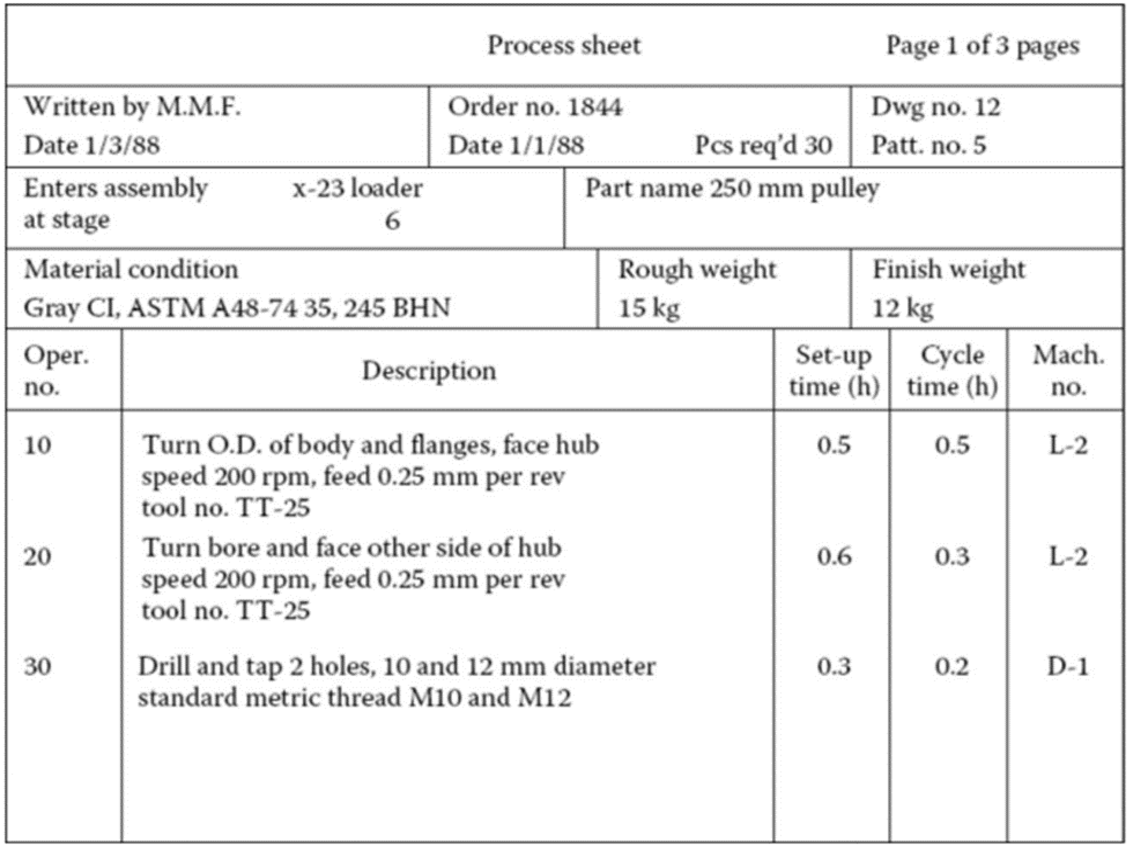
The testing and refinement phase is normally carried out as part of the R&D function of the company. A first prototype (alpha) is usually built from parts with the same geometry and material as the final product but not necessarily using the same manufacturing processes. Alpha prototypes are tested to ensure that the product works as intended and that it satisfies its main requirements. After modifications, a second prototype (beta) may be built to ensure reliability of the product and to measure its level of performance. Potential customers may also be involved at this stage to incorporate their feedback in making the final product.

1.6 LAUNCHING THE PRODUCT

Launching the product covers the activities of planning and scheduling, manufacturing the product, marketing, and arranging for after-sales services. This stage is best organized on the basis of planning and scheduling schemes, which are drawn to meet the product delivery times, as discussed in this section.

1.6.2 MANUFACTURING

The sequence of manufacturing processes is first established for each part of the product and recorded on a process sheet. The form and condition of the material, as well as the tooling and production machines that will be used, are also recorded on the process sheet. An example of a simple process sheet is shown in Figure 1.4.



Process sheet
Page 1 of 3 pages

Written by M.M.F.
Date 1/3/88
Order no. 1844
Date 1/1/88
Pcs req'd 30
Dwg no. 12
Patt. no. 5

Enters assembly at stage x-23 loader 6
Part name 250 mm pulley

Material condition Gray CI, ASTM A48-74 35, 245 BHN
Rough weight 15 kg
Finish weight 12 kg

Oper. no.	Description	Set-up time (h)	Cycle time (h)	Mach. no.
10	Turn O.D. of body and flanges, face hub speed 200 rpm, feed 0.25 mm per rev tool no. TT-25	0.5	0.5	L-2
20	Turn bore and face other side of hub speed 200 rpm, feed 0.25 mm per rev tool no. TT-25	0.6	0.3	L-2
30	Drill and tap 2 holes, 10 and 12 mm diameter standard metric thread M10 and M12	0.3	0.2	D-1

FIGURE 1.4 Example of a simple process sheet.

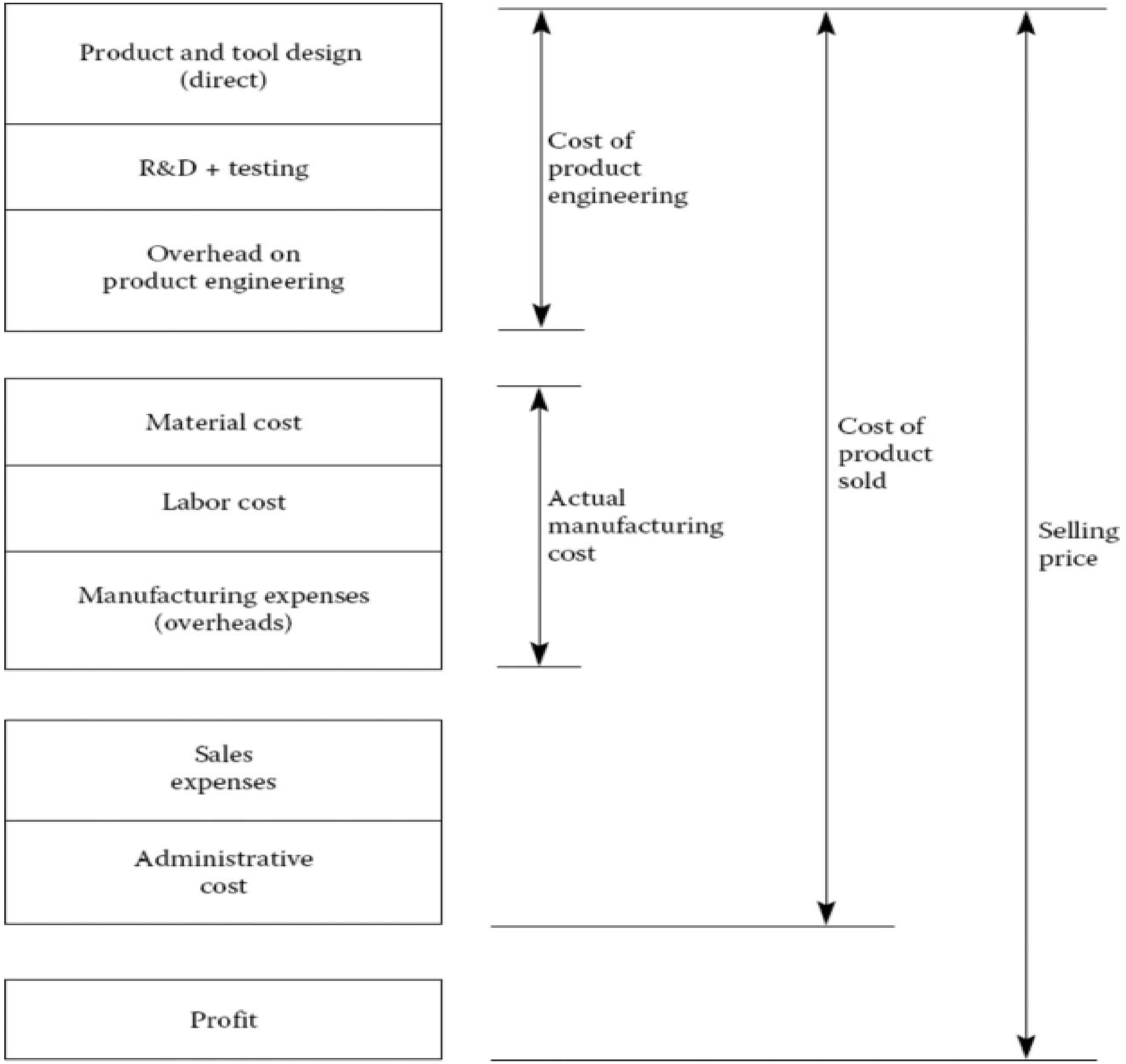


FIGURE 1.6 Factors involved in determining the selling price of a product.

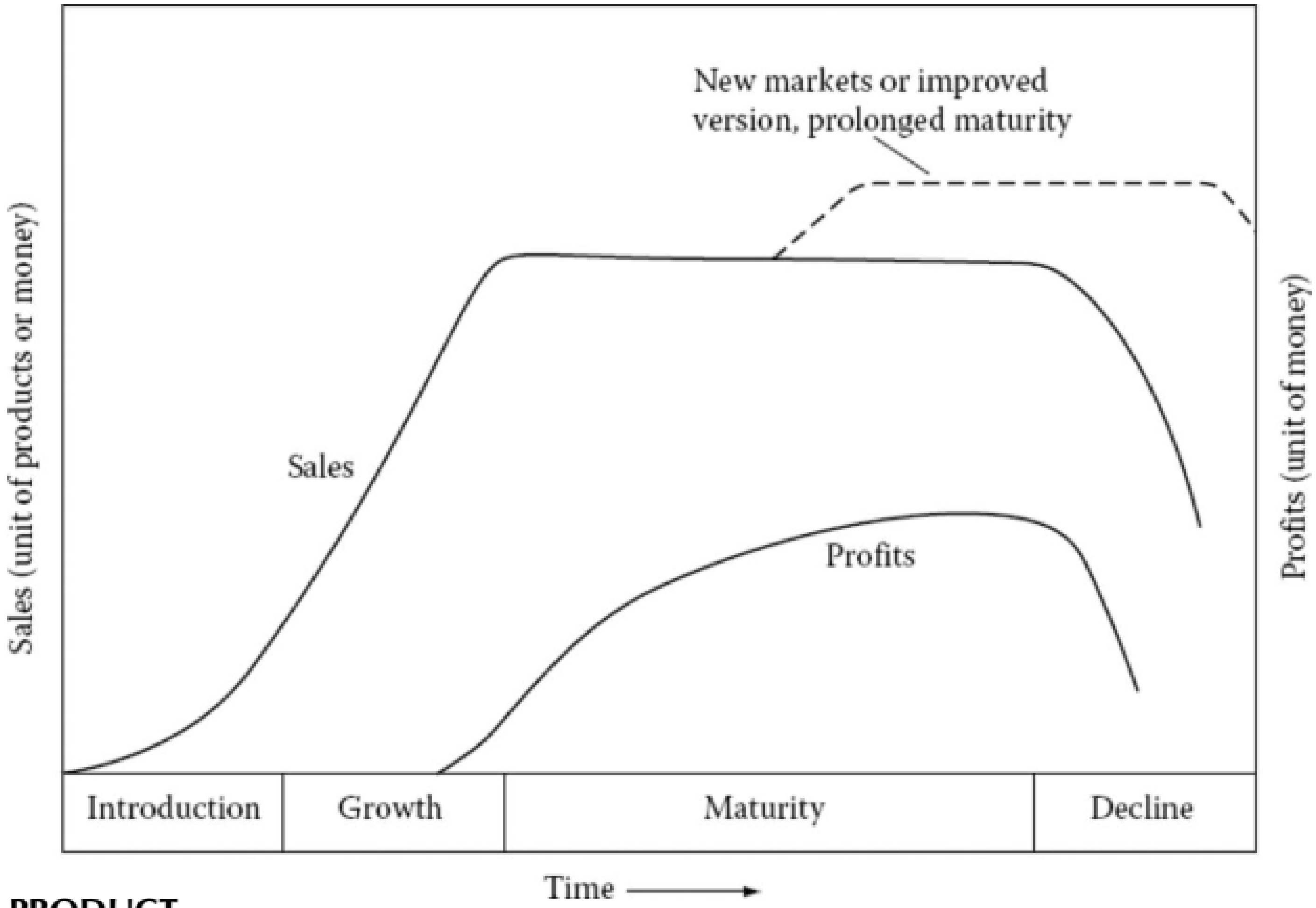


FIGURE 1.7 Market cycle of a product.

1.9 PLANNING FOR RETIREMENT OF THE PRODUCT AND ENVIRONMENTAL CONSIDERATIONS

1.9.1 Recycling of Materials

1.9.2 Recyclability of Materials

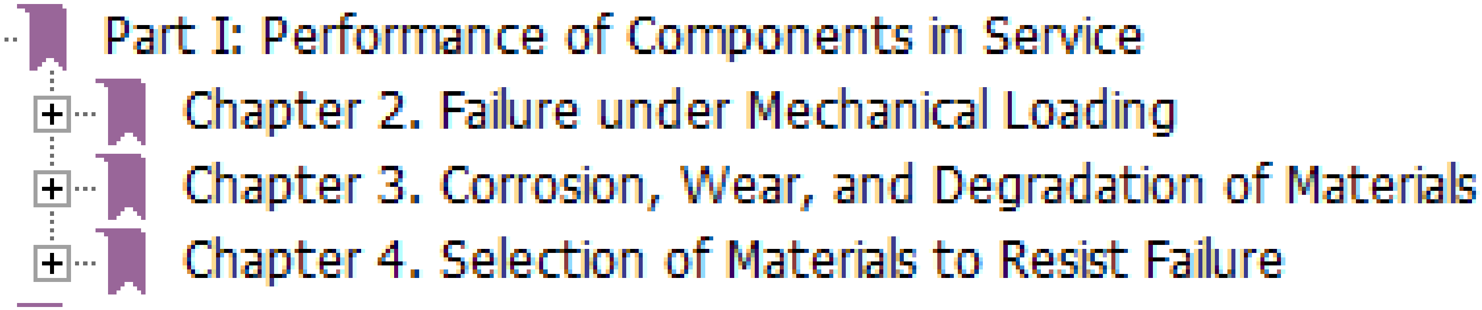
1.10 SUMMARY

1. Ideally, product development is performed by an interdisciplinary team with representatives from different segments of an industrial enterprise including engineering design, materials and manufacturing, finance, legal, sales, and marketing. This is because in addition to satisfying the technical requirements, a successful product should also be esthetically pleasing, safe to use, economically competitive, and compliant with legal and environmental constraints.
2. The activities involved in product development include seeking consumer views and translating them into technical requirements, developing concepts and performing feasibility study, performing system-level design, developing detail design and selecting materials and processes, testing and refining a prototype, launching the product, and selling the product. The HOQ approach makes it easier to correlate customer needs with product technical characteristics.

3. The selling price of a product is determined by the cost of product engineering (design, R&D, testing, and refinement), manufacturing cost (material and labor costs), sales expense and administrative cost, income taxes, and net profit.
4. The market cycle of a product consists of an introduction stage, a growth stage, a maturity stage in which the production rates and sales volume reach the design value, and decline where sales decrease, leading to the end of the market cycle of the product. Because most profits are made during the maturity stage, it should be prolonged by developing new markets and introducing design modifications.
5. Because material industry consumes a considerable amount of energy in making its products, it is no longer acceptable that engineering materials are used and then discarded in landfills. Better alternatives include waste reduction and recycling. Efficient recycling needs an infrastructure for sorting and scrap processing.

Part I

Performance of Components in Service



Of the above types of failure, corrosion represents about 30% of the failur of engineering component and fatigue about 25%. Failures as a result of plast deformation, ductile or brittle facture, wear, and creep represent about 10–15 each.

These types of failure can occur as a result of a variety of causes, which can arranged in order of importance as follows:

1. Poor selection of materials represents about 40% of the causes of failure of engineering components. Failure to identify clearly the functional requirements of a component could lead to the selection of a material that only partially satisfies these requirements. As an example, a material can have adequate strength to support the mechanical loads, but its corrosion resistance is insufficient for the application.
2. Manufacturing defects, as a result of fabrication imperfections and faulty heat treatment, represent about 30% of the causes of failure of engineering components. Incorrect manufacturing could lead to the degradation of an otherwise satisfactory material. Examples include decarburization and internal stresses in a heat-treated component. Poor surface finish, burrs, identification marks, and deep scratches due to mishandling could lead to failure under fatigue loading.

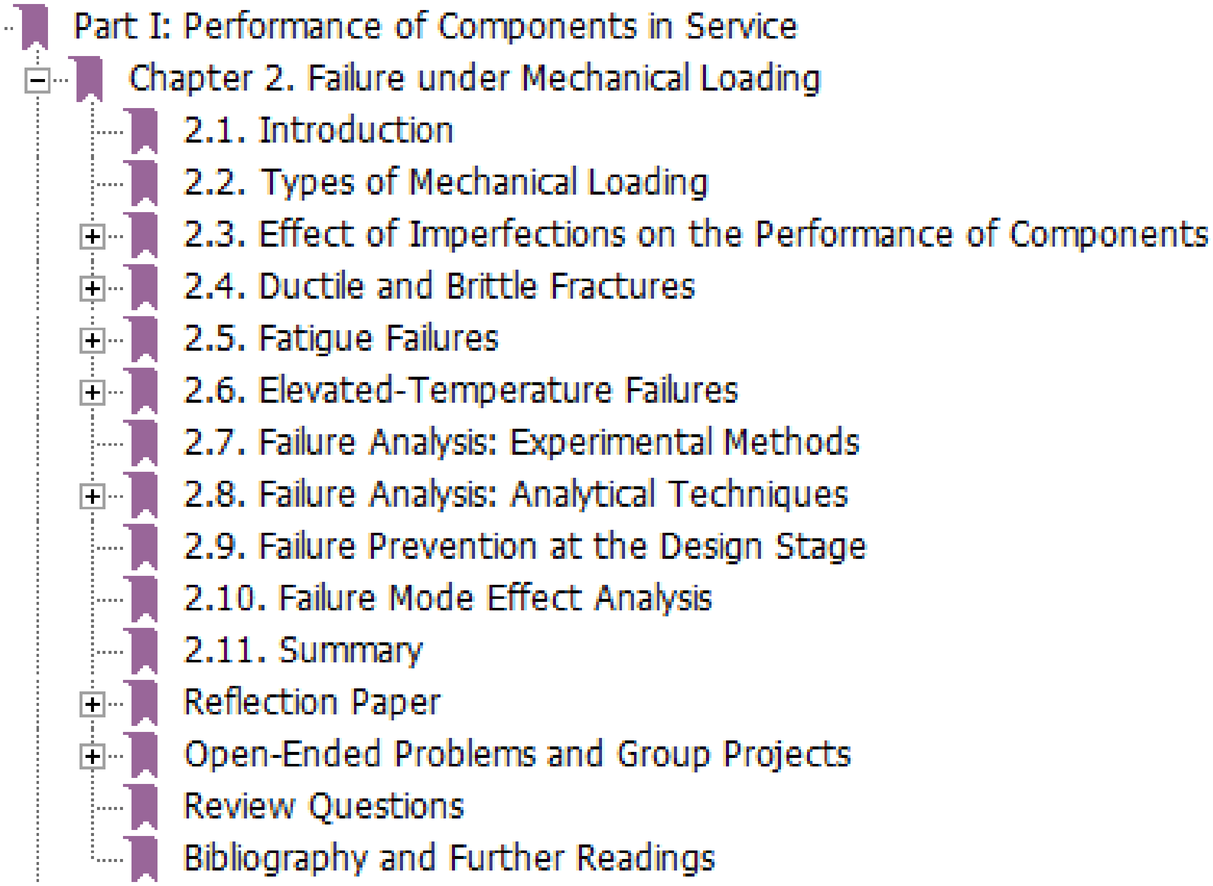
3. Design deficiencies constitute about 20% of the causes of failure of engineering components. Failure to evaluate working conditions correctly due to the lack of reliable information on loads and service conditions is a major cause of inadequate design. Incorrect stress analysis, especially near notches, and complex changes in shape could also be a contributing factor.
4. Exceeding design limits, overloading, and inadequate maintenance and repair represent about 10% of the causes of failure of engineering components. If the load, temperature, speed, voltage, etc. are increased beyond the limits allowed by the factor of safety in design, the component is likely to fail. As an example, if an electric cable carries a higher current than the design value, it overheats, and this could lead to melting of the insulating polymer and then short circuit. Subjecting the equipment to environmental conditions for which it was not designed also falls under this category. An example is using a freshwater pump for pumping seawater. In addition, when maintenance schedules are ignored and repairs are poorly carried out, service life is expected to be shorter than anticipated by the design.

In spite of the designers' and manufacturers' efforts to avoid failure, components do fail in service, and it is important to determine the causes of failure and how to avoid them in the future. Major failure incidents are normally analyzed by interdisciplinary teams consisting of field experts, designers, materials and manufacturing engineers, as well as service personnel. Failures under mechanical loading are discussed in Chapter 2, failures due to corrosion and wear are discussed in Chapter 3, and selection of materials to resist failure is discussed in Chapter 4.

After completing Part I, the reader will be able to

1. Assess the effect of mechanical loading and service environment on the performance of components.
2. Recognize the different types of failure of components as a result of mechanical loading and environmental attack.
3. Perform experimental and analytical failure analysis on failed components and products, determine the probable causes of failure, and recommend ways of avoiding it in the future.
4. Select the appropriate materials and processes that can resist a given type of loading or a source of failure.

2 Failure under Mechanical Loading



- Part I: Performance of Components in Service
  - Chapter 2. Failure under Mechanical Loading
    - 2.1. Introduction
    - 2.2. Types of Mechanical Loading
    - 2.3. Effect of Imperfections on the Performance of Components
    - 2.4. Ductile and Brittle Fractures
    - 2.5. Fatigue Failures
    - 2.6. Elevated-Temperature Failures
    - 2.7. Failure Analysis: Experimental Methods
    - 2.8. Failure Analysis: Analytical Techniques
    - 2.9. Failure Prevention at the Design Stage
    - 2.10. Failure Mode Effect Analysis
    - 2.11. Summary
    - Reflection Paper
    - Open-Ended Problems and Group Projects
    - Review Questions
    - Bibliography and Further Readings

2.2 TYPES OF MECHANICAL LOADING

Failure under mechanical loading can take place either as a result of permanent change in the dimensions of a component, which results in an unacceptably low level of performance, or as a result of actual fracture. The general types of mechanical loading encountered in practice are as follows:

1. Static loading subjects the material to stresses, which, if sufficiently high, can cause yielding of the component material. Yielding causes permanent deformation, which could result in misalignment or hindrance to mechanical movement. Static loading can also cause unacceptable levels of deflection if the component does not have sufficient stiffness. Compressive static loading can cause buckling in slender columns or in thin-walled tubes. At excessively high levels of static loading failure can occur by fracture due to static overload. This type of failure can be considered as an advanced stage of failure by yielding. Fracture can be either ductile or brittle.

2. Impact loading can cause fracture of a component if the amount of energy it delivers is higher than the toughness of the material. When impact loading takes place at low temperature, fracture takes place by cleavage in a brittle manner, as in the case of steels below brittle–ductile transition temperature and plastics below glass transition temperature.

3. Alternating and fluctuating loading can cause failure by fatigue fracture, especially in the presence of material defects or stress raisers. Fatigue fractures usually take place suddenly without apparent visual signs.

4. High temperature loading causes the material to creep. When the creep strain exceeds allowable tolerances and causes interference of parts. In extreme cases, failure can take place through rupture of the component subjected to creep. In bolted joints and similar applications, failure can take place when the initial stressing has relaxed below allowable limits, so that the joints become loose or leakage occurs.

5. Friction and abrasive loading causes wear in the material. Excessive wear can result in unacceptable play in bearings and loss of accuracy of movement. Other types of wear failure are galling and seizure of parts. Because wear is primarily a surface phenomenon, it will be discussed in Chapter 3, together with corrosion failures.

2.3 EFFECT OF IMPERFECTIONS ON THE PERFORMANCE OF COMPONENTS

It is now recognized that the great majority of engineering components can contain potential sites for cracks in the form of discontinuities, heterogeneities, flaws, inclusions, or microstructural defects that can be classified as follows:

- Microstructural features of materials, such as oxide or sulfide inclusions, large carbide and intermetallic precipitates, and inhomogeneous distribution of alloying elements leading to hard or soft spots.
- Processing defects such as shrinkage and gas pores in castings, slag inclusions and similar welding defects, laps and stringers in forgings, contaminants in powder metallurgy parts, and decarburization in heat treatment.
- Damage during service such as surface pits due to corrosion, cracks at discontinuities due to fatigue loading, surface damage due to wear and fretting, and internal voids and cracks due to creep.

TABLE 2.1
Nondestructive Methods of Crack Detection

Method	Applications and Standard Covering the Practice
Visual examination. The naked eye or a magnifying glass is used to locate and measure cracks.	Surface cracks
Penetrant test. Liquids that enter surface discontinuities by capillary action are first applied to the surface and then wiped off. A developer is then applied to help delineate the areas where the liquid has penetrated.	Defects open to the surface of metallic and nonmetallic materials (ASTM E 165)
Radiographic examination. X-rays and γ-rays are used to penetrate materials and are then caught on a sensitized film. Cavities or inclusions absorb the rays differently from the rest of the material and are delineated on the developed film.	Radiographs show the size and shape of discontinuities (ASTM E 94)
Magnetic particle method. A liquid containing iron powder is first brushed on the surface, and the part is then placed in a strong magnetic field. The particles pile up at discontinuities.	Detects surface cracks in magnetic materials (ASTM E 109 and E 138)
Ultrasonic tests. Ultrasonic vibrations that are transmitted through the material are reflected back at an internal discontinuity earlier than when reaching the opposite surface. The difference between the reflected waves is used to locate the position of the discontinuity.	Internal defects in ferrous and nonferrous metals and alloys (ASTM E 127)
Eddy current inspection. A coil is excited to induce eddy currents in the component to be inspected. In turn, this excitation induces a current in the coil. The presence of defects affects the induction of the component, which affects the current in the coil.	Used for the inspection of surface and subsurface defects in electrically conducting materials

2.3.2 FRACTURE TOUGHNESS OF MATERIALS

Based on the Griffith theory for the fracture strength of materials, the effect of having a flaw of a given size on the fracture stress σ_f of a given material, in MPa or psi, can be determined using the following expression:

$$\sigma_f = \frac{K_{IC}}{Y(\pi a)^{1/2}} \quad (2.1),$$

where

K_{IC} is the fracture toughness of the material in MPa $(m)^{1/2}$ or psi $(in.)^{1/2}$,

Y is a correction factor that depends on the geometry of the part and is usually taken as 1, and

a is the flaw size for edge crack and $2a$ for center.

As K_{IC} is a material property, the designer can use it to determine the flaw size that can be tolerated in a component for a given applied stress level. Conversely, the designer can determine the stress level that can be safely used for a flaw size that may be present in a component. Examples 2.1 and 2.2 illustrate the use of fracture toughness in design.

Fracture toughness data are available for a wide range of materials and some examples are given in Section 4.5. Like other material properties, fracture toughness is influenced by several factors including strain rate or loading rate, temperature, and microstructure, as discussed in more detail in Section 4.5. Also, increasing the yield and tensile strengths of the material usually causes a decrease in K_{IC}. The use of fracture toughness in design is discussed in Section 6.4.

Fracture toughness is widely accepted as a design criterion for high-strength materials where ductility is limited. In such cases, the relationship between K_{IC}, applied stress, and crack length governs the conditions for fracture in a part or a structure. This relationship is shown schematically in Figure 2.1. If a particular combination of stress and flaw size in a structure reaches the K_{IC} level, fracture can occur. Thus, there are many combinations of stress and flaw size that may cause fracture in a structure made of a material having a particular value of K_{IC}. The figure shows that materials with higher K_{IC} values tolerate larger flaws at a given stress level or higher stress levels for a given flaw size.

Figure 2.1 also shows that if a material of known K_{IC} is selected for a given application, the size of the flaw that will cause fracture can be predicted for the anticipated applied stress. If the design stress of a part is taken as 0.5 YS, the critical flaw length would be (a_1). Therefore, provided that no defect of size greater than (a_1) is present, failure should not occur on loading. If in a proof test, the part is loaded to a stress above the expected service stress and the test was successful, then a flaw of size greater than a_2 could not have existed. During service life, crack growth of the order of ($a_1 - a_2$) could be tolerated before failure.

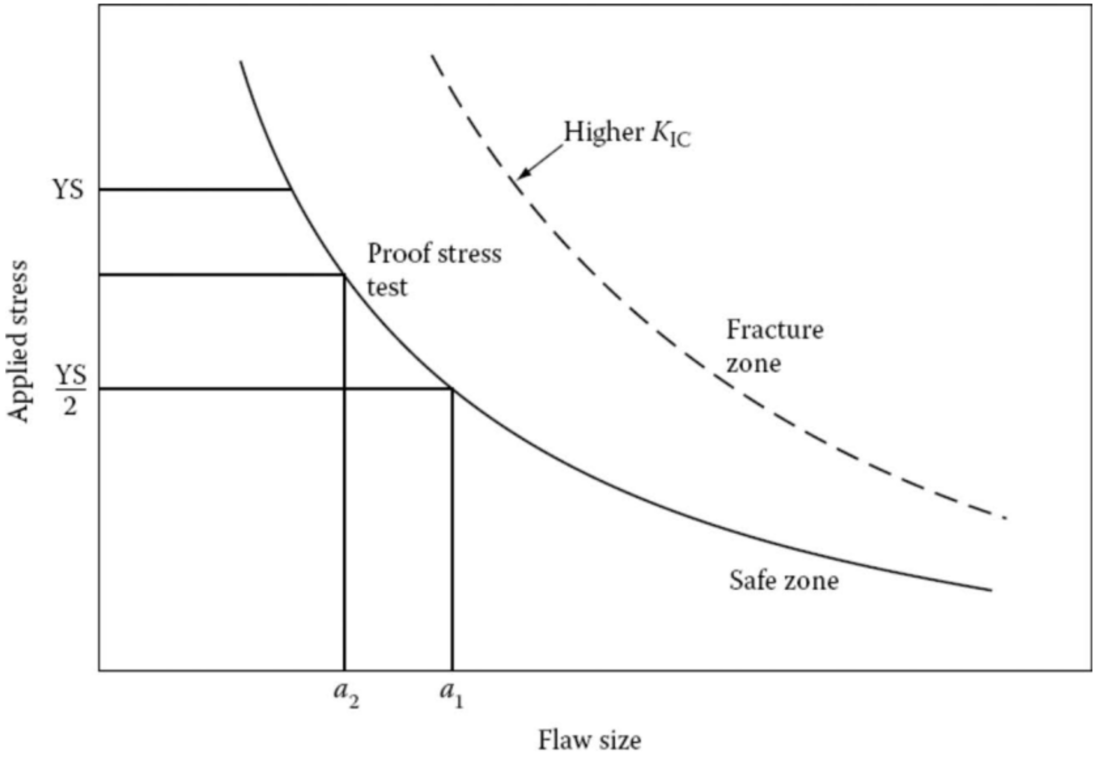


FIGURE 2.1 Schematic relationship between stress, flaw size, and fracture toughness.

From Equation 2.1 and Figure 2.1, it can be shown that the maximum allowable flaw size is proportional to $(K_{IC}/YS)^2$, where K_{IC} and YS are measured at the expected service temperature and loading rate. Thus, the ratio (K_{IC}/YS) can be taken as an index for comparing the relative toughness of structural materials. Higher values of (K_{IC}/YS) are more desirable as they indicate tolerance to larger flaws without fracture, as discussed in Section 4.5. The sensitivity of the NDT techniques used to detect manufacturing defects that approach the critical size in the part or structure is determined by the value of the allowed flaw size.

8.3 DESIGN PHILOSOPHY

The interaction of material properties, such as the fracture toughness, with the design stress and crack size controls the conditions for fracture in a component. For example, it is seen from Fig. 8.7*a* that the fracture condition for an infinitely large cracked plate would be

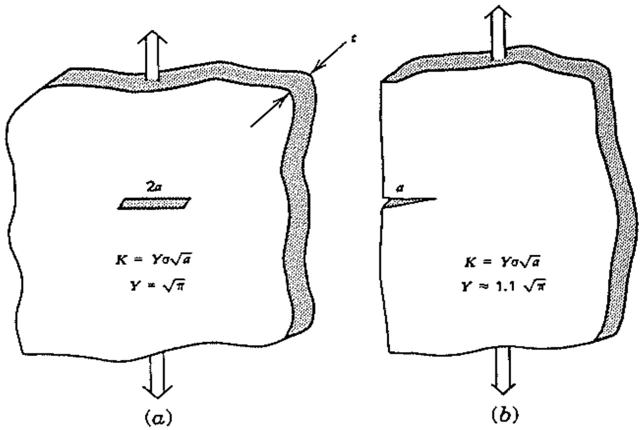
$$K = K_c = \sigma\sqrt{\pi a} \qquad (8\text{-}28)$$

Material selection

Design stress

Allowable flaw size or NDT flaw detection

This relation may be used in one of several ways to design against a component failure. For example, if you are to build a system that must withstand the ravages of a liquid metal environment, such as in some nuclear reactors, one of your major concerns is the selection of a suitable corrosion-resistant material. Once done, you have essentially fixed K_c. In addition, if you allow for the presence of a relatively large stable crack—one that can be readily detected and repaired—the design stress is fixed and must be less than $K_c/\sqrt{\pi a}$.



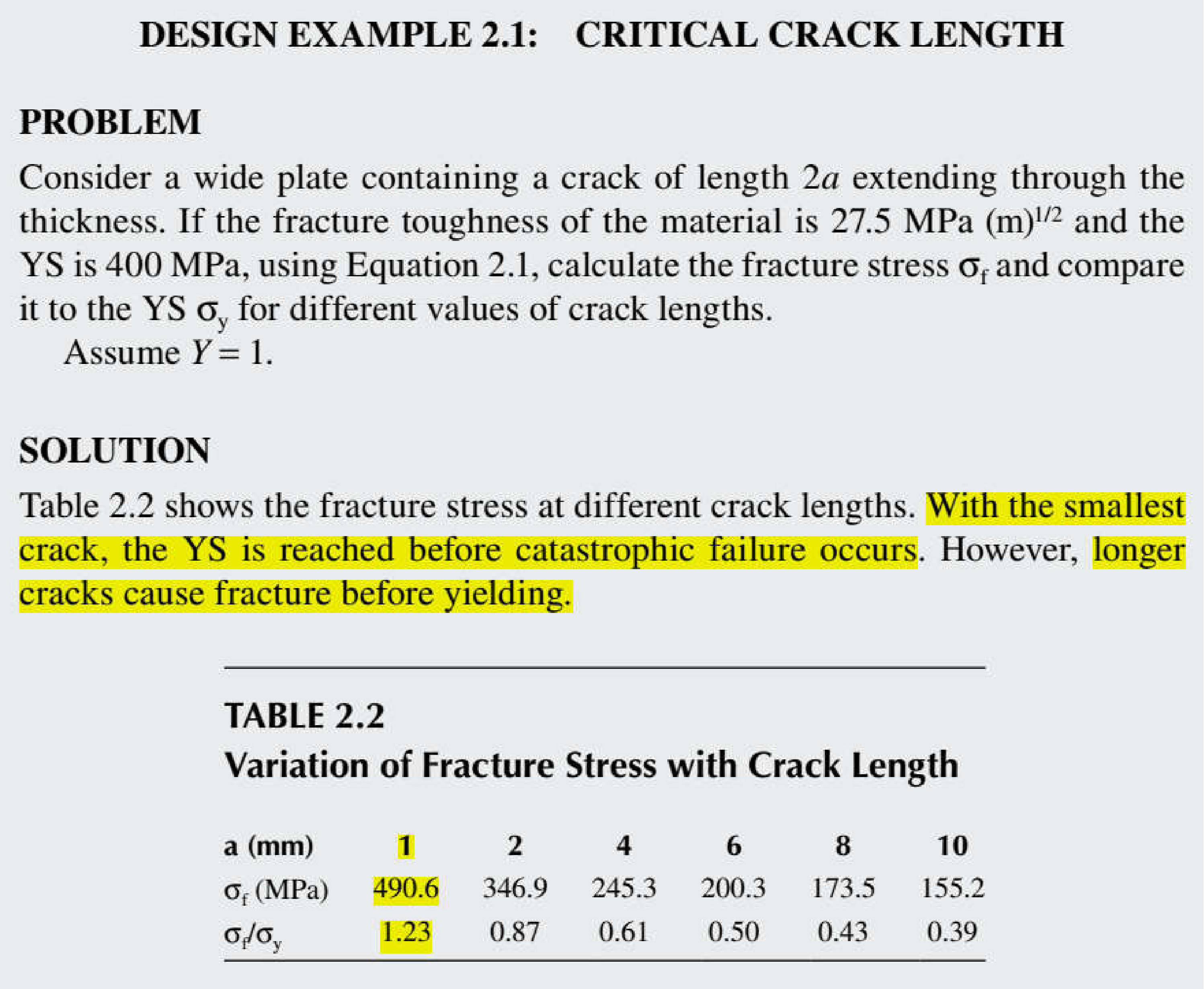
(Hertzberg)

Table 1: Stress intensity factors for several common geometries.

Type of Crack	Stress Intensity Factor, K_I
Center crack, length $2a$, in an infinite plate	$\sigma_\infty \sqrt{\pi a}$
Edge crack, length a, in a semi-infinite plate	$1.12\ \sigma_\infty \sqrt{\pi a}$
Central penny-shaped crack, radius a, in in infinite body	$2\ \sigma_\infty \sqrt{\frac{a}{\pi}}$
Center crack, length $2a$ in plate of width W	$\sigma_\infty \sqrt{W \tan\left(\frac{\pi a}{W}\right)}$
2 symmetrical edge cracks, each length a, in plate of total width W	$\sigma_\infty \sqrt{W \left[\tan\left(\frac{\pi a}{W}\right) + 0.1 \sin\left(\frac{2\pi a}{W}\right)\right]}$

رابطه کلی:

$$K = Y\sigma\sqrt{\pi a}$$



DESIGN EXAMPLE 2.1: CRITICAL CRACK LENGTH

PROBLEM

Consider a wide plate containing a crack of length $2a$ extending through the thickness. If the fracture toughness of the material is 27.5 MPa $(m)^{1/2}$ and the YS is 400 MPa, using Equation 2.1, calculate the fracture stress σ_f and compare it to the YS σ_y for different values of crack lengths.

Assume $Y = 1$.

SOLUTION

Table 2.2 shows the fracture stress at different crack lengths. With the smallest crack, the YS is reached before catastrophic failure occurs. However, longer cracks cause fracture before yielding.

TABLE 2.2
Variation of Fracture Stress with Crack Length

a (mm)	**1**	**2**	**4**	**6**	**8**	**10**
σ_f (MPa)	490.6	346.9	245.3	200.3	173.5	155.2
σ_f/σ_y	1.23	0.87	0.61	0.50	0.43	0.39

DESIGN EXAMPLE 2.2: USING FRACTURE TOUGHNESS IN A MATERIAL SELECTION

PROBLEM

Ti-6Al-4V (K_{IC} = 60 MPa $(m)^{1/2}$) and aluminum AA7075 alloy (K_{IC} = 24 MPa $(m)^{1/2}$) are widely used in making lightweight structures. If the available nondestructive testing (NDT) equipment can only detect flaws larger than 4 mm in length, can we safely use either of these alloys for designing a component that will be subjected to a stress of 400 MPa?

SOLUTION

From Equation 2.1 and taking $Y = 1$,

$$\text{For Ti}-6\text{Al}-4\text{V},\ \sigma_f = 400 = 60/(\pi a)^{1/2}\quad 2a = 14\ \text{mm}$$

$$\text{For AA7075},\ \sigma_f = 400 = 24/(\pi a)^{1/2}\quad 2a = 2.3\ \text{mm}$$

The preceding figures show that the critical crack can be detected in the titanium alloy but not in the aluminum alloy. Titanium alloy can be used safely but not the aluminum alloy.

2.4 DUCTILE AND BRITTLE FRACTURES

Machine and structural elements can fail in service as a result of either ductile or brittle fracture. The terms ductile and brittle are usually used to indicate the extent of macroscopic or microscopic plastic deformation that precedes fracture. For example, materials with plastic strains of less than 2% at fracture are considered brittle. The terms ductile and brittle are also related to fracture toughness, and materials with K_{IC} less than 15 MPa $(m)^{1/2}$ are considered brittle. Impact toughness, which is a measure of the energy needed for fracture, can also be used as an indication, and materials that absorb less than 15 ft. lb. (20.3 J) are considered brittle.

2.4.1 DUCTILE FRACTURES

Service failures that occur solely by ductile fracture are relatively infrequent and may be a result of errors in design, incorrect selection of materials, improper fabrication techniques, or abuse, which arises when a part is subjected to load and environmental conditions that exceed those of the intended use.

The following case study illustrates an approach to failure analysis and the type of solution that may be available to the engineer who tries to solve the problem.

CASE STUDY 2.3: DUCTILE FRACTURE OF A LADDER

PROBLEM

An aluminum ladder, which is 3 m long and made of four T-sections and hollow cylindrical rungs, is shown in Figure 2.2. The ladder failed when a man weighing 100 kg climbed halfway up when it was leaning against a wall at an angle of 15°. Although this was the first time the man used the ladder, his wife, who weighed 60 kg, had used it many times earlier. As a result of failure, T-sections S2 and S3 suffered severe plastic deformation and buckling caused by bending, while T-sections S1 and S4 cracked just under the rung where the man was standing (Figure 2.2).

ANALYSIS

Investigation showed that a large reduction in area accompanied the fracture, and chemical analysis showed that the T-sections were made of AA 6061 alloy. The hardness of the alloy was in the range 25–30 RB in most areas but was about 20 RB in section S2. These hardness values correspond to T4 temper condition of the AA 6061 alloy.

It is expected that the weakest section S2, which was on the tension side during loading, has yielded causing the load to be redistributed and section S3 to yield. This, in turn, caused sections S1 and S4 to be overloaded in tension.

SOLUTION

As failure is caused by overload during normal use, it is recommended that a stronger material be used. It would be sufficient to change the temper condition from T4 to T6. The AA 6061 T6 has a hardness of 45–55 RB and YS about twice that of the AA 6061 T4.

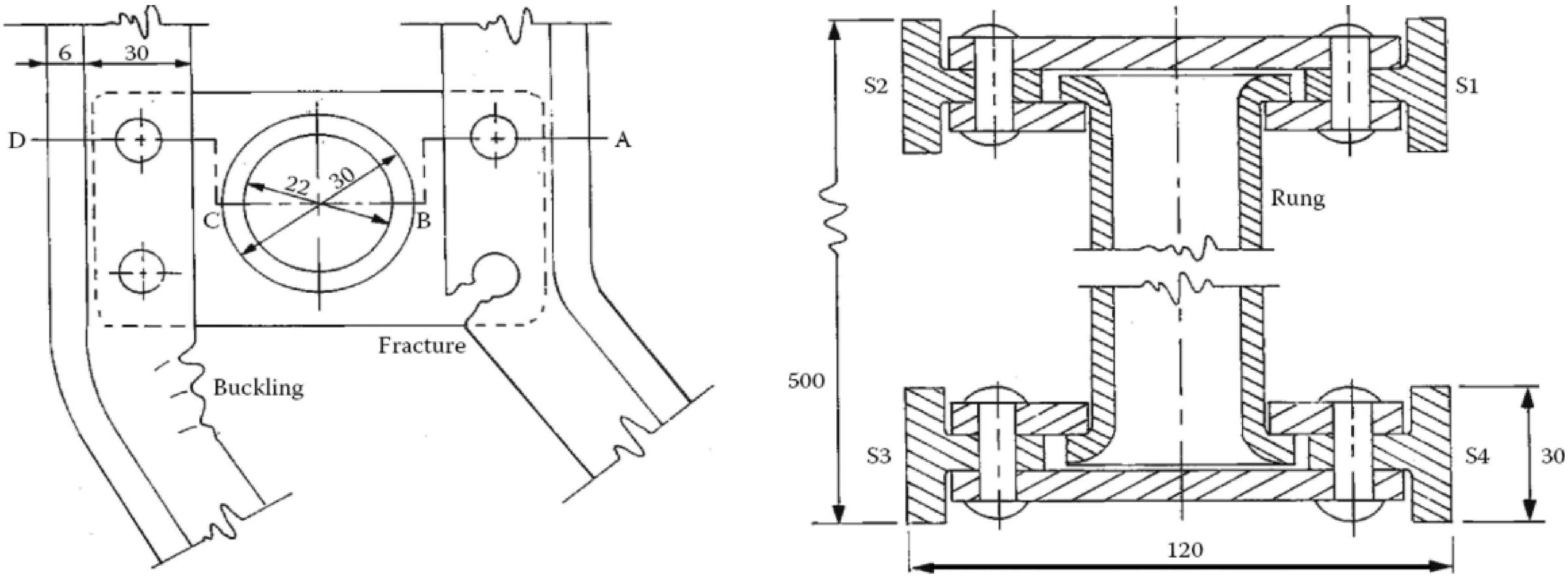


FIGURE 2.2 Failure of an aluminum ladder.

2.4.2 BRITTLE FRACTURES

Brittle fractures are usually initiated at stress raisers, such as large inclusions, cracks or surface defects, and sharp corners or notches. The single-most frequent initiator of brittle fracture is the fatigue crack, which accounts for more than 50% of all brittle fractures in the manufactured products. Brittle fractures are insidious in character because they may occur under static loading at stresses below the YS and without warning.

Once started, the brittle fracture will run at high speed, reaching 1200 m/s in steel, until total failure occurs or until it runs into conditions favorable for its arrest. The risk of occurrence of brittle fracture depends on the notch toughness of the material under a given set of service conditions. A characteristic feature of brittle fracture surfaces is the chevron pattern, which consists of a system of ridges curving outward from the centerline of the plate, as shown in Figure 2.3. These ridges, or chevrons, may be regarded as arrows with their points on the centerline and invariably pointing toward the origin of the fracture, thus providing an indication of its propagation pattern. This feature is useful in the analysis of service failures.

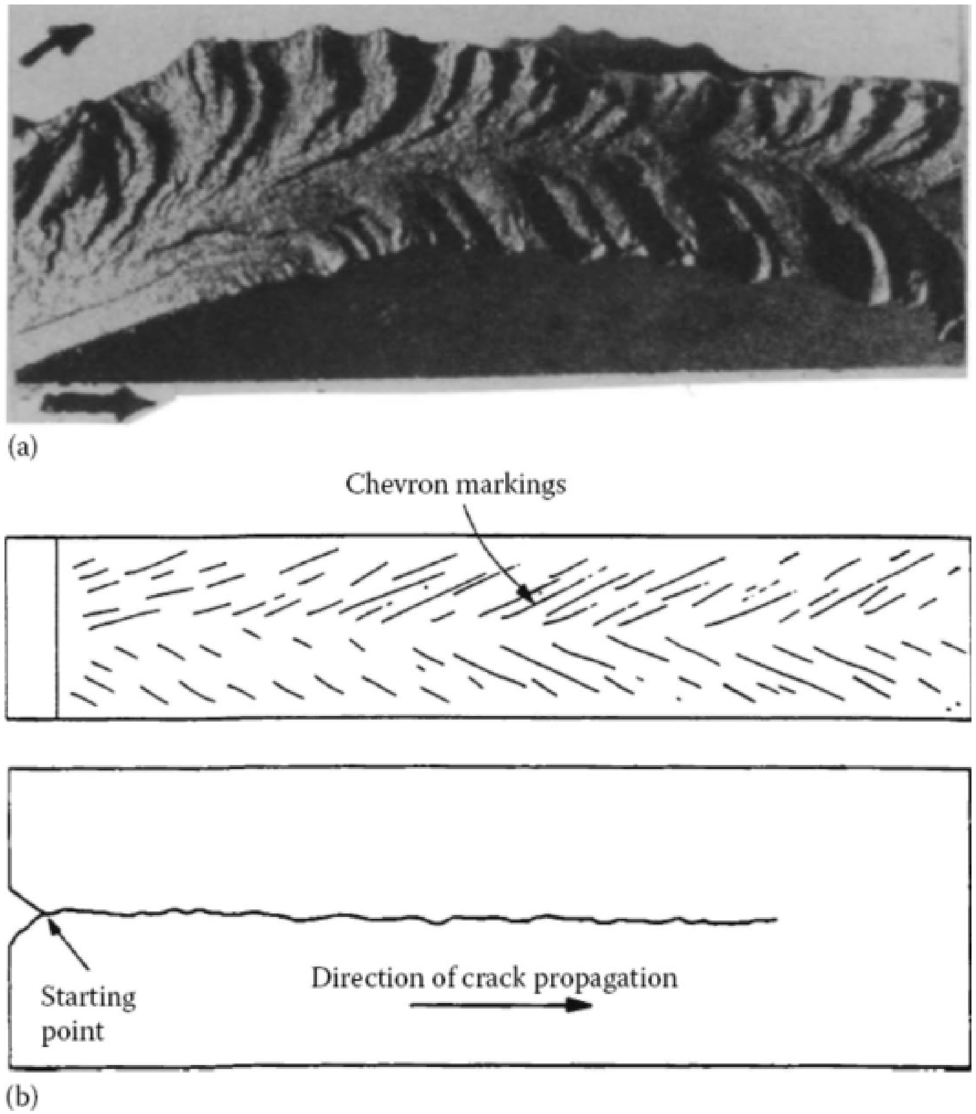


FIGURE 2.3 Chevron patterns in brittle fracture. (a) Chevron markings in steel. (From

2.4.3 DUCTILE–BRITTLE TRANSITION

The temperature at which the component is working is one of the most important factors that influence the nature of fracture. Brittle fractures are usually associated with low temperature, and in some steels, conditions may exist where a difference of a few degrees, even within the range of atmospheric temperatures, may determine the difference between ductile and brittle behavior. This sharp ductile–brittle transition is only observed in body-centered cubic (bcc) and hexagonal close-packed (hcp) metallic materials and not in face-centered cubic (fcc) materials, as illustrated schematically in Figure 2.4.

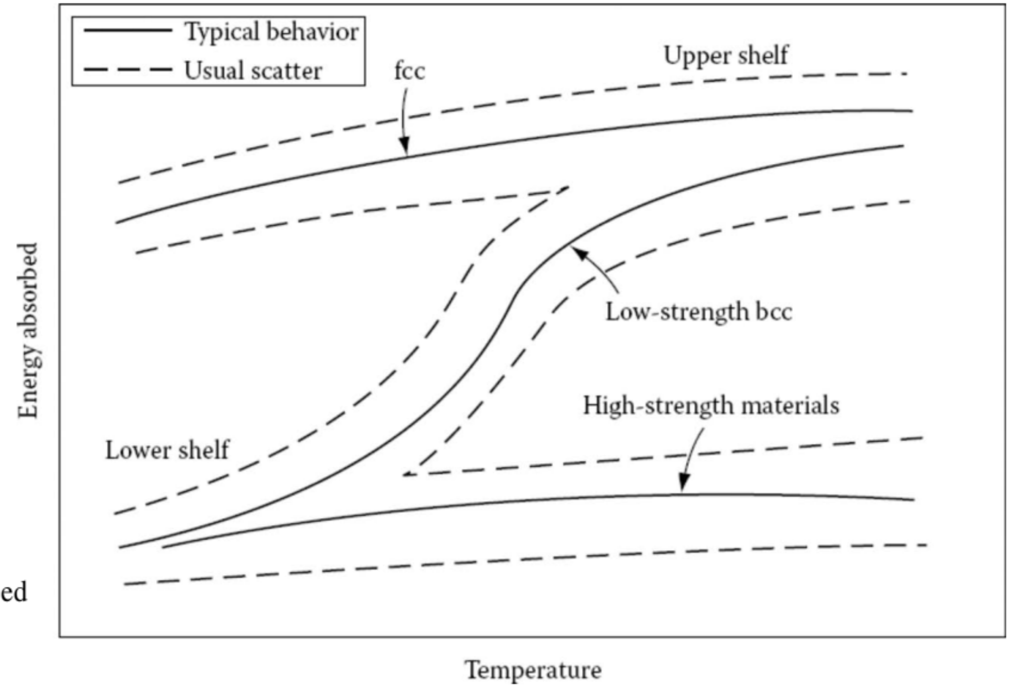
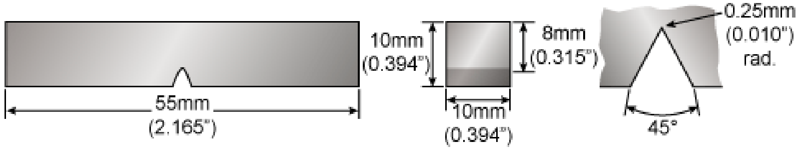
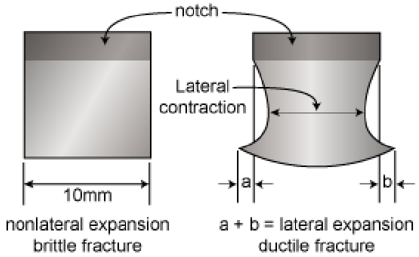
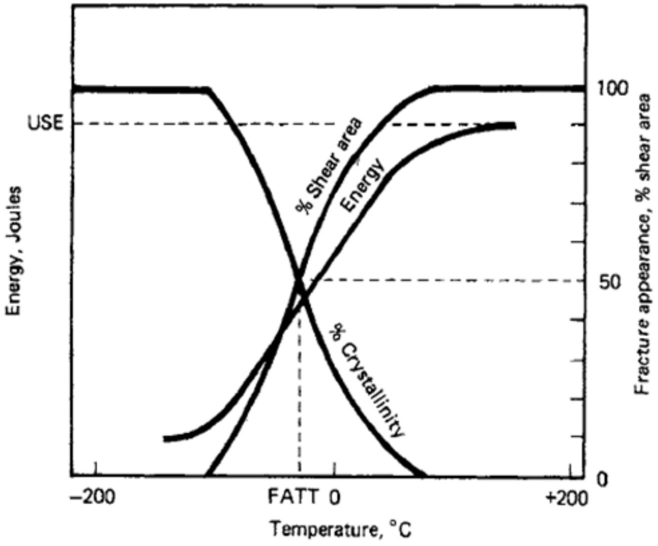


FIGURE 2.4 Schematic representation of the effect of temperature on the energy absorbed in fracture.

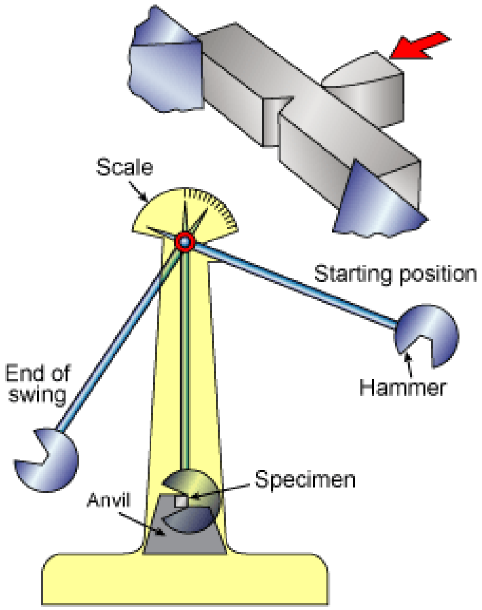
The most widely used tests for characterizing the ductile-to-brittle transition are the Charpy, ASTM Standards A23 and A370, and Izod. The temperature at which the material behavior changes from ductile to brittle is called the ductile–brittle transition temperature (T_c) and may be taken as the temperature at which the fractured surfaces exhibit 50% brittle fracture appearance. In Charpy V-notch (CVN) experiments, the transition temperature can be set at a level of 20.3 J (15 ft. lb.) or at 1% lateral contraction at the notch. The transition temperature based on fracture appearance always occurs at a higher value than if based on a ductility or energy criterion. Therefore, the fracture appearance criterion is more conservative.







Charpy diagram for low-strength steel.



2.5 FATIGUE FAILURES

Generally, fatigue fractures occur as a result of cracks, which usually start at some discontinuity in the material or at other stress concentration locations, and then gradually grow under repeated application of load. As the crack grows, the stress on the load-bearing cross section increases until it reaches a high level enough to cause catastrophic fracture of the part. This sequence is reflected in the fracture surfaces that usually exhibit smooth areas that correspond to the gradual crack growth stage and rough areas that correspond to the catastrophic fracture stage, as shown in Figure 2.5. The smooth parts of the fracture surface usually exhibit beach marks, which occur as a result of changes in the magnitude of the fluctuating fatigue load. Another feature of fatigue fractures is that they lack macroscopic plastic deformation and, in this respect, they resemble brittle fractures. The following case studies are used to illustrate some of the frequent causes of fatigue fracture and to show some of the solutions that may be used to solve the problem.

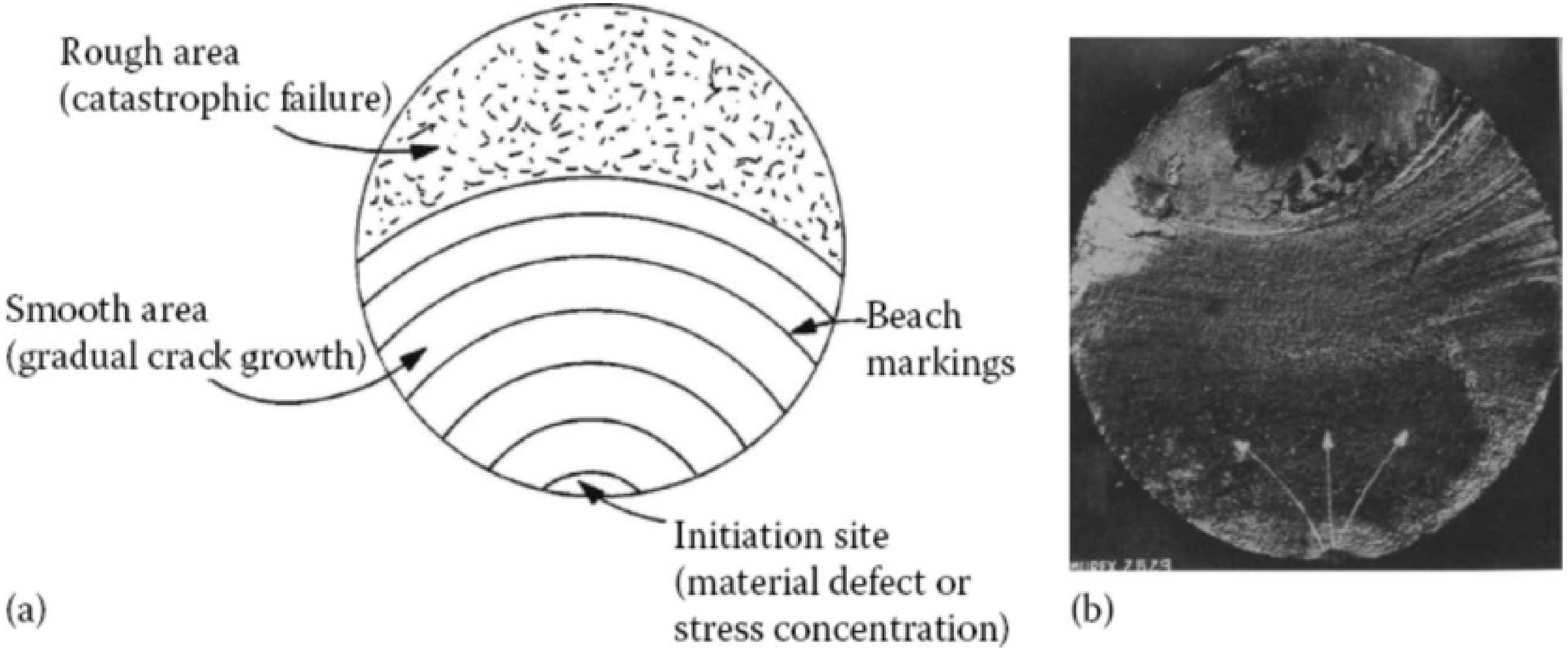


FIGURE 2.5 General appearance of a fatigue fracture surface. (a) Schematic representation; (b) fatigue fracture of automobile axle shaft. (From Rollason, E.C., *Metallurgy for Engineers,* 4th edn., Edward Arnold, London, U.K., 1977.)

CASE STUDY 2.4: FATIGUE FAILURE OF A PRESSURE LINE

PROBLEM

The steel pressure line of a hydraulic pump in a power-generation unit started leaking at the exit-line flange assembly shown in Figure 2.6. The source of leakage was found to be a crack in the fillet weld.

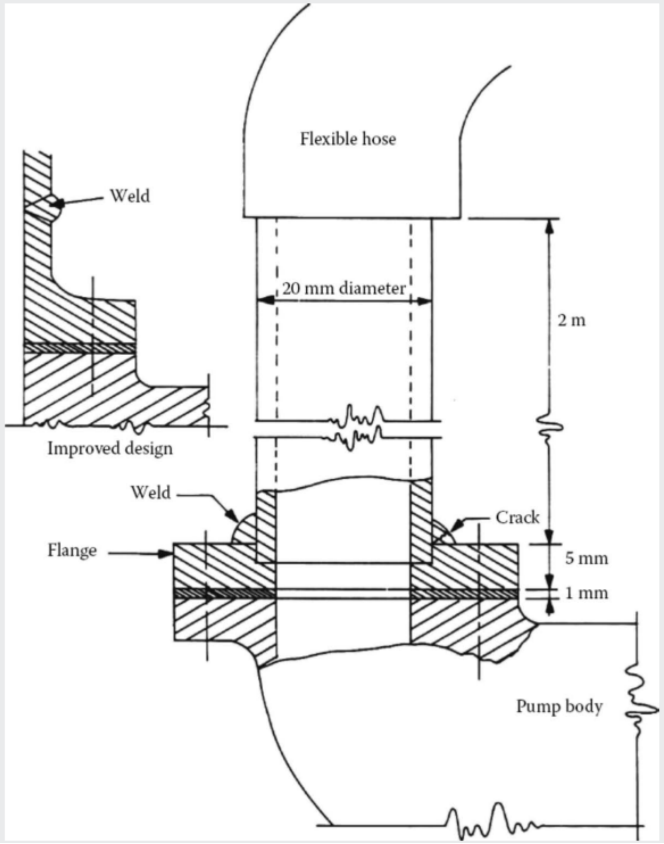
ANALYSIS

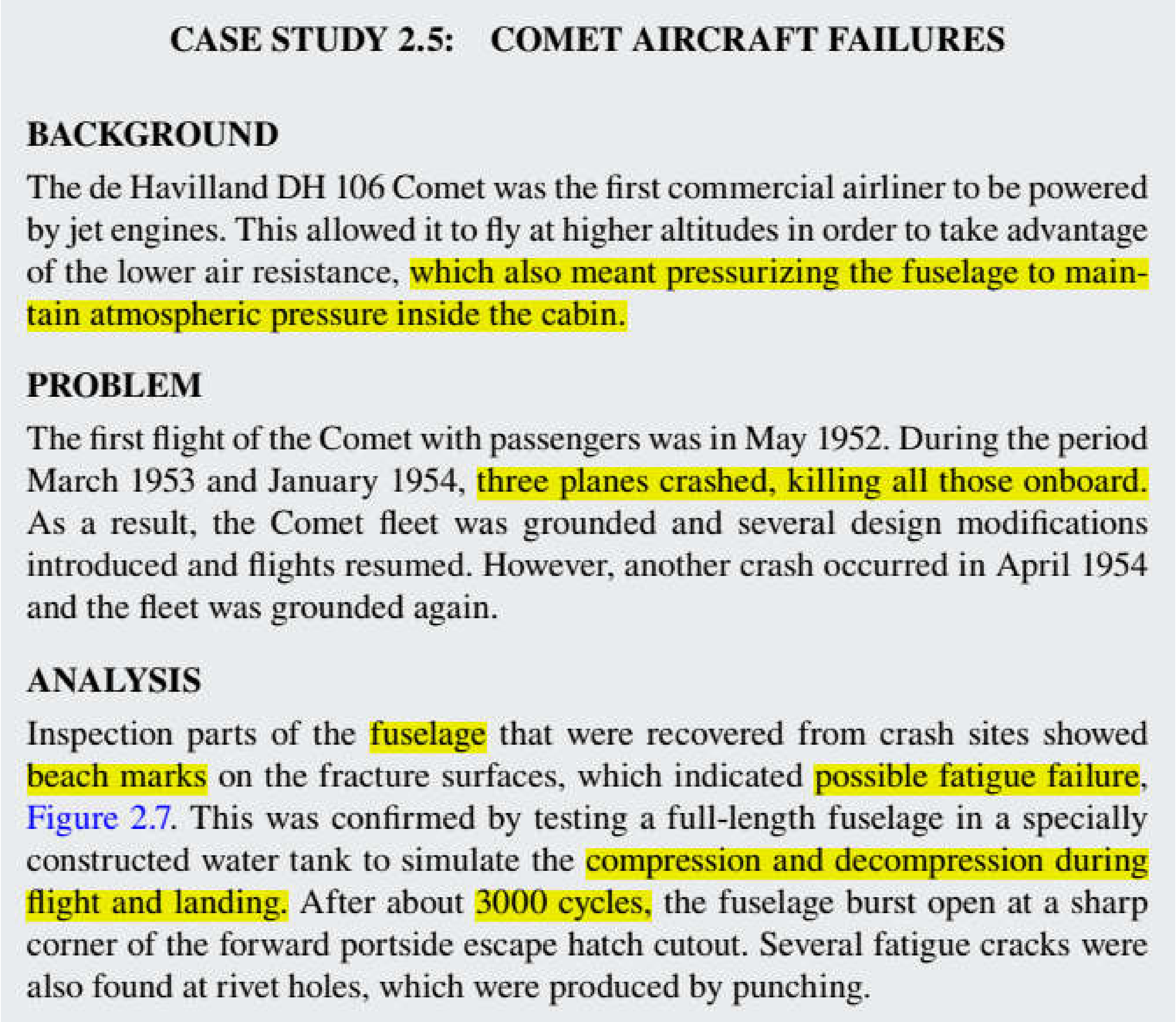
Investigation of the working conditions showed that although the pressure in the line was within the design limits, excessive vibrations existed in the 2-m long tube, which was not sufficiently supported by the flexible hose at its end. This caused the line to act as a cantilever beam with maximum forces at the flange.

It is concluded that the crack in the fillet weld took place as a result of fatigue loading caused by the vibrations in the line.

SOLUTION

The corrective action taken was to change the design to move the weld from the area of high stress concentration, as shown in Figure 2.6. The line was also adequately supported at the point where it joined the flexible hose to minimize vibrations.





CASE STUDY 2.5: COMET AIRCRAFT FAILURES

BACKGROUND

The de Havilland DH 106 Comet was the first commercial airliner to be powered by jet engines. This allowed it to fly at higher altitudes in order to take advantage of the lower air resistance, which also meant pressurizing the fuselage to maintain atmospheric pressure inside the cabin.

PROBLEM

The first flight of the Comet with passengers was in May 1952. During the period March 1953 and January 1954, three planes crashed, killing all those onboard. As a result, the Comet fleet was grounded and several design modifications introduced and flights resumed. However, another crash occurred in April 1954 and the fleet was grounded again.

ANALYSIS

Inspection parts of the fuselage that were recovered from crash sites showed beach marks on the fracture surfaces, which indicated possible fatigue failure, Figure 2.7. This was confirmed by testing a full-length fuselage in a specially constructed water tank to simulate the compression and decompression during flight and landing. After about 3000 cycles, the fuselage burst open at a sharp corner of the forward portside escape hatch cutout. Several fatigue cracks were also found at rivet holes, which were produced by punching.

SOLUTIONS

All the remaining Comets were withdrawn from service, and new versions were built with rounded corners for all openings and windows in order to reduce stress concentration. The skin sheeting was also made thicker. Rivet holes were drilled instead of punching to produce smoother surfaces. A periodic inspection procedure was also introduced. With these changes, commercial flights of the new Comet resumed in 1958 and successfully continued for nearly 30 years.

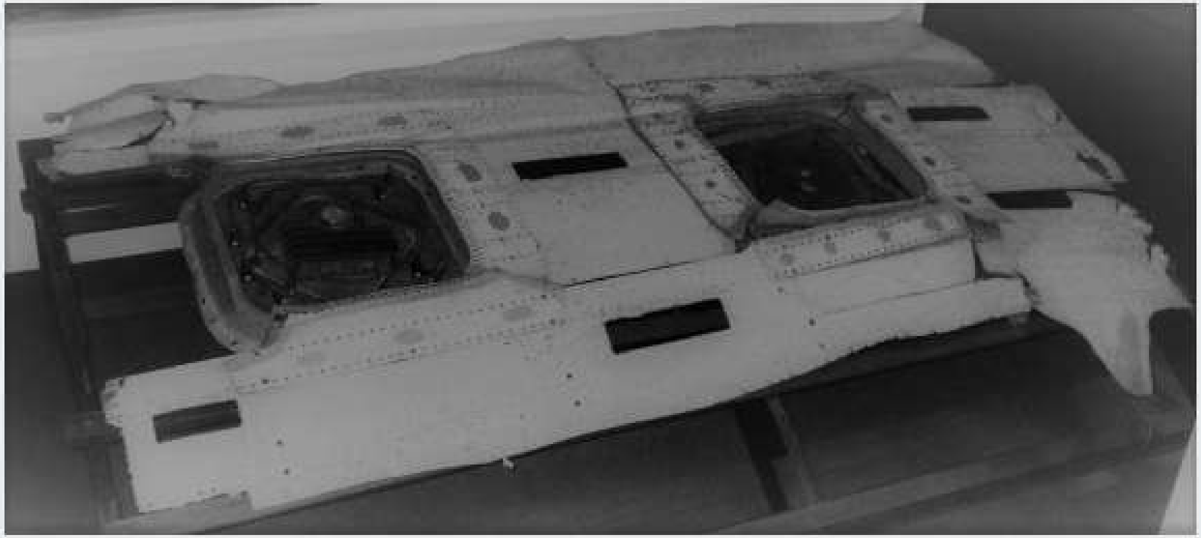


FIGURE 2.7 Fuselage fragment of de Havilland Comet G-ALYP, which crashed January 10, 1954. This fragment, retrieved from the bottom of the Mediterranean Sea, was determined to be the original cause of the crash as it tore loose, the Science Museum, London, photo by Krelnik, 2009, Creative Commons, license CC BY-SA 3.0.

2.5.1 TYPES OF FATIGUE LOADING

The simplest type of fatigue loading is the alternating tension–compression without a static direct stress (Figure 2.8a). In this case, the stress ratio, defined as $R = \sigma_{min}/\sigma_{max}$, is –1. If a static mean stress σ_m is superimposed on the alternating stress, then the stress varies between the limits of

$$\sigma_{max} = \sigma_m + \sigma_a \text{ and } \sigma_{min} = \sigma_m - \sigma_a,$$

as shown in Figure 2.8b. A special case is the pulsating stress with $R = 0$.

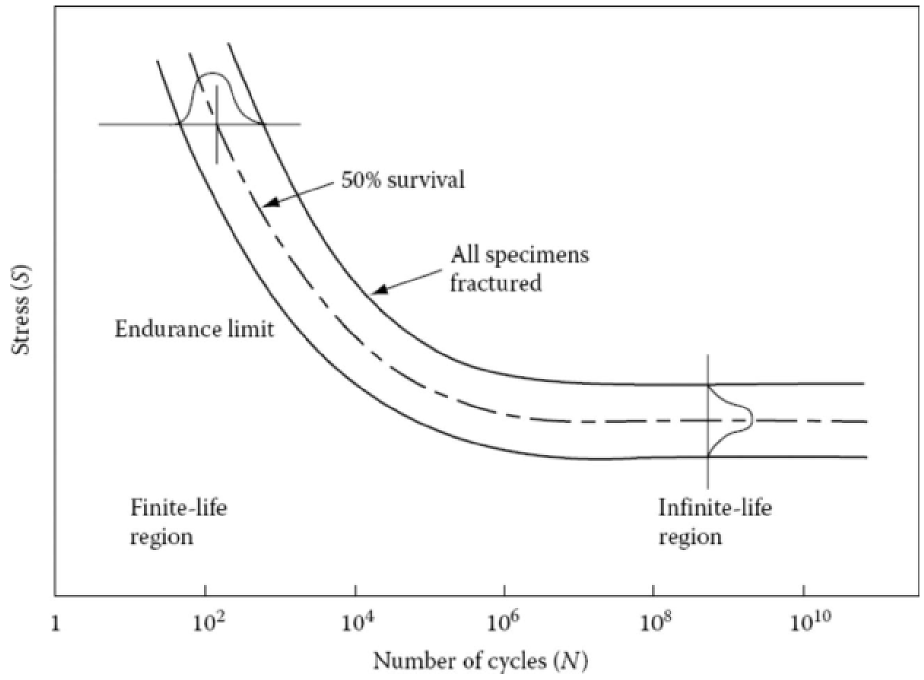


FIGURE 2.9 Representation of fatigue test results on the S–N curve.

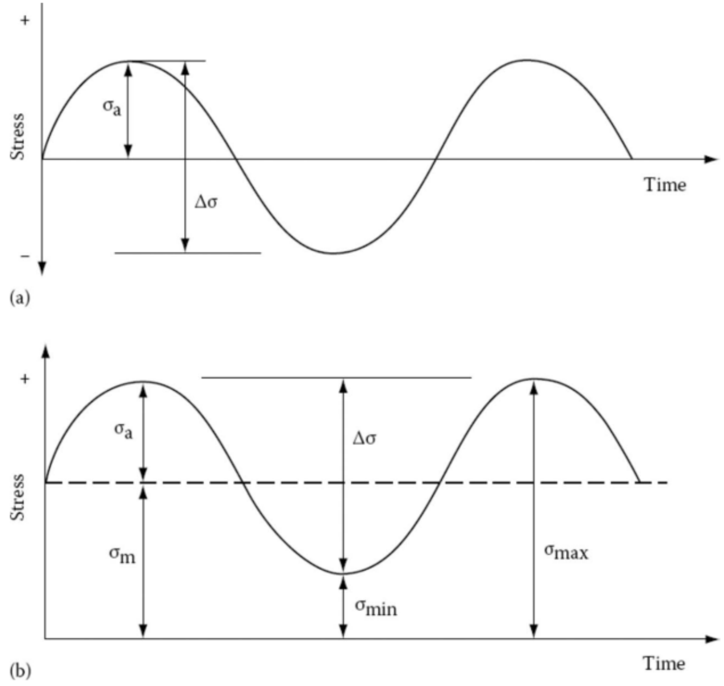


FIGURE 2.8 Types of fatigue loading. (a) Alternating stress, $R = -1$; (b) fluctuating stress.

The standard deviation for endurance limit results is usually in the range of 4–10%, but in the absence of statistical values, an 8% standard deviation can be assumed. The reported endurance results can be taken to correspond to 50% survival reliability. Statistical variation of material properties is discussed in Section 5.9.

The endurance limit, or fatigue strength, of a given material can usually be related to its tensile strength, as shown in Table 4.7. The endurance ratio, defined as endurance limit/tensile strength, can be used to predict fatigue behavior in the absence of endurance limit results. As the table shows, the endurance ratio of most ferrous alloys varies between 0.4 and 0.6.

ALT Text for Figure 2.10: The *S*–*N* curve for steel shows infinite life becomes horizontal below a certain stress, the endurance limit, but the *S*–*N* curve for aluminum does not show infinite life and continues to decrease with the increasing number of cycles.

An important limitation of *S*–*N* curves and the endurance limit results is that they are usually determined for very smooth, relatively small specimens under controlled conditions and simple loading systems. This limitation can be overcome by using endurance-limit modifying factors to account for the effect of component size and surface finish, type of loading, and service conditions. The use of endurance-limit modifying factors in design is discussed in Section 6.5.

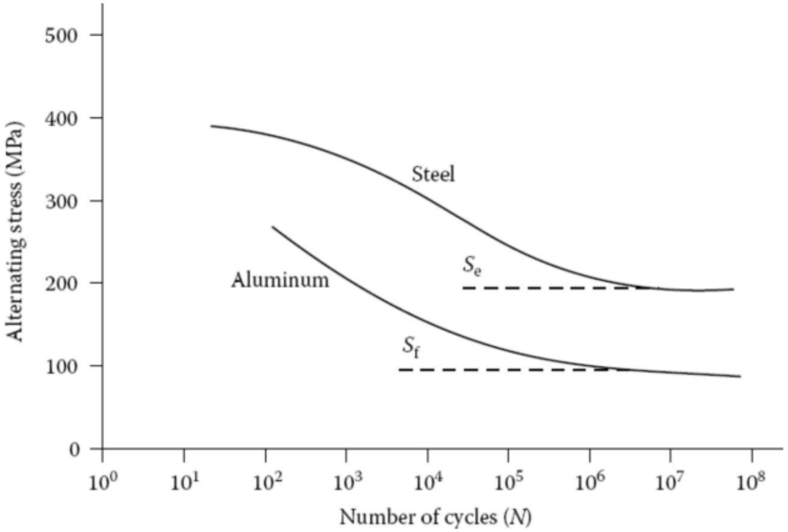


FIGURE 2.10 Fatigue results as represented by the *S*–*N* curves. Steel exhibits an endurance limit and its curve levels off at S_e. Aluminum does not exhibit an endurance limit, and its curve continues to decline for all values of *N*.

2.6 ELEVATED-TEMPERATURE FAILURES

The effect of service environment on material performance at elevated temperature can be divided into the following three main categories:

1. Mechanical effects such as creep and stress rupture.
2. Chemical effects such as oxidation.
3. Microstructural effects such as grain growth and overaging.

Although oxidation and creep can directly lead to the failure of a part in service, the microstructural changes can lead to weakening of the material and, therefore, can indirectly lead to failure. Many of the strengthening mechanisms that are effective at room temperature become ineffective at elevated temperatures. Generally, nonequilibrium structures change during long-term high-temperature service and this leads to lower creep strength. Thus, materials that depend on their fine grains for strengthening may lose this advantage by grain growth, and materials that have been strain hardened by cold working may recover or anneal. Structures that have been precipitation hardened to peak values may overage, and steels that have been hardened and tempered may overtemper.

2.6.1 CREEP

A major factor that limits the life of components in service at elevated temperatures is creep. Creep is defined as the time-dependent deformation, which occurs under the combined effect of stress and elevated temperature, normally in the range of 35–70% of the melting point of the material expressed in absolute temperature. Creep occurs as a result of the motion of dislocations within the grains, grain boundary rotation, and grain boundary sliding. It is sensitive to grain size, alloying additions, microstructure of the material, and service conditions.

When creep reaches a certain value, fracture occurs. Creep fracture (also called stress rupture) usually takes place at strains much less than the fracture strains in tension tests at room temperature.

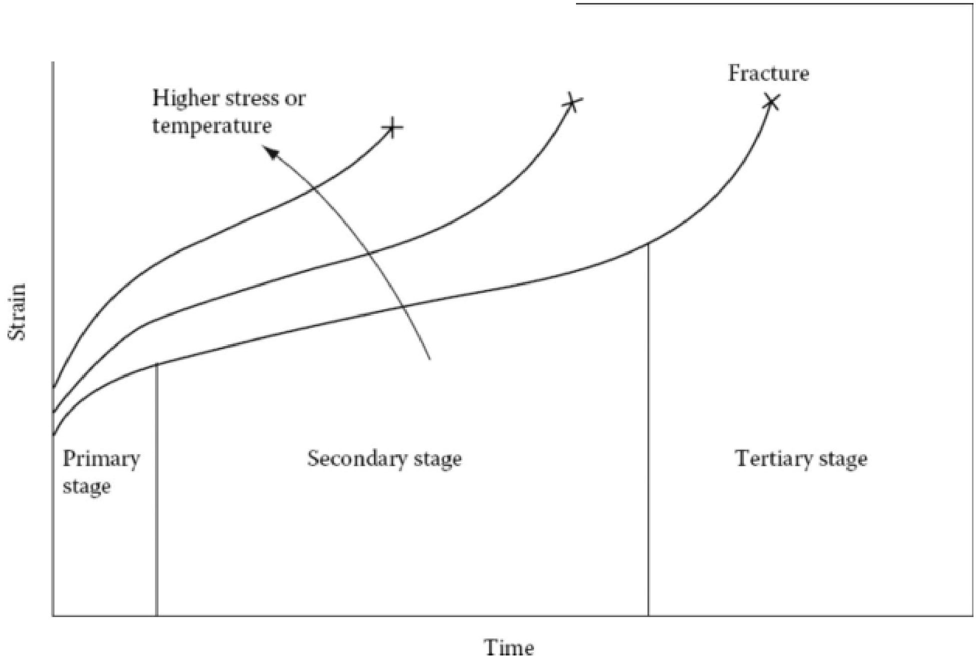


FIGURE 2.11 Schematic creep curve under tensile loading.

In most practical cases, the strain that is suffered by a component under creep conditions can be divided into the stages shown schematically in Figure 2.11. Following an initial instantaneous deformation, creep takes place at a decreasing strain rate, which is the slope of the curves in Figure 2.11, during the primary or transient stage. This is followed by the secondary creep or steady-state stage, where the strain rate is constant under constant stress conditions.

At the end of the steady-state stage, tertiary creep starts and the strain rate increases rapidly with increasing strain and fracture finally occurs. Tertiary creep can be caused by

1. Reduction of the cross-sectional area of the component due to cracking or necking.
2. Oxidation and other environmental effects, which reduce the cross-sectional area.
3. Microstructural changes that weaken the material such as coarsening of precipitates.

Under certain conditions, some materials may not exhibit all the mentioned stages of creep. For example, at high stresses or high temperatures, the primary stage may not be present, with secondary creep or even tertiary creep starting soon after load application. Another example is the case where fracture occurs before the tertiary stage is reached, as in the case of some low-ductility cast alloys. Creep ductility is an important factor in material selection. Although the permissible creep strain in practice is usually of the order of 1%, selecting materials with higher creep ductility means a higher safety margin.

The steady-state creep rate is often a high-temperature design parameter and may be required to be lower than a specified value to ensure a minimum life of a component in service. At a given temperature, the steady-state creep rate ($\dot{\varepsilon}$) can be expressed as a function of the applied stress (σ) as follows:

$$\dot{\varepsilon} = B\sigma^{m} \qquad (2.2),$$

where B and m are experimental constants and depend on the material and operating temperature. Equation 2.2 is often called Norton's equation and m is Norton Index. At low stresses and high temperatures, creep takes place as a result of atomic diffusion either through the grains or along the grain boundaries of metals. In such cases, m in Equation 2.2 can be taken as unity. At higher stresses, creep takes place as a result of dislocation movement and m can take values ranging from 2 to 9, depending on the material and temperature values. The following design example illustrates the use of Equation 2.2 in designing of components for high-temperature service.

2.6.2 COMBINED CREEP AND FATIGUE

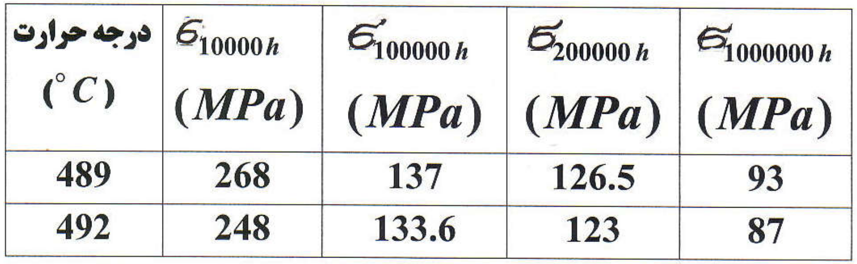
In many high-temperature applications in practice, the applied loads are cyclic and could lead to a combined creep–fatigue failure. Under these conditions, the life of a component is determined by the initiation and growth of a creep or a fatigue crack. At high load frequencies and relatively lower temperatures, crack growth is independent of the frequency or temperature. This is because the material just ahead of the crack does not suffer any time-dependent processes, such as oxidation or creep relaxation. Under these conditions, the mechanism of crack growth is essentially the same as room temperature fatigue.

At low frequencies and relatively high temperatures, crack growth is affected by time-dependent processes. A mixture of the two extreme cases of behavior is expected at intermediate temperatures and load frequencies.

هدر خروجی سوپرهیتر دمای بالا
Alloy Steel   SA 335

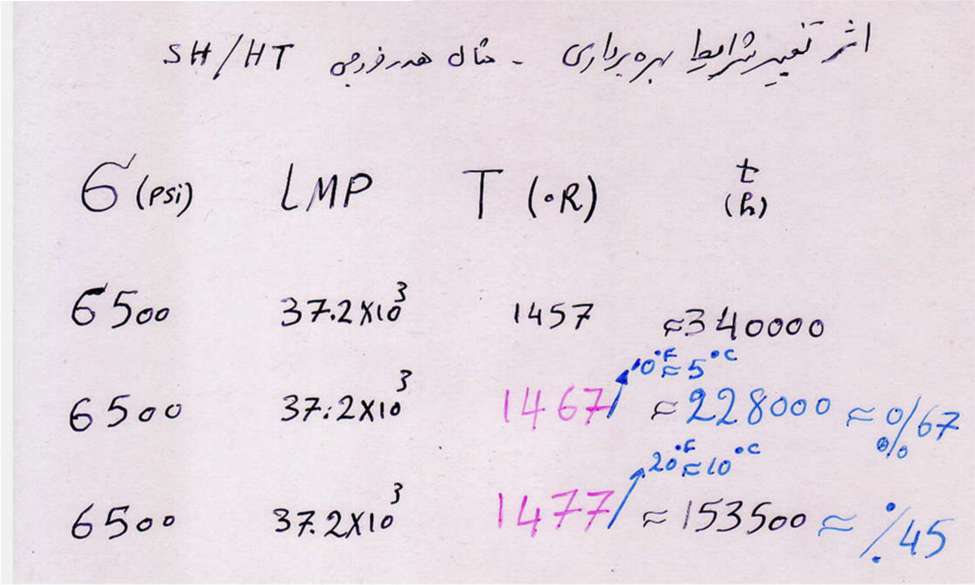
Standard	Grade	Chemical composition						
		C	Si	Mn	P	S	Cr	Mo
SA335	P12	0.05-0.15	0.50-1.0	0.30-0.60	≤0.030	≤0.030	1.00-1.50	0.50-1.00

مشخصات خزشی آلیاژ SA 335 P12 در دماهای مختلف



درجه حرارت $(^\circ C)$	$\sigma_{10000\,h}$ (MPa)	$\sigma_{100000\,h}$ (MPa)	$\sigma_{200000\,h}$ (MPa)	$\sigma_{1000000\,h}$ (MPa)
489	268	137	126.5	93
492	248	133.6	123	87

$$T(\log t_r + C) = m$$



اثر تغییر شرایط بهره‌برداری - مثال هدر خروجی SH/HT

σ (psi)	LMP	T (°R)	t (h)		T (°C)
6500	37.2×10^3	1457	≈340000		536
6500	37.2×10^3	1467 $10^\circ F \approx 5^\circ C$	≈228000	≈ 0/67 %	542
6500	37.2×10^3	1477 $20^\circ F \approx 10^\circ C$	≈153500	≈ %45	547

در یک تنش ثابت (≈ 45 MPa) افزایش
دما به مقدار ۶ درجه سانتیگراد، ۳۳٪
عمر قطعه را کاهش داده است.

DESIGN EXAMPLE 2.6: DESIGNING FOR STEADY-STATE CREEP USING NORTON'S EQUATION

PROBLEM

A cylindrical pressure vessel has an internal diameter of 45 cm and a wall thickness of 20 mm and operates at 800°C. When operating at the design pressure, the vessel diameter is expected to reach its maximum allowable increase in diameter of 5 mm in 4 years. As a result of increasing demand, it was decided to increase the operating pressure by 25%. Calculate the expected decrease in life of the vessel as a result of this action.

SOLUTION

Given the stress level and operating temperature for the vessel material, a Norton Index *m* can be assumed as 4. The creep strain rate under the original design conditions ($\dot{\varepsilon}$) is

$$\dot{\varepsilon} = (5)/450 \times 4 \times 360 \times 24 = 2.5 \times 10^{-7}$$

$$= B\sigma^4$$

From Equation 2.7, the creep strain rate under conditions of increased pressure is

$$\dot{\varepsilon}_n = B(1.25\sigma)^4 = 2.5 \times 10^{-7} \times (1.25)^4$$

Expected life of the vessel under increased operating pressure = (5)/450 × 360 × 24 × 2.5 × 10^{-7} = 2.1 years.

Remark: Please notice how an increase of 25% in stress has resulted in about 50% reduction in expected life.

2.6.3 THERMAL FATIGUE

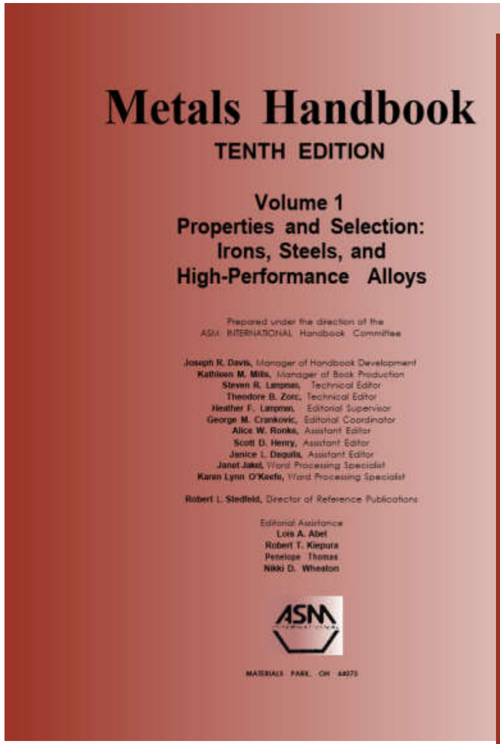
Another form of elevated-temperature failures is thermal fatigue. Stresses and strains induced in a component due to thermal gradients can cause failure if repeated a sufficient number of times. Faster changes in temperature, lower thermal conductivity of the material, higher elastic constant, higher thermal expansion coefficient, lower ductility, and thicker component sections often account for shorter service life. Ceramic materials are particularly prone to thermal fatigue in view of their limited thermal conductivity and brittleness.

In high-temperature applications, the environment plays an important role in determining the performance of components. Selecting the material that will resist the environment, controlling the environment, or protecting the surface is essential for prolonged service. Examples of aggressive environments are those that contain vanadium compounds, sulfur compounds, or salt. A vacuum environment may be more harmful than air if some of the alloy constituents evaporate at high temperatures.

2.7 FAILURE ANALYSIS: EXPERIMENTAL METHODS

When a component fails in service, it is important that the source of failure is located to identify the responsible party and to avoid similar failures in future designs. Owing to the complexity of most failure cases, it is useful to follow a systematic approach to the analysis such as the following:

1. Gathering background information about the function, source, fabrication, materials used, and service history of the failed component is an important step.
2. Site visits involve locating all the broken pieces, making visual examination, taking photographs, and selecting the parts to be removed for further laboratory investigation. Macroscopic, microscopic, chemical analysis, nondestructive, and destructive tests are normally used to locate possible material and manufacturing defects. Presence of oxidation and corrosion products, temper colors, surface markings, etc., can also provide valuable clues toward failure mode identification.
3. Based on the gathered information, it should be possible to identify the origin of failure, direction of crack propagation, and sequence of failure. Presence of secondary damage not related to the main failure should also be identified.
4. The final step in failure analysis usually involves writing a report to document the findings and to give the conclusions. This report usually includes the background information and service history of the failed part, description of the specimens examined and procedure of examination, information about materials and comparison with specifications, manufacturing methods, causes of failure, and how to avoid such failure in the future.



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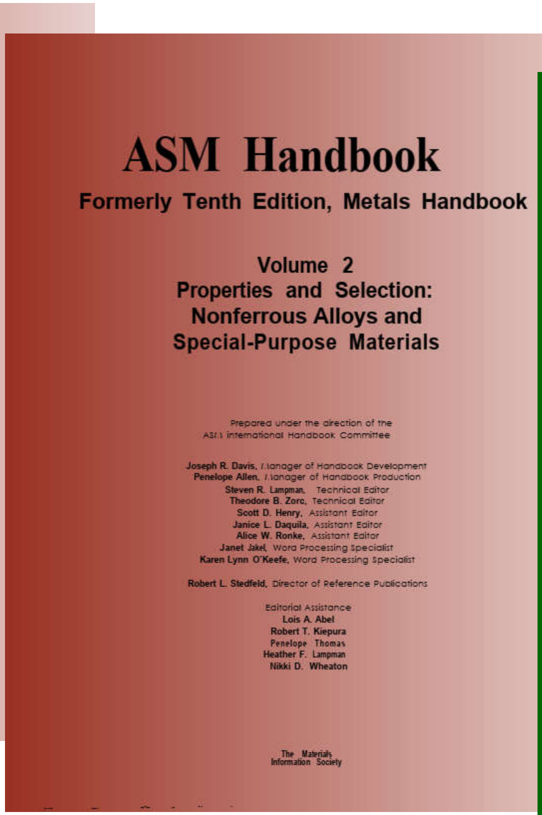

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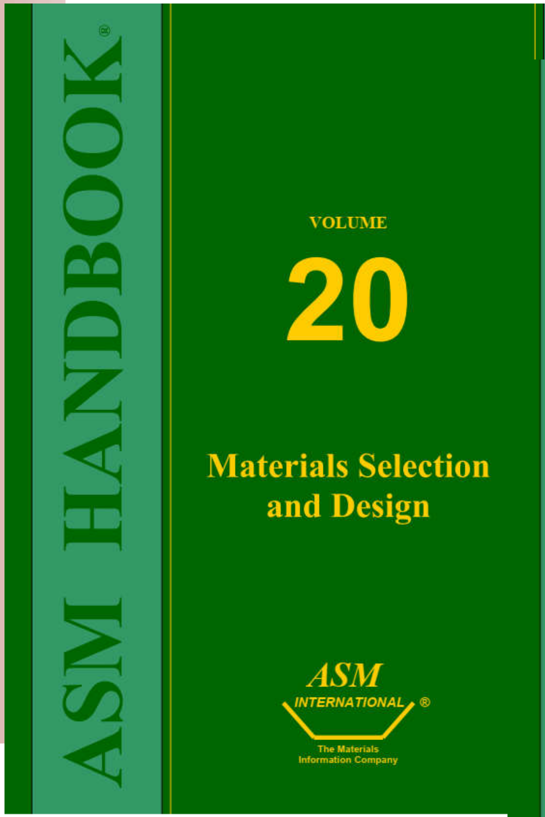

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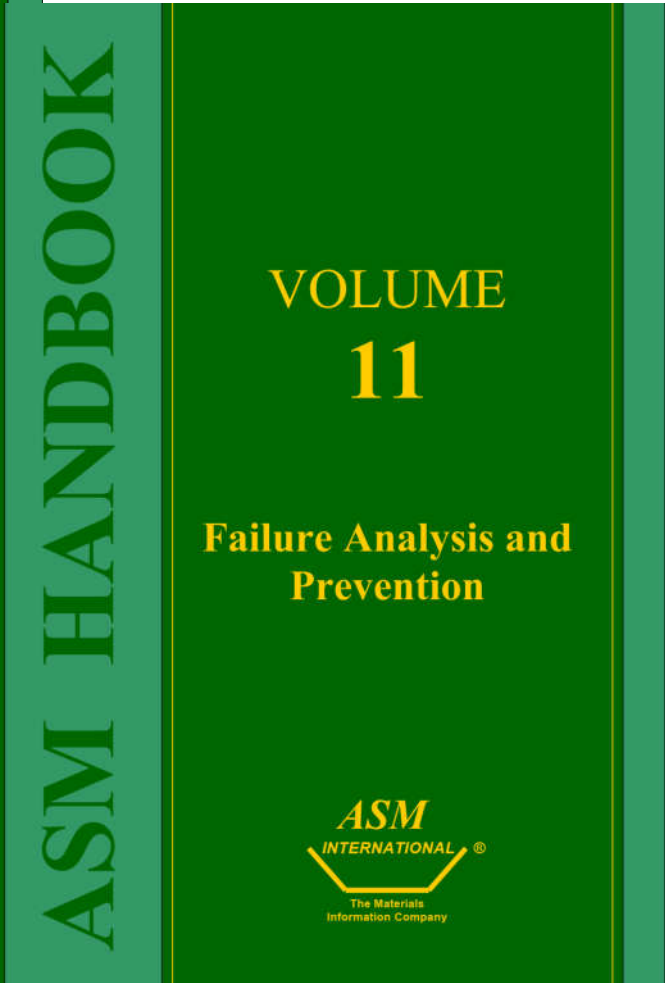

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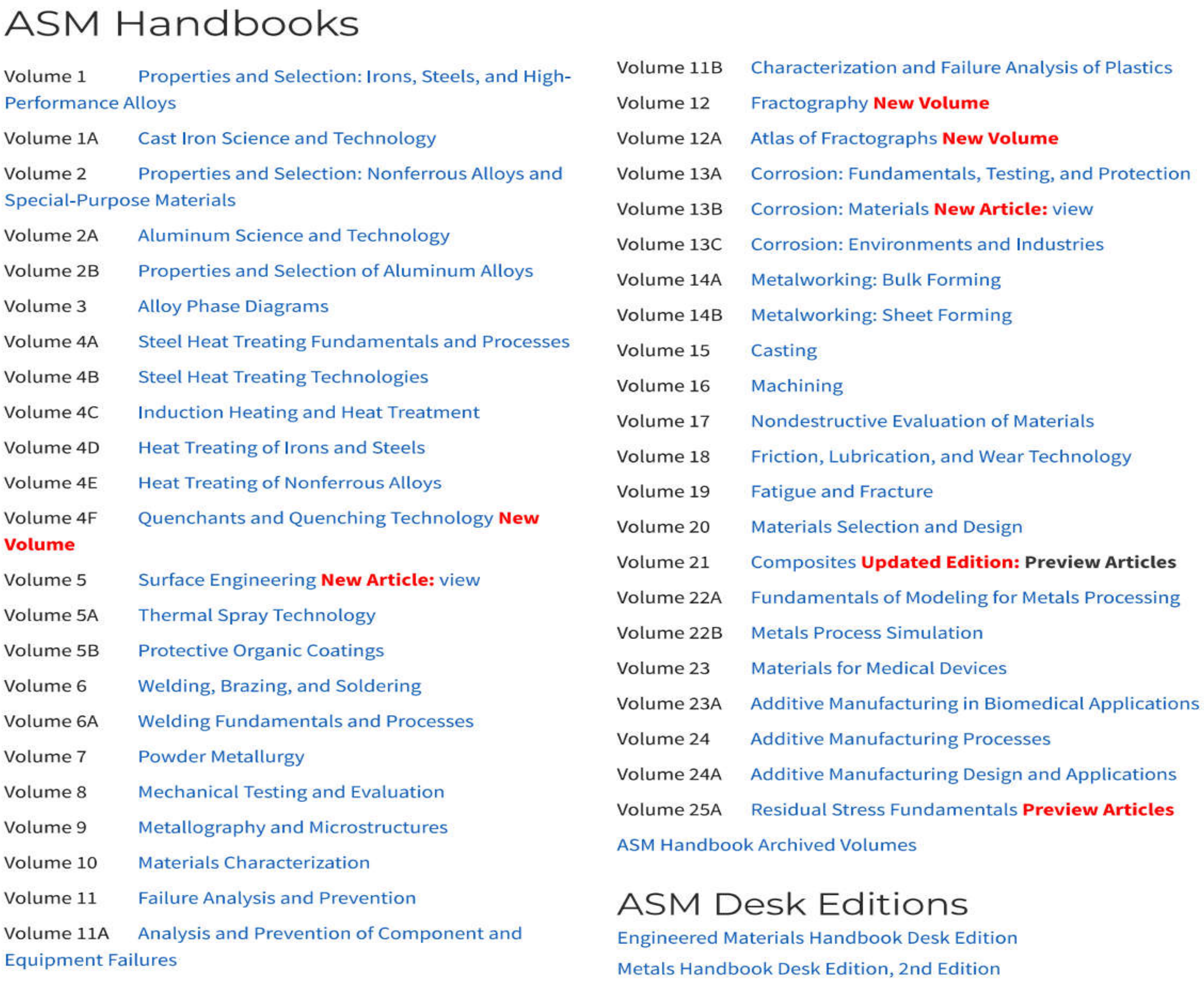

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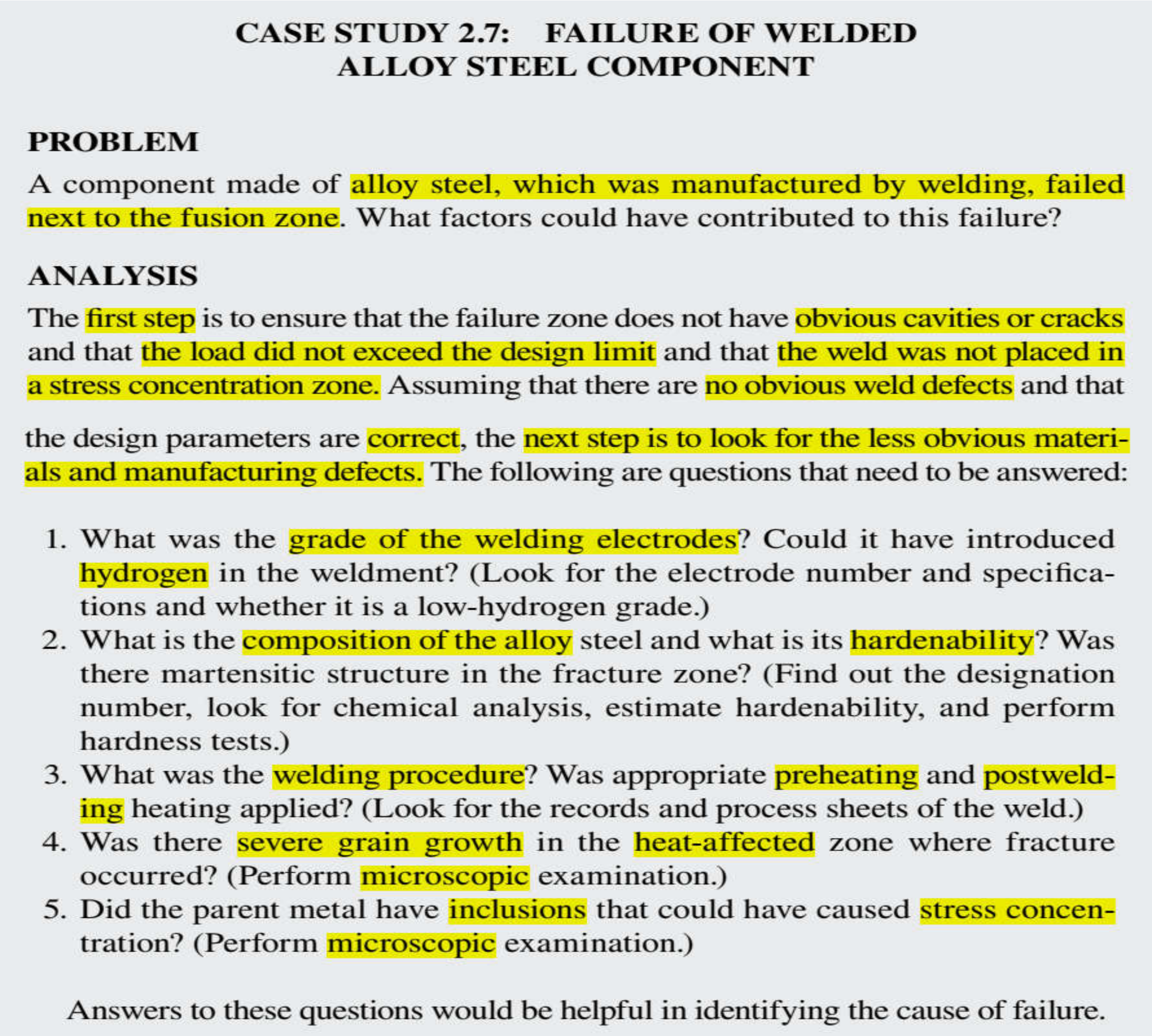


CASE STUDY 2.7: FAILURE OF WELDED ALLOY STEEL COMPONENT

PROBLEM

A component made of alloy steel, which was manufactured by welding, failed next to the fusion zone. What factors could have contributed to this failure?

ANALYSIS

The first step is to ensure that the failure zone does not have obvious cavities or cracks and that the load did not exceed the design limit and that the weld was not placed in a stress concentration zone. Assuming that there are no obvious weld defects and that the design parameters are correct, the next step is to look for the less obvious materials and manufacturing defects. The following are questions that need to be answered:

1. What was the grade of the welding electrodes? Could it have introduced hydrogen in the weldment? (Look for the electrode number and specifications and whether it is a low-hydrogen grade.)
2. What is the composition of the alloy steel and what is its hardenability? Was there martensitic structure in the fracture zone? (Find out the designation number, look for chemical analysis, estimate hardenability, and perform hardness tests.)
3. What was the welding procedure? Was appropriate preheating and postwelding heating applied? (Look for the records and process sheets of the weld.)
4. Was there severe grain growth in the heat-affected zone where fracture occurred? (Perform microscopic examination.)
5. Did the parent metal have inclusions that could have caused stress concentration? (Perform microscopic examination.)

Answers to these questions would be helpful in identifying the cause of failure.

2.8 FAILURE ANALYSIS: ANALYTICAL TECHNIQUES

Several analytical techniques and computer-based methods have been developed to help the engineer in solving failure problems. Identification of failure mode is not only important for determining the cause of failure, but also a powerful tool for reviewing the design. The following discussion gives a brief review of some of the analytical techniques that have been developed for systematic identification of failure modes. Reference should be made to the original publications for more details.

2.8.1 Root Cause Analysis

2.8.2 Fault Tree Analysis

2.8.3 Failure Experience Matrix

2.8.4 Expert Systems

CASE STUDY 2.8: FAILURE OF A CRANKSHAFT OF AN AUXILIARY POWER-GENERATION DIESEL ENGINE

PROBLEM

The crankshaft of an auxiliary power-generation diesel engine failed after 2 years of service.

ANALYSIS

The failed crankshaft is made of forged steel. Failure analysis attributed the failure to fatigue loading with the fatigue crack initiating at a surface defect in the crankshaft. The major causes that could have caused a surface defect in the forged crankshaft are judged to be casting defect in the steel ingot before forging, a defect that developed during the forging process, or a surface defect that developed during the heat treatment process that followed forging. Table 2.3 gives a simplified root cause analysis for the failure.

CONCLUSION

Table 2.3 shows that four root causes are identified as likely to occur. The recommended tests to verify the most likely cause include chemical analysis and optical microscopy. The recommended preventive action will be based on the test results and can include better control of impurities in the steel, better filtering process of the liquid steel, better design of the forging dies, and better control of the reheating furnace temperature. Recommended preventive actions include nondestructive inspection for surface defects; these include visual inspection, liquid penetrant test, and magnetic particle tests, as described in Section 2.3.1.

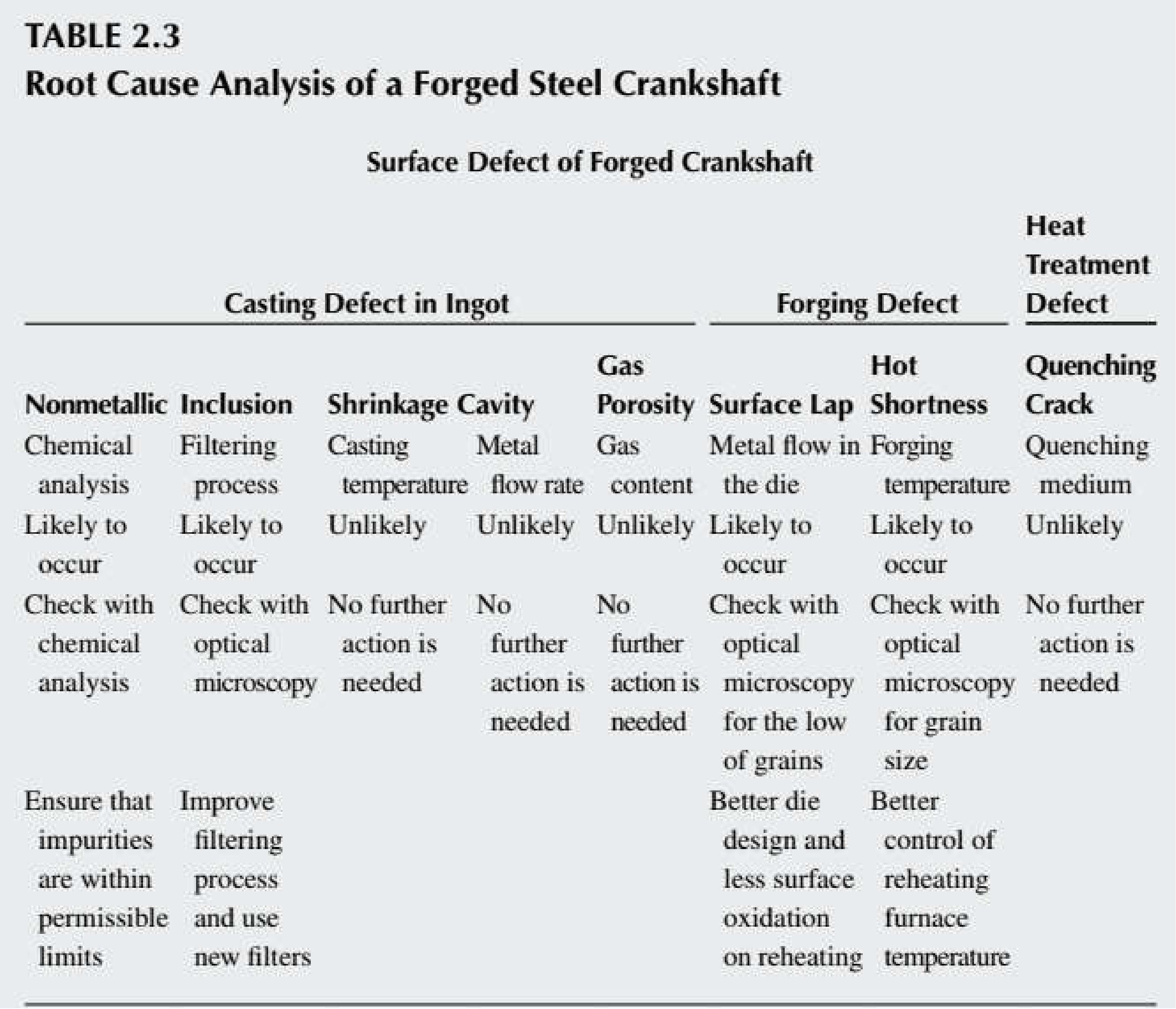


TABLE 2.3

Root Cause Analysis of a Forged Steel Crankshaft

Surface Defect of Forged Crankshaft							
Casting Defect in Ingot					**Forging Defect**		**Heat Treatment Defect**
Nonmetallic Inclusion		**Shrinkage Cavity**		**Gas Porosity**	**Surface Lap**	**Hot Shortness**	**Quenching Crack**
Chemical analysis	Filtering process	Casting temperature	Metal flow rate	Gas content	Metal flow in the die	Forging temperature	Quenching medium
Likely to occur	Likely to occur	Unlikely	Unlikely	Unlikely	Likely to occur	Likely to occur	Unlikely
Check with chemical analysis	Check with optical microscopy	No further action is needed	No further action is needed	No further action is needed	Check with optical microscopy for the low of grains	Check with optical microscopy for grain size	No further action is needed
Ensure that impurities are within permissible limits	Improve filtering process and use new filters				Better die design and less surface oxidation on reheating	Better control of reheating furnace temperature	

2.9 FAILURE PREVENTION AT THE DESIGN STAGE

Anticipating the different ways by which a product could fail while still at the design stage is an important factor that should be considered when selecting a material or a manufacturing process for a given application. The possibility of failure of a component can be analyzed by studying on-the-job material characteristics, the stresses, and other environmental parameters that will be acting on the component, and the possible manufacturing defects that can lead to failure. The various sections of the analysis include the following:

1. *Environmental profile.* This provides a description of the expected service conditions that include operating temperature and atmosphere, radiation, presence of contaminants and corrosive media, other materials in contact with the component and the possibility of galvanic corrosion, and lubrication.
2. *Fabrication and process flow diagram.* Such flow diagrams provide an account of the effect of the various stages of production on the material properties and of the possibility of quality control. Certain processes can lead to undesirable directional properties, internal stresses, cracking, or structural damage, which can lead to unsatisfactory component performance and premature failure in service.
3. The FMEA provides a logical way of identifying all possible scenarios of failures of a product during the design stage and how to modify the design to avoid them. The FMEA is described in the following Section.

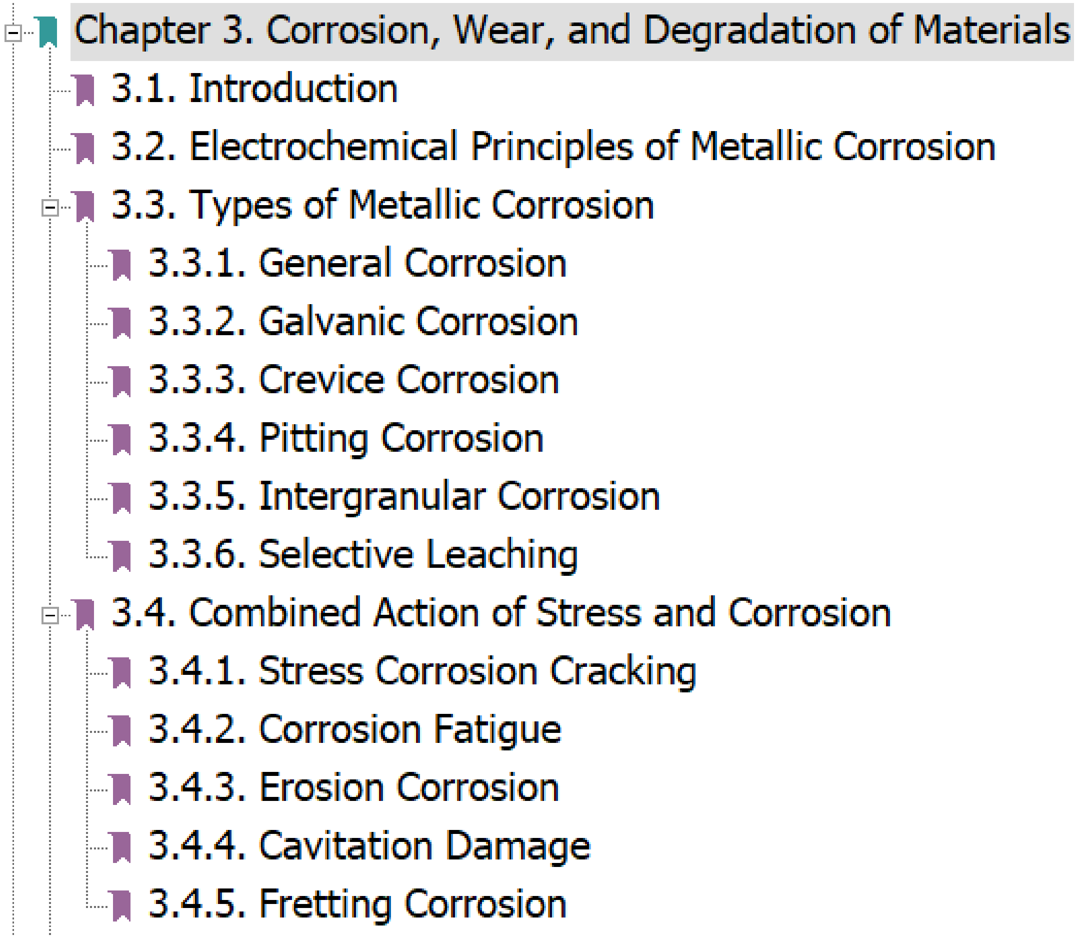
TABLE 2.5

Using FMEA in Designing Water Storage Tank

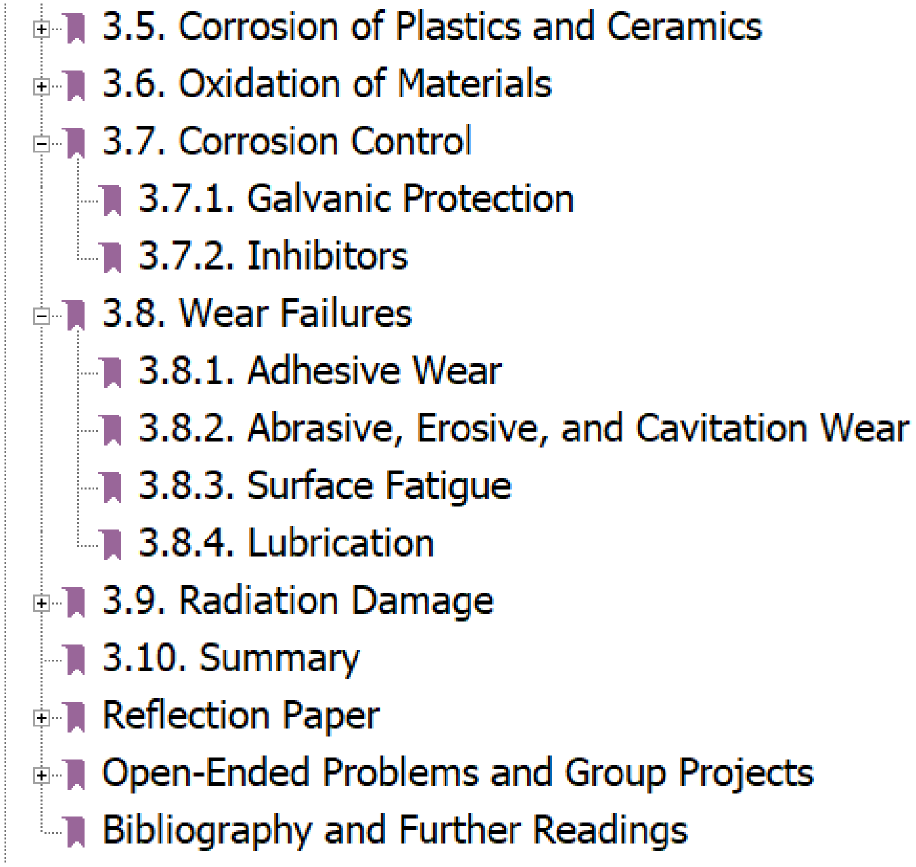
Product: Water storage tank

Subsystems/parts: Tank shell, inlet valve system, outlet filter system

System/ Subsystem/ Part	Function	Possible Failure Mode	Consequence of Failure	Severity (S)	Possible Cause of Failure	Likelihood of Occurrence (O)	Ease of Detecting Failure (D)	RPN (S × O × D)	Criticality (S × O)	Action to Reduce Risk
Tank shell	Contains water	Water leak	Loss of water	7	a. Cracks in welds	a. 5	a. 7	a. 245	a. 35	a. Inspect welds
					b. General corrosion	b. 4	b. 5	b. 140	b. 28	b. Weld filler same as tank material
										c. Galvanic protection
Inlet valve system	Controls water entering the tank	a. Valve is not shut when tank is full.	a. Water floods surroundings.	8	a. Valve stuck open	a. 5	a. 7	a. 280	a. 40	a. Use corrosion-resistant material for valve
		b. Valve is shut when tank is empty.	b. No water supply from tank		b. Valve stuck shut	b. 5	b. 7	b. 280	b. 40	b. Better tolerance for moving valve parts
Outlet filter system	Ensures no debris in water out of tank	a. Filter does not let water through.	a. No water supply from tank	8	a. Filter clogged	a. 6	a. 6	a. 288	a. 48	a. Improve filter design
		b. Filter lets debris through.	b. Debris in water from tank		b. Filter broken	b. 4	b. 7	b. 224	b. 32	b. Use better filter material



- Chapter 3. Corrosion, Wear, and Degradation of Materials
  - 3.1. Introduction
  - 3.2. Electrochemical Principles of Metallic Corrosion
  - 3.3. Types of Metallic Corrosion
    - 3.3.1. General Corrosion
    - 3.3.2. Galvanic Corrosion
    - 3.3.3. Crevice Corrosion
    - 3.3.4. Pitting Corrosion
    - 3.3.5. Intergranular Corrosion
    - 3.3.6. Selective Leaching
  - 3.4. Combined Action of Stress and Corrosion
    - 3.4.1. Stress Corrosion Cracking
    - 3.4.2. Corrosion Fatigue
    - 3.4.3. Erosion Corrosion
    - 3.4.4. Cavitation Damage
    - 3.4.5. Fretting Corrosion



- 3.5. Corrosion of Plastics and Ceramics
- 3.6. Oxidation of Materials
- 3.7. Corrosion Control
  - 3.7.1. Galvanic Protection
  - 3.7.2. Inhibitors
- 3.8. Wear Failures
  - 3.8.1. Adhesive Wear
  - 3.8.2. Abrasive, Erosive, and Cavitation Wear
  - 3.8.3. Surface Fatigue
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- 3.9. Radiation Damage
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- Bibliography and Further Readings

4 Selection of Materials to Resist Failure

4.1 INTRODUCTION

In addition to design deficiencies, manufacturing defects, overloading, and inadequate maintenance, a poor selection of materials is known to be a major source of failure of engineering components in service. Generally, most widely used engineering materials have established ranges of applications and service conditions that match their capabilities. Exceeding such capabilities could lead to a failure in service. However, erring on the conservative side by underutilizing the material capabilities will usually result in uneconomic products.

The discussion in this chapter identifies the material properties that are required for a given type of loading or service environment. The different types of materials that are most suited for a given application are then examined.

4.2 SELECTION OF MATERIALS FOR STATIC STRENGTH

4.2.1 ASPECTS OF STATIC STRENGTH

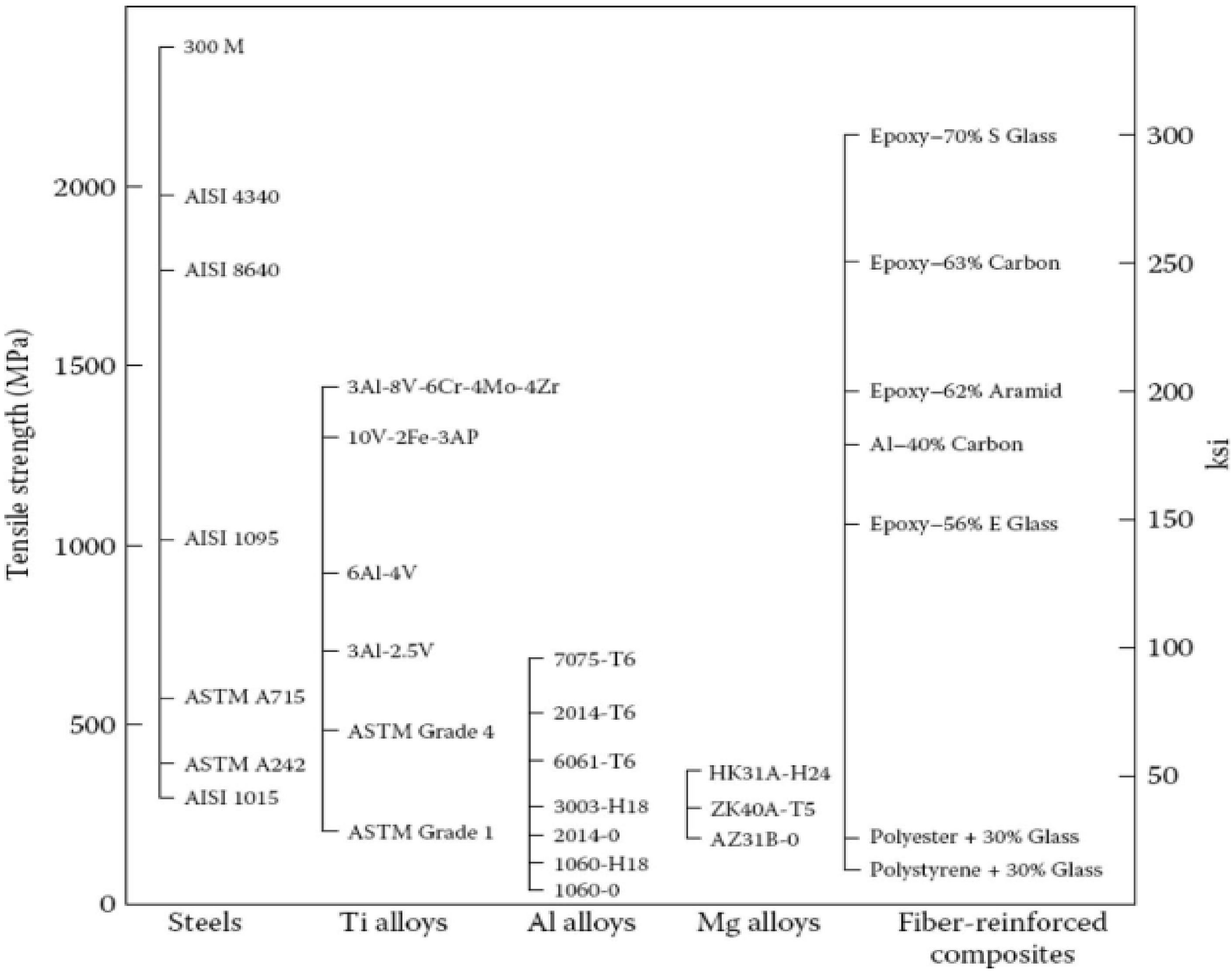
Static strength can be defined as the ability to resist a short-term steady load at moderate temperatures. This resistance is usually measured in terms of yield strength, ultimate tensile strength, compressive strength, and hardness. When the material does not exhibit a well-defined yield point, the stress required to cause 0.1% or 0.2% plastic strain, that is, the proof stress, is used instead. Most ductile wrought metallic materials are equally strong in tension and compression; brittle materials, however, are generally much stronger in compression than in tension.

Although many engineering materials are almost isotropic, there are important cases where significant anisotropy exists. In the latter cases, the strength depends on the direction in which it is measured. The degree of anisotropy depends on the nature of the material and its manufacturing history. Anisotropy in wrought metallic materials is more pronounced when they contain elongated inclusions and when processing consists of repeated deformation in the same direction. Composites reinforced with unidirectional fibers also exhibit pronounced anisotropy, which can be useful if the principal external stress acts along the direction of highest strength.

4.2.2 LEVEL OF STRENGTH

The level of strength in engineering materials may be viewed either in absolute terms or relative to similar materials. For example, it is generally understood that high-strength steels have tensile strength values in excess of 1400 MPa (ca. 200 ksi), which is also high strength in absolute terms. Relative to light alloys, however, an aluminum alloy with a strength of 500 MPa (ca. 72 ksi) would also be designated as high-strength alloy even though this level of strength is low for steels.

From the design point of view, it is more convenient to consider the strength of materials in absolute terms. From the manufacturing point of view, however, it is important to consider the strength as an indication of the degree of development of the material concerned, that is, relative to similar materials. This is because highly developed materials are often complex, more difficult to process, and relatively more expensive compared to other materials in their class. Figure 4.1 gives the strength of some materials, both in absolute terms and relative to similar materials. In a



IGURE 4.1 Comparison of some engineering materials on the basis of tensile strength.

given class of materials, the medium-strength members are usually more widely used because they generally combine optimum strength, ease of manufacture, and economy. The most developed members in a given class of materials are usually highly specialized, and, as a result, they are produced in much lower quantities. The low-strength members of a given class are usually used to meet requirements other than strength. Requirements such as electric and thermal conductivities, formability, corrosion resistance, or cost may be more important than high strength in some applications.

Frequently, higher-strength members of a given class of materials are also more expensive. Using a stronger but more expensive material could result in a reduction of the total cost of the finished component. This is because the amount of material used would be less as a result of smaller cross section, as discussed in Section 8.5.

4.2.3 LOAD-CARRYING CAPACITY

The load-carrying capacity of a given component is a function of both the strength of the material used in making it and its dimensions. This means that a lower-strength material can be used in making a component to bear a certain load, provided that its cross-sectional area is increased proportionally. However, the designer is not usually completely free in choosing the strength level of the material selected for a given part. Other factors like space and weight limitations could limit the choice. Space limitations can usually be solved by using stronger material, which will allow smaller cross-sectional area and smaller total volume of the component.

Weight limitations are encountered with many applications including aerospace, transport, construction, and portable appliances. The weight of a component is a function of both its volume and density. For example, the weight w of a tie-rod of cross-sectional area A and length l is given by

$$w = Al\rho = \left(\frac{L}{S}\right) l\rho \tag{4.1}$$

where

ρ is the density of the material,
L is the applied tensile load, and
S is the working strength of the material, which is equal to the yield strength of the material divided by a factor of safety, typically in the range 1.5–3.

Equation 4.1 shows that the weight of the tie-rod can be minimized by maximizing the ratio S/ρ, which is the specific strength of the material. In selecting a material for a tie-rod from a list of candidates, S/ρ can be used as the main performance index for comparison. The optimum material in this case is the one that has the highest S/ρ. Figure 4.2 compares the materials of Figure 4.1 on the basis of specific strength. The figure shows that the light alloys—Ti, Al, and Mg—have similar specific strengths to steel, whereas fiber-reinforced composites have a clear advantage over other materials.

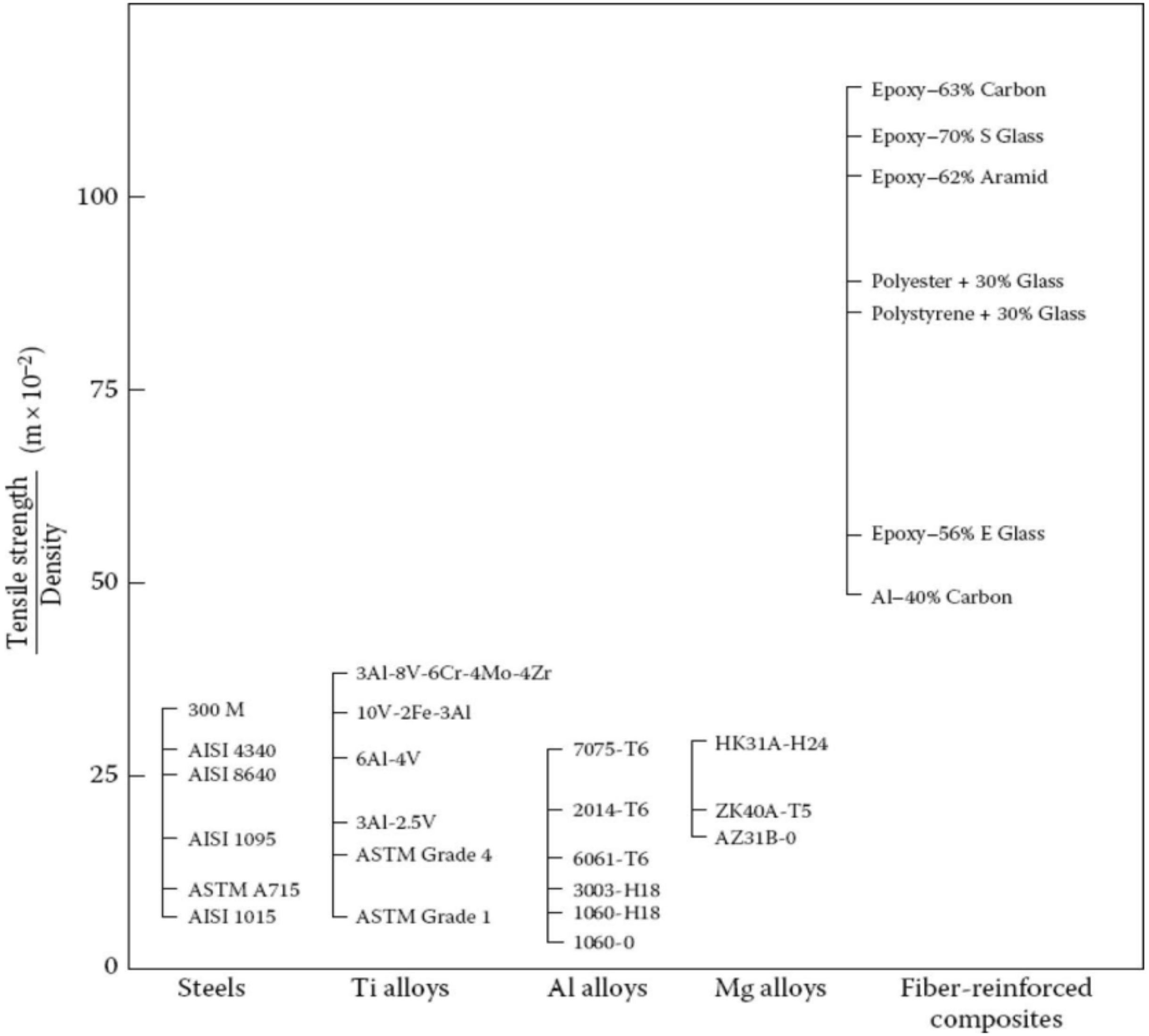


FIGURE 4.2 Comparison of some engineering materials on the basis of specific tensile strength.

shown in Table 4.1. The table shows that although strength and density have equal influence on the performance index in cylinders under tension, compression, or internal pressure, density has more influence in the case of flat plates, rectangular sections, and cylinders under torsion or bending since *S* has a power less than unity.

TABLE 4.1
Performance Indices in Selection for Static Strength

Cross Section and Loading Condition	Performance Index
Solid cylinder in tension or compression	S/ρ
Solid cylinder in torsion	$S^{2/3}/\rho$
Solid cylinder in bending	$S^{2/3}/\rho$
Solid rectangle in bending	$S^{1/2}/\rho$
Flat plate in bending	$S^{1/2}/\rho$
Flat plate under in-plane compression	$S^{1/2}/\rho$
Thin-walled cylindrical pressure vessel	S/ρ

In cases where a component carries a compressive load, reducing the cross-sectional area by choosing a strong material could cause failure by buckling due to increased slenderness of the part. Example 4.1 illustrates this point.

DESIGN EXAMPLE 4.1 MATERIAL SELECTION FOR A COMPRESSION ELEMENT

PROBLEM

A load of 50 kN is to be supported on a cylindrical compression element of 200 mm length. As the compression element has to fit with other parts of the structure, its diameter should not exceed 20 mm. Weight limitations are such that the mass of the element should not exceed 0.25 kg. Which of the materials given in Table 4.2 is most suited for making the compression element?

SOLUTION

Table 4.2 shows the calculated diameter of the compression element when made of different materials. The diameter is calculated on the basis of strength and buckling. The larger value for a given material is used to calculate the mass of the element. The results in Table 4.2 show that only epoxy–62% Kevlar satisfies both the diameter and weight limits.

TABLE 4.2
Comparison of Compression Element Materials

Material	Strength (MPa)	Elastic Modulus (GPa)	Specific Gravity	Diameter Based on Strength (mm)	Diameter Based on Buckling[a] (mm)	Mass Based on Larger Diameter (kg)	Remarks
Steels							
ASTM A675 grade 45	155	211	7.8	20.3	15.75	—	Reject (1)
ASTM A675 grade 80	275	211	7.8	15.2	15.75	0.3	Reject (2)
ASTM 717 grade 80	550	211	7.8	10.8	15.75	0.3	Reject (2)
Aluminum							
AA 2014-T6	420	70.8	2.7	12.3	20.7	—	Reject (1)
Plastics and Composites							
Nylon 6/6	84	3.3	1.14	27.5	44.6	—	Reject (1)
Epoxy–70% glass	2100	62.3	2.11	5.5	21.4	—	Reject (1)
Epoxy–62% Kevlar	1311	82.8	1.38	7.0	19.9	0.086	Accepted

Note: Reject (1) = material is rejected because it violates the limits on diameter; Reject (2) = material is rejected because it violates the limits on weight.

[a] Assuming that the ends of the compression element are not constrained, the Euler formula can be used to calculate the minimum diameter that will allow safe use of the compression member without buckling.

4.3.1 EFFECT OF MATERIAL STIFFNESS ON DEFLECTION UNDER LOAD

Stiffness of a component can be defined as its resistance to deflection under load. In many cases, such resistance is a function of both material stiffness and geometry of the component. For example, when a load is placed on a beam, the beam is bent and every portion of it is moved in a direction parallel to the direction of the load. The distance that a point on the beam moves, deflection, depends on its position in the beam, the type of beam, and the type of supports. A beam that is simply supported at both ends suffers maximum deflection (y) in its middle when subjected to a concentrated central load (L). In this case, the maximum deflection, y, is given by

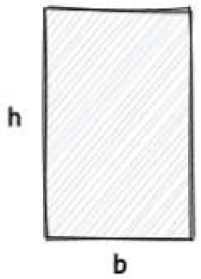
$$y = \frac{Ll^3}{48EI} \tag{4.2}$$

where

l is the length of the beam,
E is Young's modulus of the beam material, and
I is the second moment of the area of the beam cross section, with respect to the neutral axis.

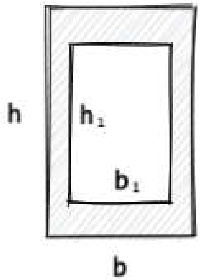
Equation 4.2 shows that the stiffness of a beam may be increased by increasing its second moment of area, which is computed from the cross-sectional dimensions, and by selecting a high-modulus material for its manufacture.

Moment of Inertia Equations



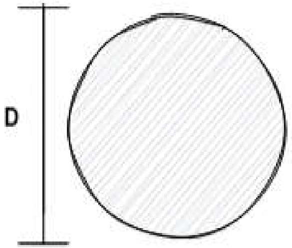
Rectangular

$$I_x = \frac{bh^3}{12}$$



Hollow Rectangular

$$I_x = \frac{bh^3}{12} - \frac{b_1 h_1^3}{12}$$



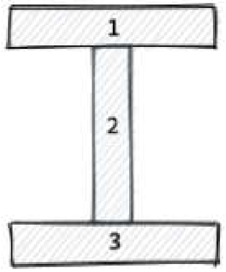
Circular

$$I_x = \frac{\pi}{64} D^4$$

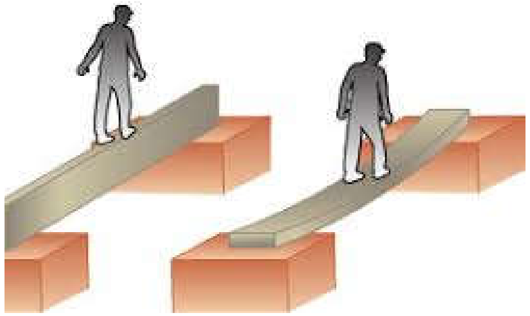
Complex Shapes

Any section moment of inertia can be calculated by simply summing the moment of inertia for each individual part.

For instance, an I-Beam is just a group of rectangular shapes:



$$I_x = \Sigma\ (\text{each } I_x)$$
$$= I_{x,1} + I_{x,2} + I_{x,3}$$



Other Notes: The same way you can add moment of inertia in parts, you can also subtract (like a hollow section)

SkyCiv

Equation 4.2 shows that the stiffness of a beam may be increased by increasing its second moment of area, which is computed from the cross-sectional dimensions, and by selecting a high-modulus material for its manufacture.

An important characteristic of metallic materials is that their elastic moduli are very difficult to change by changing the composition or heat treatment. However, the elastic moduli of composite materials can be changed over a wide range by changing the volume fraction and orientation of the constituents. Table 4.3 gives representative values of the modulus of elasticity of some engineering materials. When a metallic component is loaded in tension, compression, or bending, Young's modulus, E, is used in computing its stiffness. When the loading is in shear or torsion, the modulus of rigidity, G, is used in computing stiffness. The relationship between these two elastic constants is given by

$$G = \frac{E}{2(1+\nu)} \tag{4.3}$$

where ν is Poisson's ratio.

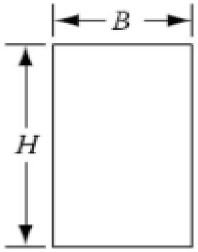
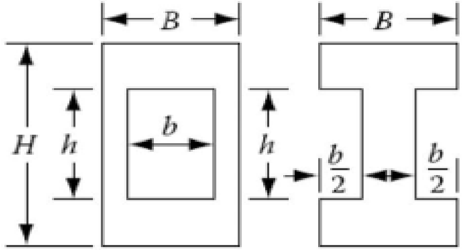
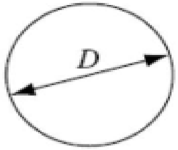
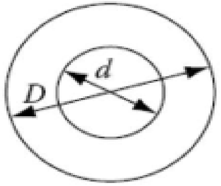
TABLE 4.3
Comparison of Stiffness of Selected Engineering Materials

Material	Modulus of Elasticity *E* (GPa)	Density ρ (mg/m^3)	$(E/\rho)\times 10^{-5}$	$(E^{1/2}/\rho)\times 10^{-2}$	$(E^{1/3}/\rho)$
Steel (carbon and low alloy)	207	7.825	26.5	5.8	35.1
Aluminum alloys (average)	71	2.7	26.3	9.9	71.2
Magnesium alloys (average)	40	1.8	22.2	11.1	88.2
Titanium alloys (average)	120	4.5	26.7	7.7	50.9
Epoxy–73% E glass fibers	55.9	2.17	25.8	10.9	81.8
Epoxy–70% S glass fibers	62.3	2.11	29.5	11.8	87.2
Epoxy–63% carbon fibers	158.7	1.61	98.6	24.7	156.1
Epoxy–62% aramid fibers	82.8	1.38	60	20.6	146.6

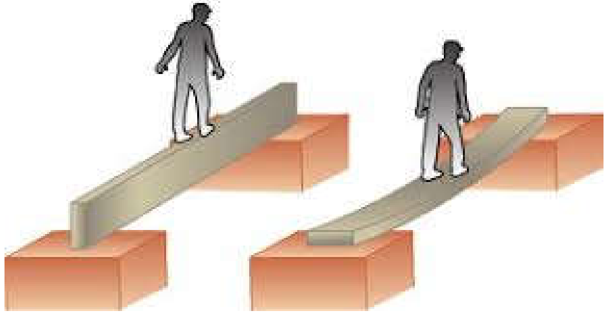
The importance of stiffness arises in complex assemblies where differences in stiffness could lead to incompatibilities and misalignment between various components, thus hindering their efficiency or even causing failure. Using high-strength materials in attempts to reduce weight usually comes at the expense of reduced cross-sectional area and reduced second moment of area. This could adversely affect stiffness of the component if the elastic constant of the new strong material does not compensate for the reduced second moment of area. Another solution to the problem of reduced stiffness is to change the shape of the component cross section to achieve higher second moment of area, *I*. This can be achieved by placing as much as possible of the material as far as possible from the axis of bending. Table 4.4 gives the formulas for calculating *I* for some commonly used shapes and the values of *I* for constant cross-sectional area.

TABLE 4.4

Effect of Shape on the Value of Second Moment of Area (*I*) of a Beam in Bending

Section Shape	**Formula for *I***	**Value of *I* for Different Geometries**		
	$\frac{BH^3}{12}$	$H/B = 1$ $H/B = 2$ $H/B = 3$ $H/B = 4$		$I = 833$ $I = 1650$ I=2511 $I = 3333$
	$\frac{BH^3 - bh^3}{12}$	$H = 19$ $h = 15$ $H = 21$ $h = 17$	$B = 10$ b=6 $B = 8$ $b = 4$	$I = 4028$ $I = 4536$
	$\frac{\pi D^4}{64}$	$D = 11.29$		$I = 796$
	$\frac{\pi(D^4 - d^4)}{64}$	$D = 20$	$d = 16.5$	$I = 4300$

Note: Cross-sectional area is the same in all cases and equals 100 units of area.



4.3.2 SPECIFIC STIFFNESS

In applications where both the stiffness and weight of a structure are important, it becomes necessary to consider the stiffness/weight, specific stiffness, of the structure. In the simple case of a structural member under tensile or compressive load, the specific stiffness is given by E/ρ, where ρ is density of the material. In such cases, the weight of a beam of a given stiffness can be easily shown to be proportional to ρ/E. The performance index in this case is E/ρ. This shows that the weight of the component can be reduced equally by selecting a material with lower density or higher elastic modulus. When the component is subjected to bending, however, the dependence of the weight on ρ and E is not as simple. From Equation 4.2 and Table 4.4, it can be shown that the deflection of a simply supported beam of square cross-sectional area is given by

$$y = \frac{Ll^3}{4Eb^4} \tag{4.4}$$

where b is the breadth or width of the beam. The weight of the beam, w, can be shown to be

$$w = lb^2\rho = \frac{1^{5/2}}{2}\left(\frac{L}{y}\right)^{1/2}\frac{\rho}{E^{1/2}} \tag{4.5}$$

This shows that for a given deflection y under load L, the weight of the beam is proportional to $\rho/E^{1/2}$. The performance index in this case is $E^{1/2}/\rho$. As E in this case is present as the square root, it is not as effective as ρ in controlling the weight of the beam. It can be similarly shown that the weight of the beam in the case of a rectangular cross section is proportional to $\rho/E^{1/3}$ and the performance index is $E^{1/3}/\rho$, which is even less sensitive to variations in E, as shown in Table 4.3.

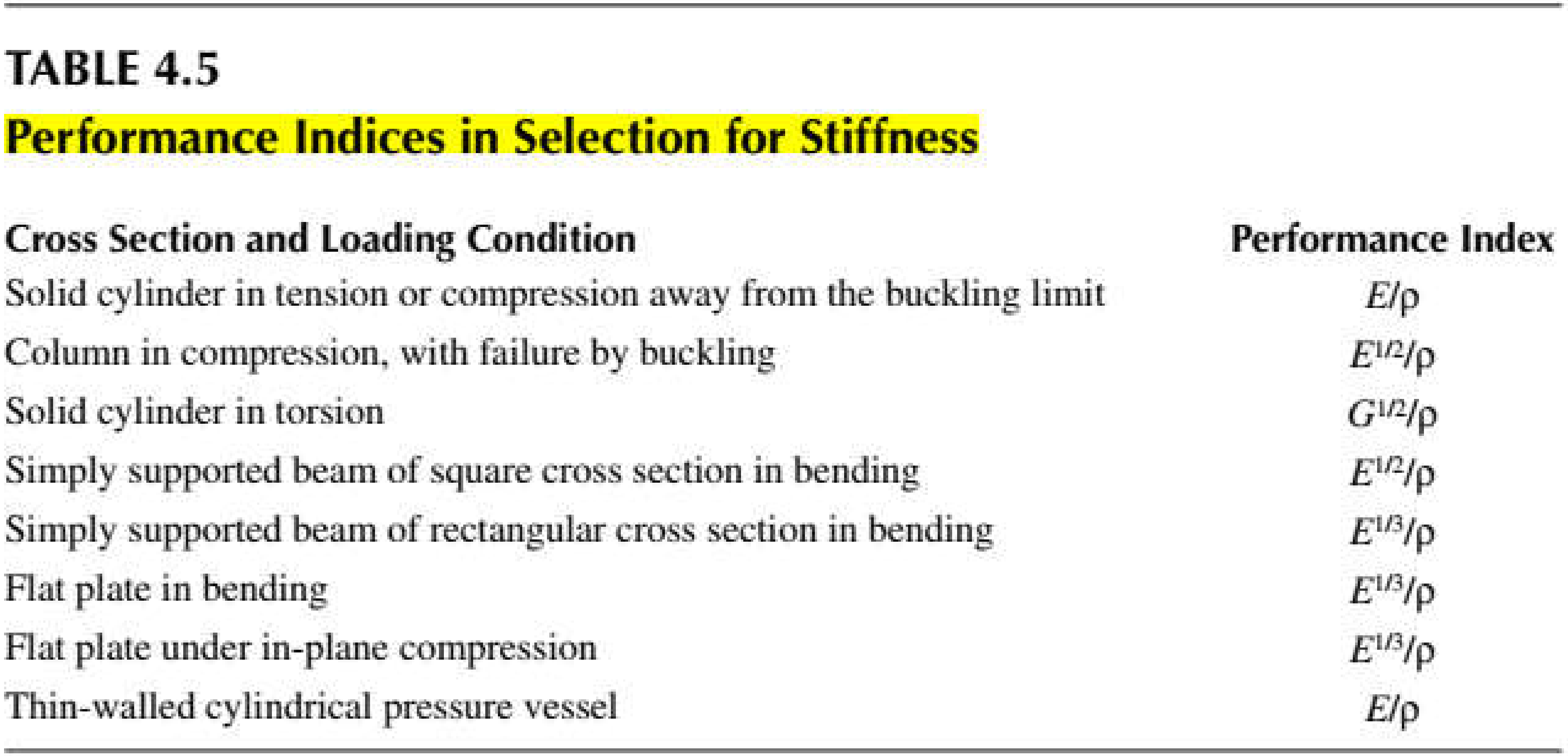


TABLE 4.5

Performance Indices in Selection for Stiffness

Cross Section and Loading Condition	Performance Index
Solid cylinder in tension or compression away from the buckling limit	E/ρ
Column in compression, with failure by buckling	$E^{1/2}/\rho$
Solid cylinder in torsion	$G^{1/2}/\rho$
Simply supported beam of square cross section in bending	$E^{1/2}/\rho$
Simply supported beam of rectangular cross section in bending	$E^{1/3}/\rho$
Flat plate in bending	$E^{1/3}/\rho$
Flat plate under in-plane compression	$E^{1/3}/\rho$
Thin-walled cylindrical pressure vessel	E/ρ

4.3.3 EFFECT OF MATERIAL STIFFNESS ON BUCKLING STRENGTH

Another selection criterion, which is also related to the elastic modulus of the material and cross-sectional dimensions, is the elastic instability, or buckling, of slender components, struts, subjected to compressive loading. The compressive load, L_b, that can cause buckling of a strut is given by Euler formula as

$$L_b = \frac{\pi^2 EI}{l^2} \tag{4.6}$$

where l is the length of the strut.

Equation 4.6 shows that increasing E and I will increase the load-carrying capacity of the strut. As buckling can take place in any lateral direction, an axially symmetric cross section can be considered. For a solid round bar of diameter, D, the second moment of area, I, is given as

$$I = \frac{\pi D^4}{64} \tag{4.7}$$

The use of the resistance to buckling as a selection criterion is illustrated in Example 4.1.

The weight of a strut, w, is given by

$$w = l\frac{\pi D^2}{4}\rho = \left(\frac{2l^2 L_b^{1/2}}{\pi^{1/2}}\right)\left(\frac{\rho}{E^{1/2}}\right) \tag{4.8}$$

Equation 4.8 shows that the weight of an axisymmetric strut can be reduced by reducing ρ or by increasing E of the material, or both, with the performance index in this case being $E^{1/2}/\rho$. However, reducing ρ is more effective, as E is present as the square root. In the case of a flat panel subjected to buckling, it can be shown that the weight is proportional to $\rho/E^{1/3}$ and the performance index is $E^{1/3}/\rho$.

DESIGN EXAMPLE 4.2 MATERIAL SUBSTITUTION FOR AN INTERIOR DOOR PANEL

PROBLEM

A motorcar manufacturer is considering material substitution of the interior door panels of one of their models as part of a weight reduction effort. The panel is 100 cm long and 50 cm wide and is currently made of polyvinyl chloride (PVC) of 3.7 mm thickness. The candidate materials under consideration include PP + 40% glass fibers and PP + 40% flax fibers. If PVC is substituted, the new panels should have at least the same stiffness and buckling resistance.

SOLUTION

The performance index for equal stiffness and buckling resistance of the panel is $E^{1/3}/\rho$.

The thickness of the new (t_n) and the original (t_o) panels for equal performance indices is related as

$$t_n = t_o \left(\frac{E_o}{E_n} \right)^{1/3},$$

where E_o and E_n are the moduli of elasticity of the original and new materials, respectively. Table 4.6 compares the thickness and corresponding weight of the different material considerations.

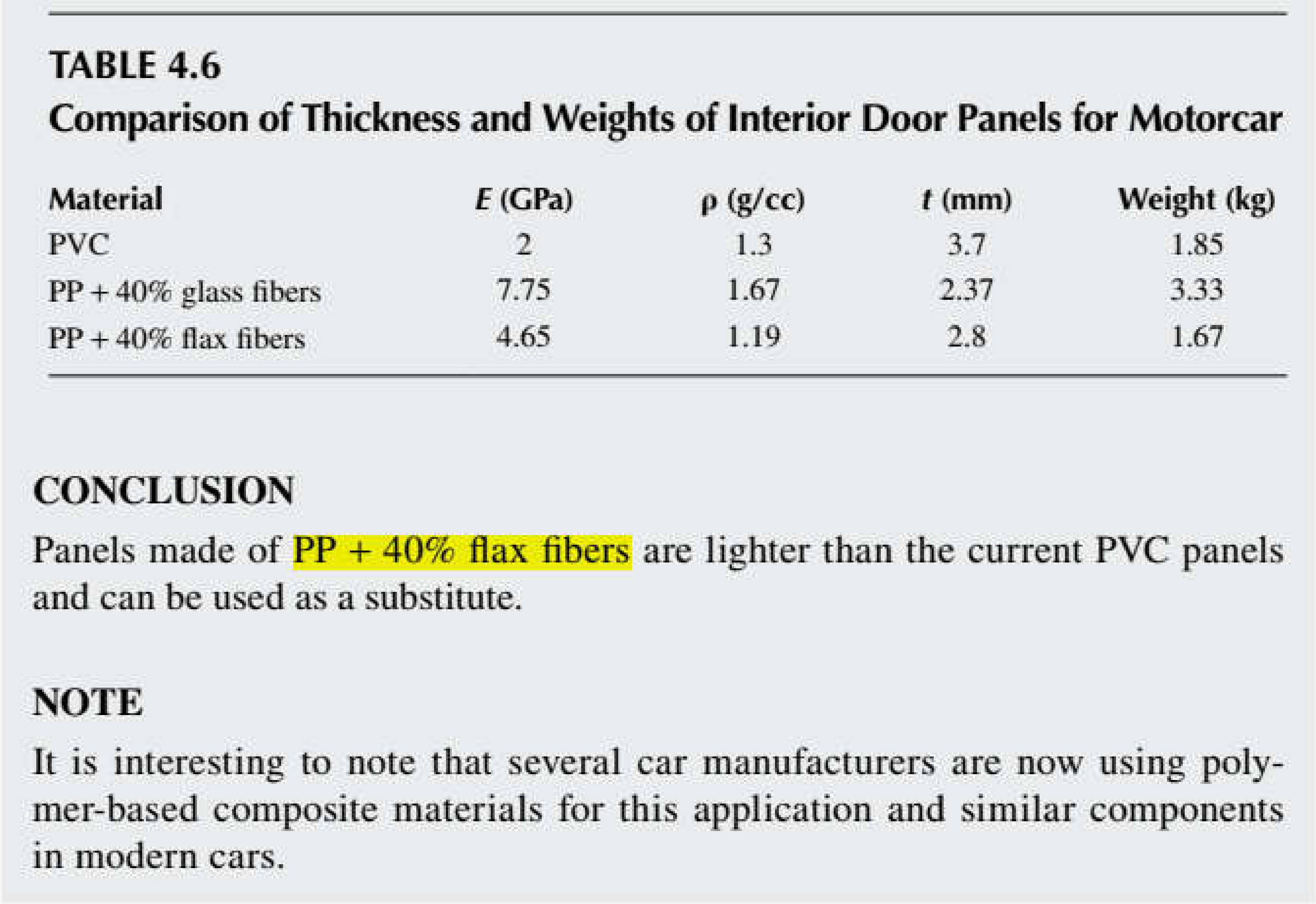


TABLE 4.6

Comparison of Thickness and Weights of Interior Door Panels for Motorcar

Material	E (GPa)	ρ (g/cc)	t (mm)	Weight (kg)
PVC	2	1.3	3.7	1.85
PP + 40% glass fibers	7.75	1.67	2.37	3.33
PP + 40% flax fibers	4.65	1.19	2.8	1.67

CONCLUSION

Panels made of PP + 40% flax fibers are lighter than the current PVC panels and can be used as a substitute.

NOTE

It is interesting to note that several car manufacturers are now using polymer-based composite materials for this application and similar components in modern cars.

4.4 SELECTION OF MATERIALS FOR HIGHER TOUGHNESS

It is now recognized that small cracks or discontinuities can exist in materials during their manufacture, processing, or service life and can lead to catastrophic failure if they exceed a critical size, as discussed in Section 2.3. It was also shown that the maximum allowable flaw size is proportional to $(K_{IC}/YS)^2$, where YS is the yield strength of the material and K_{IC} fracture toughness, which is the property of a material that allows it to withstand fracture in the presence of cracks. The ratio K_{IC}/YS can be taken as performance index when comparing the relative toughness of materials. Higher values of K_{IC}/YS are more desirable as they indicate tolerance to larger flaws without fracture.

4.4.1 METALLIC MATERIALS

There is a close relationship between toughness and other mechanical properties. Within a given class of materials, there is an inverse relationship between strength and toughness, as shown in Figure 4.3 and Table 4.7.

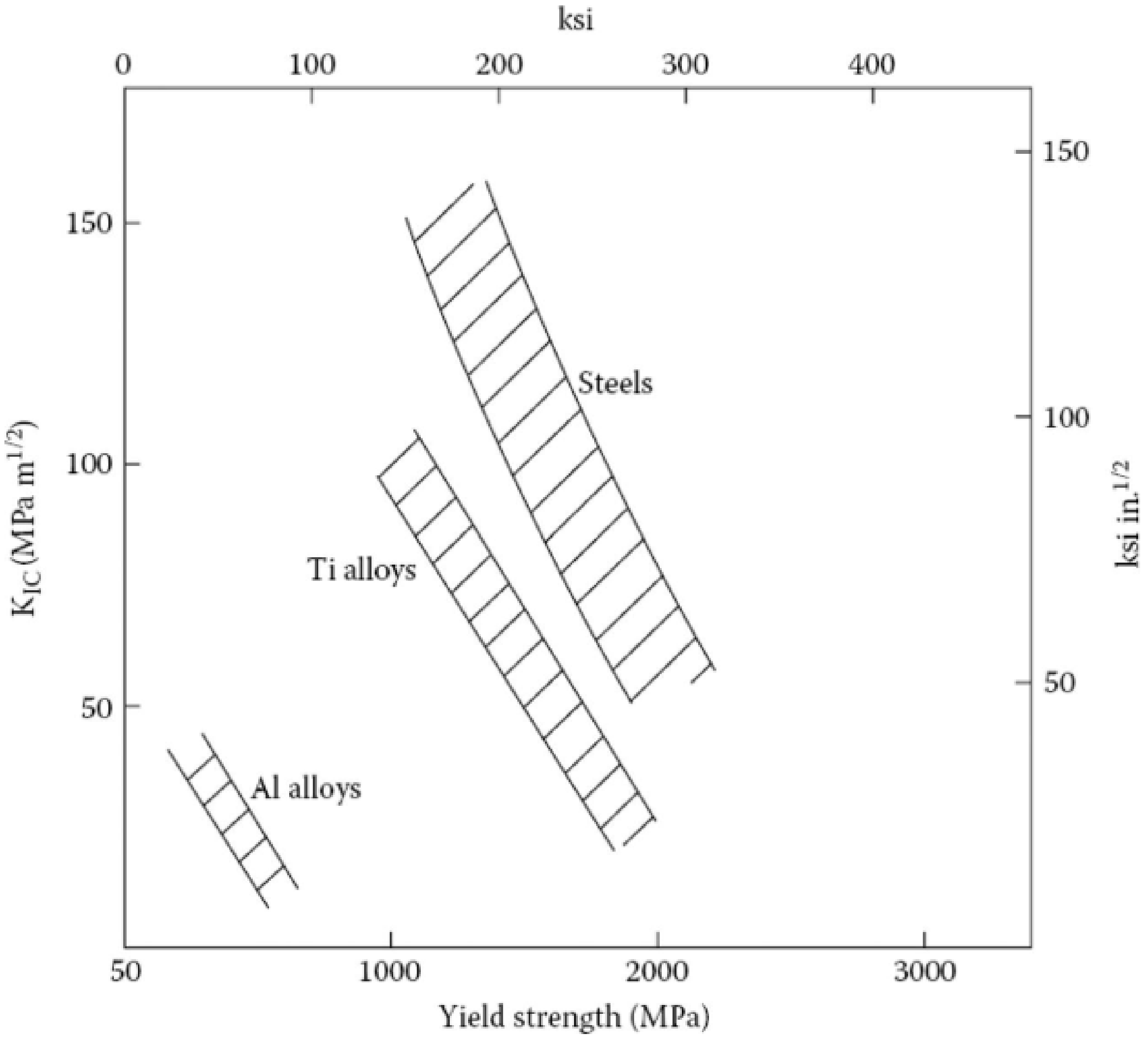


FIGURE 4.3 Variation of fracture toughness with yield strength for some alloy systems.

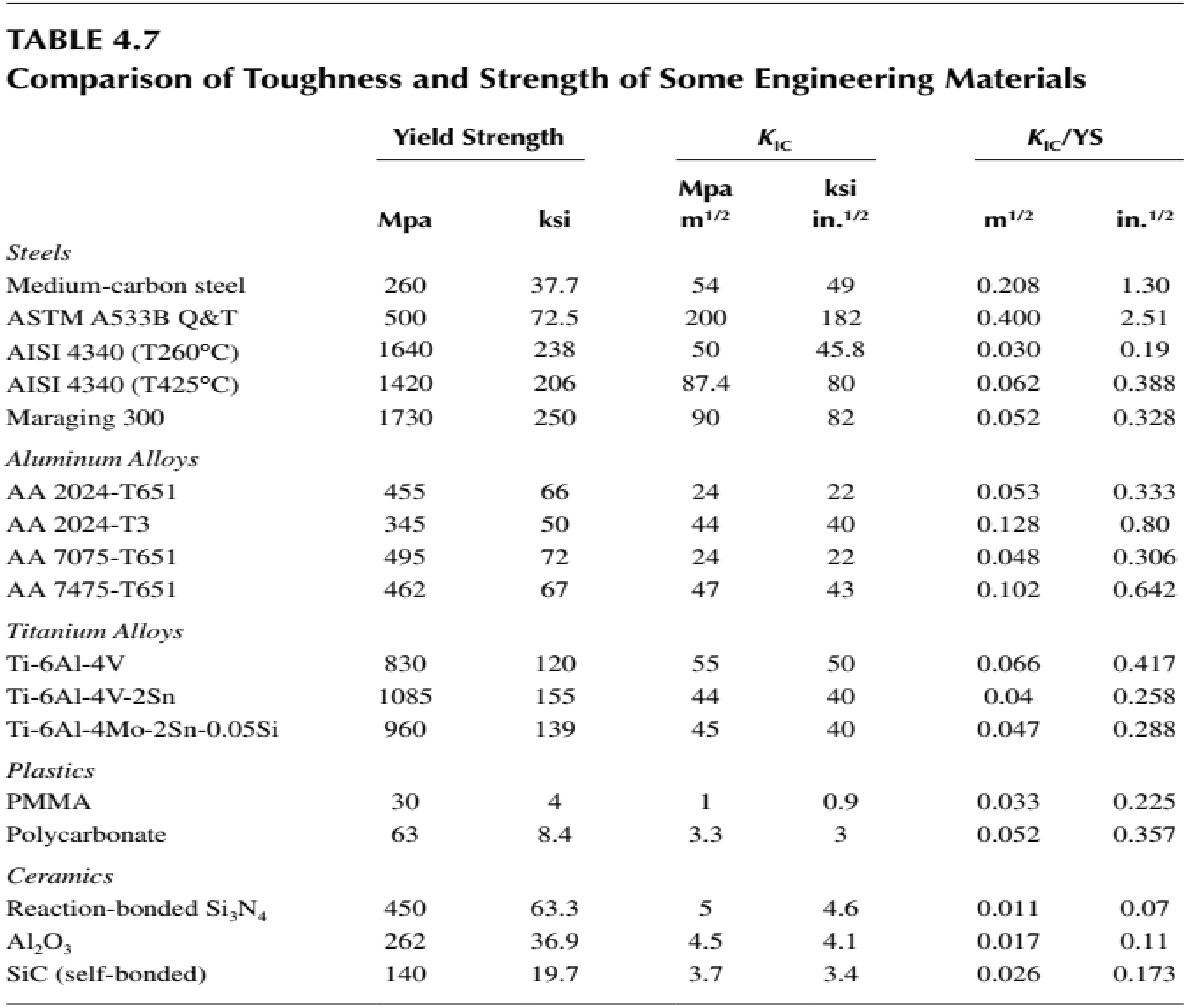


TABLE 4.7
Comparison of Toughness and Strength of Some Engineering Materials

	Yield Strength		K_{IC}		K_{IC}/YS	
	Mpa	ksi	Mpa $m^{1/2}$	ksi $in.^{1/2}$	$m^{1/2}$	$in.^{1/2}$
Steels						
Medium-carbon steel	260	37.7	54	49	0.208	1.30
ASTM A533B Q&T	500	72.5	200	182	0.400	2.51
AISI 4340 (T260°C)	1640	238	50	45.8	0.030	0.19
AISI 4340 (T425°C)	1420	206	87.4	80	0.062	0.388
Maraging 300	1730	250	90	82	0.052	0.328
Aluminum Alloys						
AA 2024-T651	455	66	24	22	0.053	0.333
AA 2024-T3	345	50	44	40	0.128	0.80
AA 7075-T651	495	72	24	22	0.048	0.306
AA 7475-T651	462	67	47	43	0.102	0.642
Titanium Alloys						
Ti-6Al-4V	830	120	55	50	0.066	0.417
Ti-6Al-4V-2Sn	1085	155	44	40	0.04	0.258
Ti-6Al-4Mo-2Sn-0.05Si	960	139	45	40	0.047	0.288
Plastics						
PMMA	30	4	1	0.9	0.033	0.225
Polycarbonate	63	8.4	3.3	3	0.052	0.357
Ceramics						
Reaction-bonded Si_3N_4	450	63.3	5	4.6	0.011	0.07
Al_2O_3	262	36.9	4.5	4.1	0.017	0.11
SiC (self-bonded)	140	19.7	3.7	3.4	0.026	0.173

Generally, the toughness of a material is influenced by its chemical composition and microstructure. For example, steels become less tough with increasing carbon content, larger grain size, and more brittle inclusions. The grain size of steels is affected by the elements present, especially those used for deoxidizing. Small additions of aluminum to steel are known to promote fine grain size, which improves the toughness. Fully killed fine-grained steels also have lower ductile–brittle transition temperatures and are normally selected for applications where brittle fracture may occur. Fine grains can also be obtained in steels by using alloying elements, by controlling the rolling practice, or by normalizing treatment. A thoroughly deoxidized steel grade has fewer nonmetallic inclusions and gives better toughness. When brittle inclusions are elongated, their influence on ductility is more pronounced in the transverse and through-thickness directions.

The method of fabrication can also have a pronounced effect on toughness, and experience has shown that a large proportion of brittle fractures originate from welds or their vicinity. This can be caused by the residual stresses generated by the welding process, by reduction of toughness of the heat-affected zone (HAZ), or by defects in the weld area.

The rate of load application also influences the toughness. Materials that are tough under slowly applied load may behave in a brittle manner when subjected to shock or impact loading.

Decreasing the operating temperature generally causes a decrease in toughness of most engineering materials. This is particularly important in the case of body-centered cubic (bcc) materials, as they tend to go through a ductile–brittle transition as the temperature decreases. All carbon and most alloy steels are of the bcc group, and their behavior is illustrated in Figure 4.4. The catastrophic failures of the welded steel structures of the liberty ships is shown in Figure 4.5 and discussed in more detail in a reflection paper in Chapter 6. As most bcc materials become too brittle to use under cryogenic temperatures, austenitic steels and nonferrous materials of face-centered cubic (fcc) structures become the only possible materials, as they do not suffer ductile–brittle transition. Several aluminum-, titanium-, copper-, and nickel-based alloys are available for cryogenic applications.

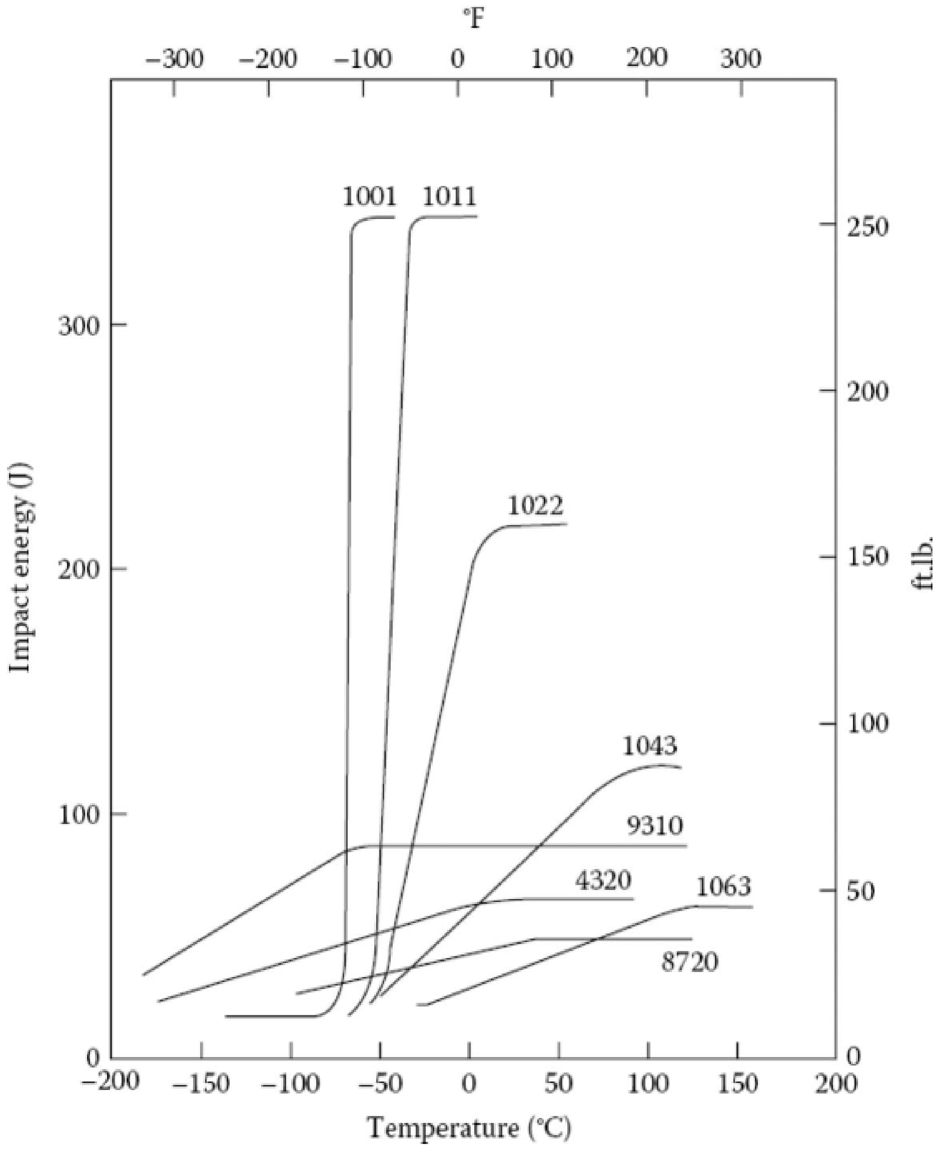


FIGURE 4.4 Effect of temperature on the notch toughness of some AISI-SAE steels.

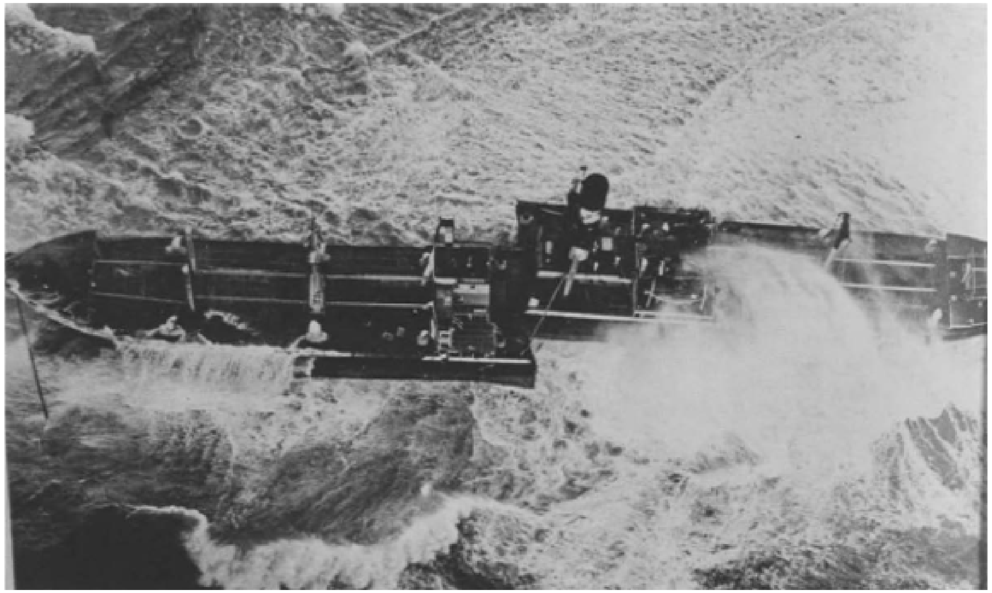


FIGURE 4.5 Catastrophic brittle fracture of a steel liberty ship at relatively low temperatures. (From Flinn, R.A. and Trojan, P.K., *Engineering Materials and Their Applications,* 4th edn., Houghton Mifflin, Boston, MA, 1990.)

Tests for Evaluating Toughness

- Many tests have been invented to assess the toughness of a material, e.g.:
  - notched tensile test
  - Charpy impact test
  - the drop weight tear test (DWTT)
  - . . .
- The early tests were highly arbitrary and merely attempted to imitate the conditions of service that were known to decrease toughness.
- The toughness of steel is decreased by:
  - decreasing temperature;
  - increasing strain rate; and
  - increasing plastic constraint.

An important aspect of selecting materials for toughness is the likelihood of detection of a crack before it reaches a critical size. As larger cracks can be more easily discovered, it follows that materials tolerating larger critical cracks are more advantageous. The materials listed in Table 4.7 are compared on the basis of the performance index K_{IC}/YS. The values in the table show that a material may exhibit a good crack tolerance even though its fracture toughness is modest. In general, therefore, the material selected for a given application must have such combination of K_{IC} and YS that the critical crack length is appropriate for that application and the available nondestructive testing (NDT) techniques, as illustrated in Example 4.3.

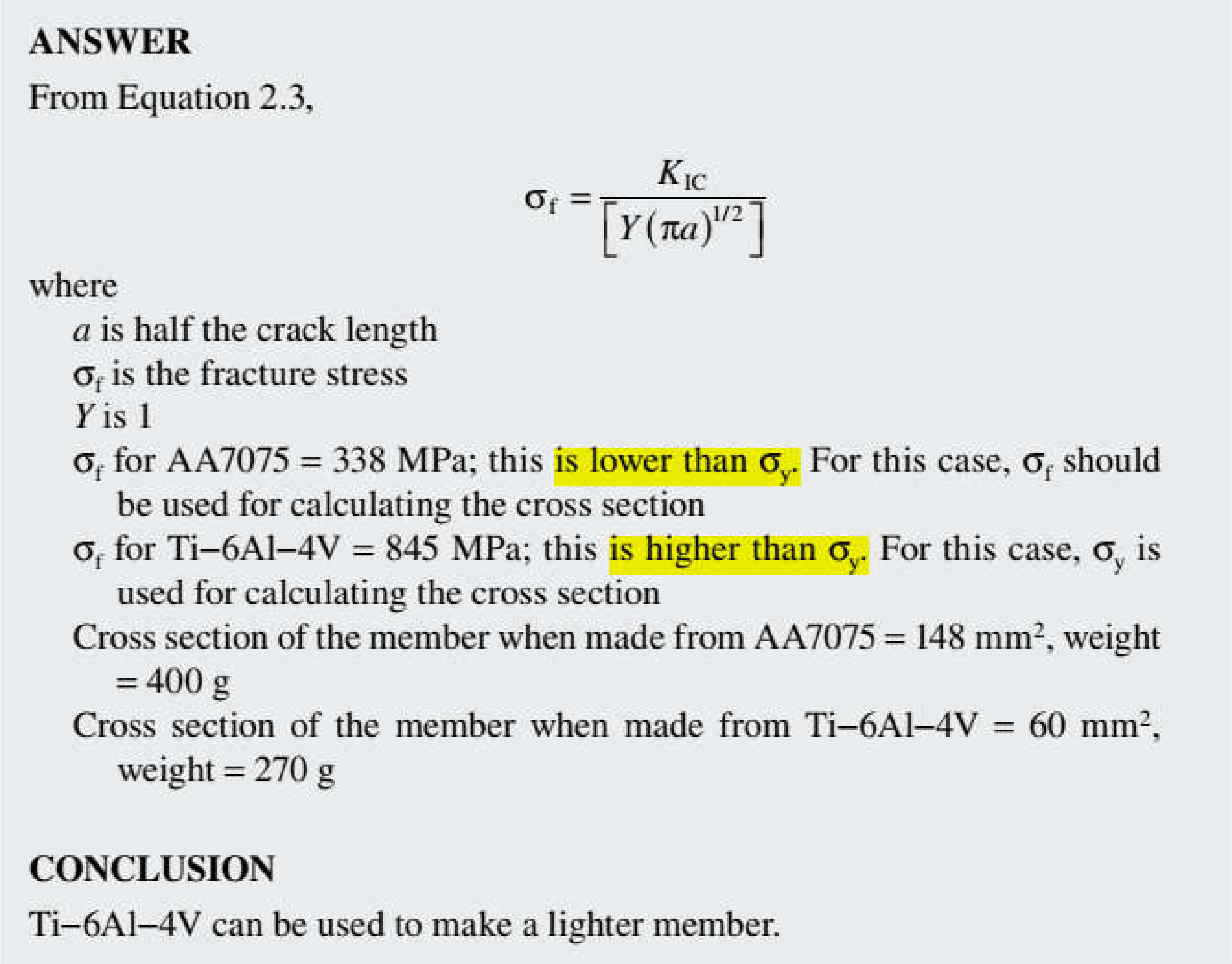
DESIGN EXAMPLE 4.3 SELECTING A MATERIAL FOR A LIGHT TIE-ROD

PROBLEM

Aluminum AA7075-T651 and titanium Ti–6Al–4V are being considered for making a 1 m long tie-rod that will carry a tensile load of 50 kN. If the available NDT equipment can only detect flaws larger than 3 mm in length, which of these two materials can be used to make a lighter member? Ignore the factor of safety in this example and assume the following:

AA7075: yield strength $\sigma_y = 495$ MPa, $K_{IC} = 24$ MPa m$^{1/2}$, specific gravity = 2.7

Ti–6Al–4V: yield strength $\sigma_y = 830$ MPa, $K_{IC} = 60$ MPa m$^{1/2}$, specific gravity = 4.5



ANSWER

From Equation 2.3,

$$\sigma_f = \frac{K_{IC}}{\left[Y(\pi a)^{1/2}\right]}$$

where

a is half the crack length

σ_f is the fracture stress

Y is 1

σ_f for AA7075 = 338 MPa; this is lower than σ_y. For this case, σ_f should be used for calculating the cross section

σ_f for Ti–6Al–4V = 845 MPa; this is higher than σ_y. For this case, σ_y is used for calculating the cross section

Cross section of the member when made from AA7075 = 148 mm^2, weight = 400 g

Cross section of the member when made from Ti–6Al–4V = 60 mm^2, weight = 270 g

CONCLUSION

Ti–6Al–4V can be used to make a lighter member.

4.4.2 PLASTICS AND COMPOSITES

Although unreinforced plastics generally have lower impact strength than most metallic materials, as shown in Table 4.7, numerous techniques have been developed to improve their toughness. Examples of such techniques include the following:

1. Alloying the plastic with a rubber phase or with another higher-impact plastic. Examples of this method include toughened nylons, which are alloyed with polyolefin or other polymeric modifier. An alloy of nylon and ABS combines the characteristics of both crystalline and amorphous polymers, which result in a combination of high-flow rate, high-temperature warp resistance, good-surface appearance, chemical resistance, and toughness.
2. Copolymerization to create a tougher chemical structure. This approach is used to produce less notch-sensitive polycarbonates that retain their ductility at lower temperatures.
3. Incorporating high-impact-resistance fibers. For example, PETE, nylon, and polyethylene fibers have been used to replace a portion of the glass fibers in injection-molded polyesters for automotive components.

In general, thermoplastic–matrix composites are tougher than those with thermoset matrix, which is one of the reasons why the former are being developed to replace current epoxies.

Copolymerization is a reaction in which two or more monomers polymerize to form a chain that contains more than one monomer.

4.4.3 CERAMICS

The fracture of ceramics is dependent on critical flaw size, which is a function of fracture toughness (K_{IC}). With careful processing, the average flaw size can be reduced to about 30 µm, but this may still be larger than the critical flaw size. In addition, a single flaw in the material that is larger than the critical flaw size is sufficient to cause fracture. This is why toughness data for ceramic materials are often inconsistent, and strength and toughness do not always respond in the same manner to changes in microstructure or interfacial properties. Table 4.7 lists typical toughness values of some ceramic materials.

An important technique to improve the toughness of ceramics like ZrO_2, $A1_2O_3$, and Si_3N_4 is to induce a phase transformation in the region of applied stress within the material. This absorbs energy at the tip of the advancing crack, arresting its propagation and significantly increasing both strength and toughness. Another technique is to introduce fibers to increase the toughness as a result of fiber debonding, crack deflection, or fiber pullout. Internal stresses due to the differences in thermal expansion between matrix and fibers in a composite can also provide a toughening effect.

Because ceramics are sensitive to surface damage, surface modification techniques are also being developed as a means of improving their toughness.

4.5 SELECTION OF MATERIALS FOR FATIGUE RESISTANCE

In many engineering applications, the behavior of a component in service is influenced by several other factors besides the properties of the material used in its manufacture. This is particularly true for the cases where the component or structure is subjected to fatigue loading. Under such conditions, the fatigue resistance can be greatly influenced by the service environment, surface condition of the part, method of fabrication, and design details. The use of endurance-limit modifying factors to account for the effect of the service environment, surface finish, method of fabrication, and component size is discussed in Section 6.5. In some cases, the role of the material in achieving satisfactory fatigue life is secondary to the mentioned parameters, as long as the material is sound and free from major flaws. For example, if the component has welded, bolted, or riveted joints, the contribution of crack initiation stage is expected to be small, and most of the fatigue life is determined by the crack propagation stage. Experience shows that crack propagation rate is more sensitive to continuum mechanics considerations than to material properties.

Fatigue strength of metallic materials generally increases with increasing tensile strength, as shown in Table 4.8. However, the higher the strength, the higher the notch sensitivity of the material and the greater the need to eliminate coarse second-phase particles and to produce a more refined, homogeneous material structure. Meeting these needs could require expensive metallurgical processes or the addition

TABLE 4.8

Comparison of Static and Fatigue Strengths of Some Engineering Materials

Material	Tensile Strength		Endurance Limit		Enduranc Ratio
	Mpa	ksi	Mpa	ksi	
Ferrous Alloys					
AISI 1010, normalized	364	52.8	186	27	0.46
1025, normalized	441	64	182	26.4	0.41
1035, normalized	539	78.2	238	34.5	0.44
1045, normalized	630	91.4	273	39.6	0.43
1060, normalized	735	106.6	315	45.7	0.43
1060, oil Q, tempered	1295	187.8	574	83.3	0.44
3325, oil Q, tempered	854	123.9	469	68	0.55
4340, oil Q, tempered	952	138.1	532	77.2	0.56
8640, oil Q, tempered	875	126.9	476	69	0.54
9314, oil Q, tempered	812	177.8	476	69	0.59
302, annealed	560	81.2	238	34.5	0.43
316, annealed	560	81.2	245	35.5	0.44
431, quenched, tempered	798	115.7	336	48.7	0.42
ASTM 20 GCI	140	20.3	70	10.2	0.50
30 GCI	210	30.5	102	14.8	0.49
60 GCI	420	61	168	24.4	0.40

	Tensile Strength		Endurance Limit		Endurance Ratio
Material	Mpa	ksi	Mpa	ksi	
Nonferrous Alloys					
AA 2011-T8	413	59.9	245	35.5	0.59
2024, annealed	189	27.4	91	13.2	0.48
6061-T6	315	45.7	98	14.2	0.31
6063-T6	245	35.5	70	10.2	0.29
7075-T6	581	84.3	161	23.4	0.28
214 as-cast	175	25.4	49	7.1	0.28
380 die-cast	336	48.7	140	20.3	0.42
Phosphor bronze, annealed	315	45.7	189	27.4	0.60
Phosphor bronze, hard drawn	602	87.3	217	31.5	0.36
Aluminum bronze, quarter hard	581	84.3	206	29.9	0.35
Incoloy 901, at 650°C (1202°F)	980	142.1	364	52.8	0.37
Udimet 700, at 800°C (1472°F)	910	132	343	49.7	0.38
Reinforced Plastics					
Polyester–30% glass	123	17.8	84	12.2	0.68
Nylon 66–40% glass	200	29	62.7	9.1	0.31
Polycarbonate–20% glass	107	15.5	34.5	5	0.32
Polycarbonate–40% glass	131	19	41.4	6	0.32

of expensive alloying elements. A measure of the degree of notch sensitivity of the material is usually given by the parameter *q*:

$$q = \frac{K_f - 1}{K_t - 1} \tag{4.9}$$

where

K_t is the stress concentration factor, which represents the severity of the notch and is given by the ratio of maximum local stress at the notch to average stress. K_t is mainly related to the geometry of the component, as discussed in Section 5.5, and is material independent.

K_f is the ratio of the fatigue strength in the absence of stress concentrations to the fatigue strength with stress concentration. Unlike K_t, K_f is material dependent.

The value of q is a measure of the degree of agreement between K_f and K_t and can be taken as a fatigue notch sensitivity index. Thus, as q increases from 0 to 1, the material becomes more sensitive to the presence of stress concentrations. Generally, increasing the tensile strength of the material makes it more notch sensitive and increases q. The value of q is also dependent on component size, and it increases as size increases. Therefore, stress raisers are more dangerous in larger components made from stronger materials.

4.5.1 STEELS AND CAST IRONS

Steels are the most widely used structural materials for fatigue applications as they offer high fatigue strength and good processability at a relatively low cost. Steels have the unique characteristic of exhibiting an endurance limit, which enables them to perform indefinitely, without failure, if the applied stresses do not exceed this limit. Table 4.8 shows that the endurance ratio of most steels ranges between 0.4 and 0.6.

The optimum steel structure for fatigue resistance is tempered martensite, since it provides maximum homogeneity. Steels with high hardenability provide high strength with relatively mild quenching and, hence, low residual stresses, which is desirable in fatigue applications. Normalized structures, with their finer structure, give better fatigue resistance than the coarser pearlitic structures obtained by annealing.

Inclusions in steel are harmful as they represent discontinuities in the structure that could act as initiation sites for fatigue cracking. Therefore, free-machining steels should not be used for fatigue applications. However, if machinability considerations make it essential to select a free-machining grade, leaded steels are preferable to those containing sulfur or phosphorus. This is because the rounded lead particles give rise to less structural stress concentrations than the other angular and elongated inclusions. By the same token, cast steels and cast irons are not recommended for critical fatigue applications. In rolled steels, the fatigue strength is subject to the same directionality as the static properties.

4.5.2 NONFERROUS ALLOYS

Unlike ferrous alloys, the nonferrous alloys, with the exception of titanium, do not normally have an endurance limit. Aluminum alloys usually combine corrosion resistance, light weight, and reasonable fatigue resistance. The endurance ratio of aluminum alloys is more variable than that of steels (Table 4.8), but an average value can be taken as 0.35.

Generally, the endurance ratio is lower for as-cast structures and precipitation-hardened alloys. Fine-grained inclusion-free alloys are most suited for fatigue applications.

4.5.3 PLASTICS

The viscoelasticity of plastics makes their fatigue behavior more complex than that of metals. In addition to the set of parameters that affect the fatigue behavior of metals, the fatigue behavior of plastics is also affected by the type of loading, small changes in temperature and environment, and method of sample fabrication. Because of their low thermal conductivity, hysteretic heating can build up in plastics causing them to fail in thermal fatigue or to function at reduced strength and stiffness levels. The amount of heat generated increases with increasing stress and test frequency. This means that failure of plastics in fatigue may not necessarily mean fracture. In flexural fatigue testing by constant amplitude of force, ASTM D671 sets an arbitrary level of stiffness—70% of the original modulus—as failure.

Some unreinforced plastics such as polytetrafluoroethylene (PTFE), polymethylmethacrylate (PMMA), and polyester ether ketone (PEEK) have fatigue endurance limits. At stresses below this level, failure does not occur. Other plastics, usually amorphous materials, show no endurance limit. In many unreinforced plastics, the endurance ratio can be taken as 0.2.

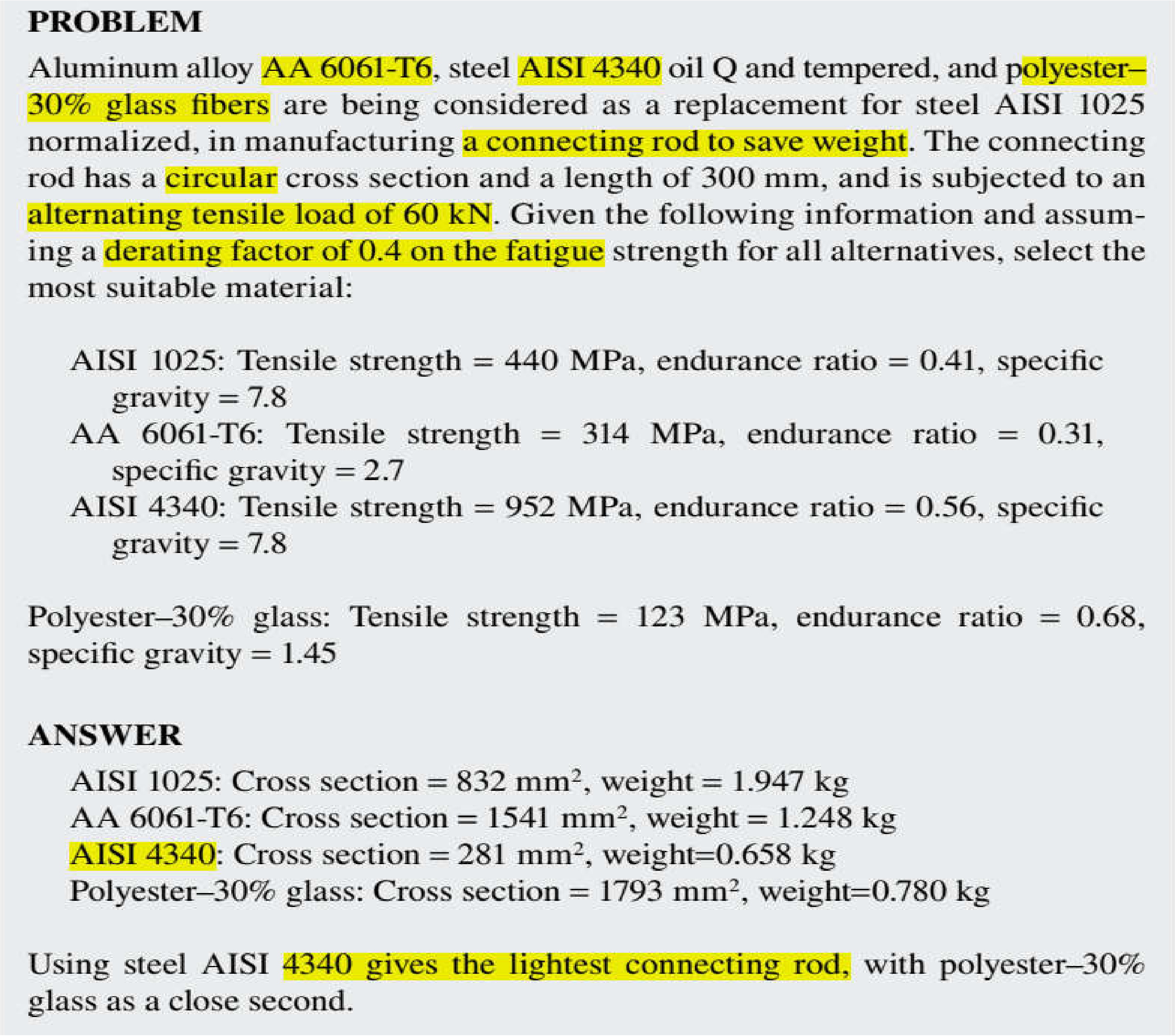
4.5.4 COMPOSITE MATERIALS

The failure modes of composite materials in fatigue are complex and can be affected by the fabrication process when differences in shrinkage between fibers and matrix induce internal stresses. There is a growing body of practical experience, however, and some FRP are known to perform better in fatigue than some metals, as shown in Table 4.8. The advantage of FRP is even more apparent when compared on per weight basis. For example, because of its superior fatigue properties, glass-fiber-reinforced epoxy has replaced steel leaf springs in several motorcar models.

Generally, fiber-reinforced crystalline thermoplastics exhibit well-defined endurance limits, whereas amorphous-based composites do not. The higher strengths, higher thermal conductivity, and lower damping account for the superior fatigue behavior of crystalline polymers.

As with static strength, fiber orientation affects the fatigue strength of fiber-reinforced composites. In unidirectional composites, the fatigue strength is significantly lower in directions other than the fiber orientation. Reinforcing with continuous unidirectional fibers is more effective than reinforcing with short random fibers. Example 4.4 illustrates the use of fatigue strength in design.

DESIGN EXAMPLE 4.4 SELECTING A MATERIAL FOR A CONNECTING ROD



PROBLEM

Aluminum alloy AA 6061-T6, steel AISI 4340 oil Q and tempered, and polyester–30% glass fibers are being considered as a replacement for steel AISI 1025 normalized, in manufacturing a connecting rod to save weight. The connecting rod has a circular cross section and a length of 300 mm, and is subjected to an alternating tensile load of 60 kN. Given the following information and assuming a derating factor of 0.4 on the fatigue strength for all alternatives, select the most suitable material:

AISI 1025: Tensile strength = 440 MPa, endurance ratio = 0.41, specific gravity = 7.8
AA 6061-T6: Tensile strength = 314 MPa, endurance ratio = 0.31, specific gravity = 2.7
AISI 4340: Tensile strength = 952 MPa, endurance ratio = 0.56, specific gravity = 7.8

Polyester–30% glass: Tensile strength = 123 MPa, endurance ratio = 0.68, specific gravity = 1.45

ANSWER

AISI 1025: Cross section = 832 mm^2, weight = 1.947 kg
AA 6061-T6: Cross section = 1541 mm^2, weight = 1.248 kg
AISI 4340: Cross section = 281 mm^2, weight=0.658 kg
Polyester–30% glass: Cross section = 1793 mm^2, weight=0.780 kg

Using steel AISI 4340 gives the lightest connecting rod, with polyester–30% glass as a close second.

4.6 SELECTION OF MATERIALS FOR HIGH-TEMPERATURE RESISTANCE

4.6.1 CREEP RESISTANCE OF METALS

It is shown in Section 2.6 that creep is a major factor that limits the service life of parts and structures at elevated temperatures. Experience shows that many of the methods used to improve low-temperature strength of metallic materials become ineffective as the operating temperature approaches 0.5 T_m (T_m is the absolute melting temperature expressed in degrees Kelvin or Rankine). This is because atomic mobility is sufficient to cause softening of cold-worked structures and coarsening of unstable precipitates. At these high temperatures, the differences in creep resistance from one material to another depend on the stability of the structure and on the hardening mechanism.

The most important method of improving creep strength is to incorporate a fine dispersion of stable second-phase particles within the grains. These particles can be introduced by dispersion, as in the case of thoria particles in nickel (TD nickel), or by precipitation, as in the case of precipitation-hardened nickel alloys. To minimize particle coarsening, it is the practice to make the chemical composition of the precipitates as complex as possible and to reduce the thermodynamic driving force for coarsening by reducing the interfacial energy between the precipitates and the matrix. Precipitates at the grain boundaries are important in controlling creep rupture ductility as they control grain boundary sliding, which causes premature failure.

4.6.2 PERFORMANCE OF PLASTICS AT HIGH TEMPERATURES

The mechanical strength of plastics at high temperatures is usually compared on the basis of deflection temperature under load (DTUL), also known as heat deflection temperature. According to ASTM D-648 specification, DTUL is defined as the temperature at which a specimen deflects 0.25 mm (0.010 in.) under a load of 455 or 1820 kPa (66 or 264 psi), when heated at the rate of 2°C/min. Generally, thermosets have higher temperature resistance than thermoplastics. However, adding glass and carbon fibers, as well as mineral and ceramic reinforcements, can significantly improve DTUL of crystalline thermoplastics such as nylon, thermoplastic polyesters, polyphenylenesulfone (PPS), and fluoroplastics. For example, at 30% glass–fiber, the DTUL of nylon 6/6 at 264 psi increases from about 71°C to 249°C (160°F–480°F).

Although several plastics can withstand short excursions to high temperatures, up to 500°C (930°F), continuous exposure can result in a dramatic drop in mechanical properties and extreme thermal degradation.

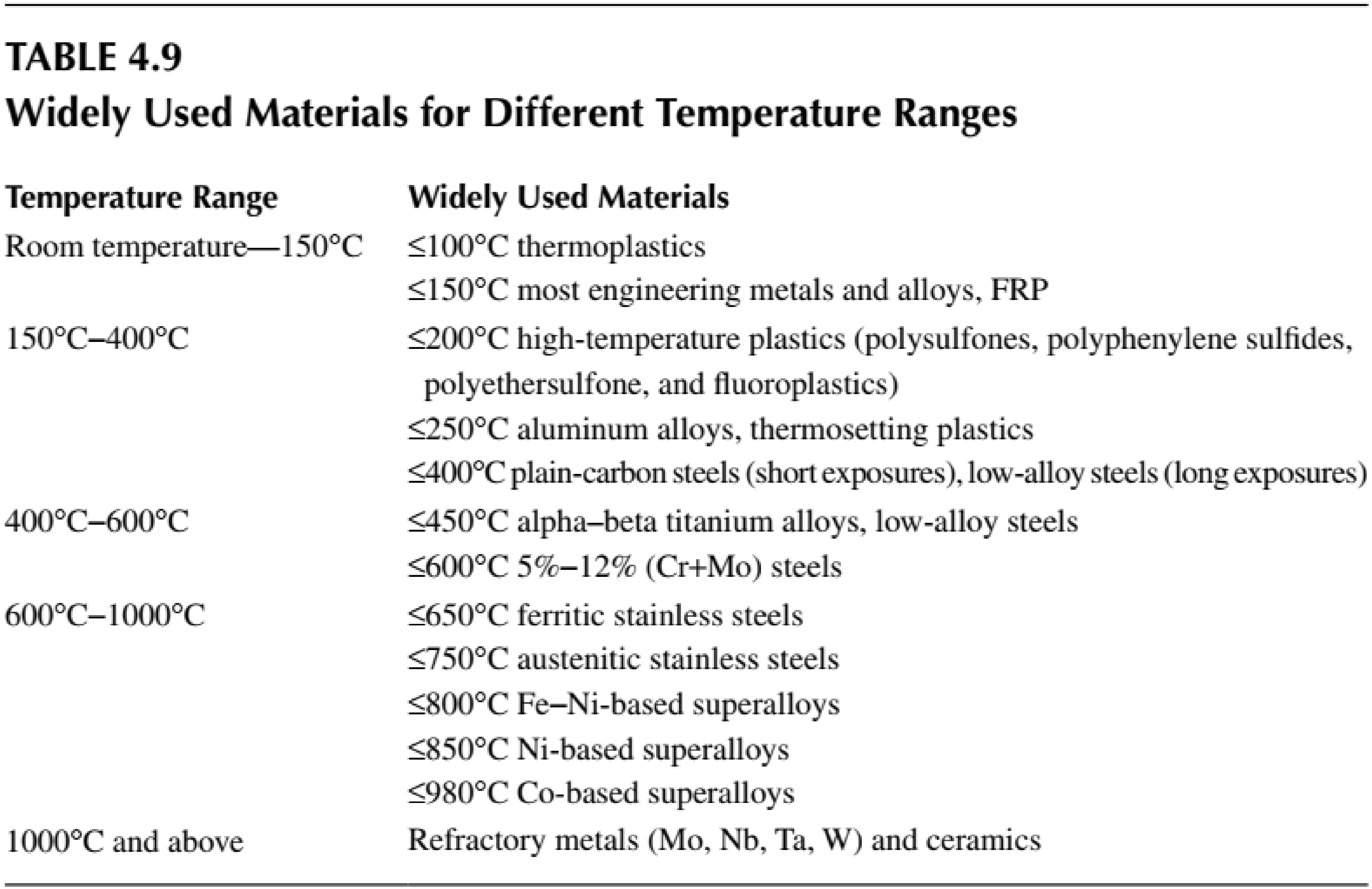


TABLE 4.9
Widely Used Materials for Different Temperature Ranges

Temperature Range	Widely Used Materials
Room temperature—150°C	≤100°C thermoplastics
	≤150°C most engineering metals and alloys, FRP
150°C–400°C	≤200°C high-temperature plastics (polysulfones, polyphenylene sulfides, polyethersulfone, and fluoroplastics)
	≤250°C aluminum alloys, thermosetting plastics
	≤400°C plain-carbon steels (short exposures), low-alloy steels (long exposures)
400°C–600°C	≤450°C alpha–beta titanium alloys, low-alloy steels
	≤600°C 5%–12% (Cr+Mo) steels
600°C–1000°C	≤650°C ferritic stainless steels
	≤750°C austenitic stainless steels
	≤800°C Fe–Ni-based superalloys
	≤850°C Ni-based superalloys
	≤980°C Co-based superalloys
1000°C and above	Refractory metals (Mo, Nb, Ta, W) and ceramics

4.6.3 WIDELY USED MATERIALS FOR HIGH-TEMPERATURE APPLICATIONS

Because operating temperature is the single most important factor that affects the selection of materials for elevated-temperature service, it is normal practice to classify temperature-resistant materials according to the temperature range in which they are expected to be used. Table 4.9 provides a summary of the widely used materials at the different temperature ranges. The following description provides an over view and the Appendices in Part IV give more details about the different materials.

4.6.3.1 Room Temperature to 150°C (300°F)

Most engineering metals and alloys, with the exception of lead, can be used in this temperature range. Several unreinforced thermoplastics are suitable for continuous service at temperatures above 100°C (212°F). In addition, fluoroplastics, polycarbonates, polyamides, polysulfones, polyphenylene sulfides, and the newly developed materials like PEEK and PPS can be used at temperatures up to 200°C. Several FRPs, for example, nylon 6/6–glass fiber, can also serve in this temperature range.

4.6.3.2 150°C–400°C (300°F–750°F)

Plain-carbon or manganese–carbon steels provide adequate properties in this temperature range, although it may be necessary to use low-alloy steels if very long service, more than 20 years, is required. High-grade cast irons can be used at temperatures up to 250°C for engine casings. Aluminum alloys can be used at temperatures up to about 250°C (480°F), although some P/M alloys have been used for short intervals at about 480°C (900°F).

High-temperature plastics can be used at temperatures up to 200°C (400°F) and will withstand temperatures up to about 300°C (500°F) for short periods. These include polysulfones, polyphenylene sulfides, polyethersulfones, and fluoroplastics. Thermoset polyamides–graphite composites can serve in the range of 260°C–290°C (500°F–550°F). New experimental plastics, like polyparaphenylene benzobisthiazole, are expected to withstand temperatures up to about 370°C (700°F) for long periods.

4.6.3.3 400°C–600°C (750°F–1100°F)

Low-alloy steels and titanium alloys are the main materials used in this temperature range. Low-alloy steels are relatively inexpensive and are used if there are no restrictions on weight. The main alloying elements that are usually added to these steels include molybdenum, chromium, and vanadium. An example of such steels is the 0.2C–1Cr–1Mo–0.25V steel, which is used for intermediate- and high-pressure steam turbine rotors.

In applications at temperatures approaching 600°C (1100°F), oxidation resistance becomes an important factor in determining the performance of materials. In such cases, at least 8% chromium needs to be added to steels. Several steels are available with chromium contents in the range of 5%–12%. These steels usually also contain molybdenum to improve their creep resistance.

Titanium alloys of alpha-phase structure exhibit better creep resistance than those of beta-phase structure. The alpha–beta 6Al–4V alloy is most widely used for general purposes and is limited to a maximum operating temperature of about 450°C (840°F). The near-alpha alloy 5.5Al–3.5Sn–3Zr–1Nb–0.25Mo–0.25Si can be used at temperatures up to about 600°C (1110°F).

4.6.3.4 600°C–1000°C (1100°F–1830°F)

The most widely used materials for this temperature range can be divided into the following groups:

- Stainless steels
- Fe–Ni-based superalloys
- Ni-based superalloys
- Co-based superalloys

Oxidation and hot corrosion resistance of the mentioned alloys becomes increasingly important with increasing operating temperature. The level of oxidation resistance in this temperature range is a function of chromium content. Aluminum can also contribute to oxidation resistance, especially at higher temperatures. Chromium is also important for hot corrosion resistance. Chromium content in excess of 20% appears to be required for maximum resistance. Table A.4 gives the composition and properties of selected stainless steels while Tables A.13 and A.14 give the composition and rupture strengths of selected Ni-based and Cr-based alloys.

When the oxidation and hot corrosion resistance of a given alloy is not adequate, protective coatings may be applied. Diffusion coatings, CoAl or NiAl, are commonly used for protection. FeCrAl, FeCrAlY, CoNiAl, or CoNiAlY overlay coatings can also be used, and they do not require diffusion for their formation.

4.6.3.5 1000°C (1830°F) and Above

The refractory metals Mo, Nb, Ta, and W as well as their alloys can be used for stressed applications at temperatures above 1000°C (1830°F). Mo-30W alloy has a melting point of 2830°C (5125°F) and excellent resistance to liquid-metal attack. Niobium can be used in contact with liquid lithium and sodium–potassium alloys at high temperatures, even above 800°C (1470°F). An addition of 1% Zr to niobium increases its resistance to embrittlement due to oxygen absorption. Tantalum can be used for structural applications at temperatures in the range of 1370°C–1980°C (2500°F–3600°F), but it requires protection against oxidation. Tantalum is also used for heat shields and heating elements in vacuum furnaces. Tungsten has the highest melting point of all materials, which makes it the obvious candidate for structural applications at very high temperatures. Molybdenum is added to tungsten to improve its machinability, and rhenium is added to improve resistance to cold fracture in lamp filaments. Surface protection is an important obstacle to the widespread use of refractory metals in high-temperature oxidizing environments. Various aluminide and silicide coatings are available commercially, but they all have a maximum temperature limit of about 1650°C (3000°F).

Ceramics can withstand extremely high temperatures and are being increasingly used for structural applications. Creep resistance, thermal conductivity, thermal expansion, and thermal-shock resistance are the major factors that determine the suitability of a ceramic material for high-temperature applications. Creep resistance of many ceramics is affected by intergranular phases. Because crystalline phases are generally more creep resistant than amorphous ones, it is the usual practice to reduce the amorphous intergranular phases as a means of improving creep resistance. Doping can also be used to improve the strength of grain boundary phases, as in the case of doping Si_3N_4 with Y_2O_3 and ZrO_2. Silicon-based ceramics have lower thermal expansion coefficient, which helps in improving their thermal-shock resistance. However, this may not be an advantage if the ceramic is used as a coating on metals where a large difference in expansion may present difficulties.

Thermal-shock resistance is a function of thermal conductivity, coefficient of thermal expansion, tensile strength, and modulus of elasticity. For structural ceramics, thermal-shock resistance is dependent on both material type and processing method. For example, silicon nitride (Si3N4) has a better thermal-shock resistance when hot-pressed than when reaction sintered. Generally, silicon carbide (SiC) and tungsten carbide have better thermal-shock resistance than zirconium oxide and aluminum oxide. Si3N4 has good thermal-shock resistance and good oxidation resistance, which make it a feasible candidate for service temperatures of about 1200°C (2192°F) in gas turbines.

CASE STUDY 3.7: DESIGNING FOR COMBINED EFFECT OF MECHANICAL LOADING, ENVIRONMENTAL ATTACK, AND WEAR AT HIGH TEMPERATURES

PROBLEM

Gas turbine blades are subjected to the combined effect of mechanical loading at high temperatures, environmental attack, and erosion and wear. As a result, more than 40% of gas turbine engine failures can be attributed to blade problems. Blades need to be replaced after 25,000–30,000 h of operation at a cost of about $3 million per raw of blades.

ANALYSIS

Failure modes in gas turbine blades operating in the hot section can be classified as follows:

a. Creep damage that can accelerate as a result of unplanned increase in operating temperature.
b. Thermal fatigue as a result of thermal stresses such as differential expansion of hot section components during start-up and shutdown operations.
c. Oxidation as a result of high-temperature exposure. Such oxide layers tend to crack and spall when the blades are subjected to vibration during engine operation and thermal cycling during start-up and shutdown.
d. Sulfidation and hot corrosion as a result of the sulfur contained in the fuel.
e. Standby corrosion during the engine shutdown as a result of the corrosive action of residuals on the blades. This surface damage can reduce fatigue life of the blades.
f. Erosion resulting from suspended particles in the hot gases.
g. Thermal overaging, especially in Ni-based superalloys, which derive their strength from gamma prime precipitates formed within the grains during manufacturing. This causes a decrease in strength and induces brittle behavior.

The aforementioned failure mechanisms can combine and cause accelerated failure of the turbine blades. For example, surface attack as a result of oxidation, sulfidation, corrosion, and erosion reduces the effective load-bearing area, which increases the effective stress and accelerates creep. In addition, overaging causes a reduction in creep resistance, which also accelerates creep.

SOLUTION

Changes in the design of gas turbine blades can allow them to resist failure. These include the introduction of cooling channels in the blades to prolong their creep life and coating them to prevent environmental attack.

Blade cooling involves creating longitudinal channels inside the blades and ducting cooler air through them. This allowed an increase of about 100°C in the operating with the same alloy composition. Film cooling is another technique in which air is passed over the surface through small holes to give a cool boundary layer between blade and gases. The drawback of blade cooling is that it can reduce the thermal efficiency by taking too much of the heat away from the combustion chamber.

Thermal barrier coatings (TBCs) are used extensively in aircraft turbines and allow another 100°C increase in operating temperatures. Currently, the peak metal temperatures of over 1100°C are experienced in some turbines with service lives around 10,000 h. TBCs that are based on yttria-stabilized zirconia (YSZ) can be penetrated by surface deposits such as glassy dust and sulfate salts, thus resulting in premature chipping or flaking. Using electron beam physical vapor deposition (EB-PVD) in making TBC results in less porous and longer-lasting coatings.

CASE STUDY 4.5: DEVELOPING MATERIALS AND PROCESSES TO RESIST FAILURE OF GAS TURBINE BLADES

PROBLEM

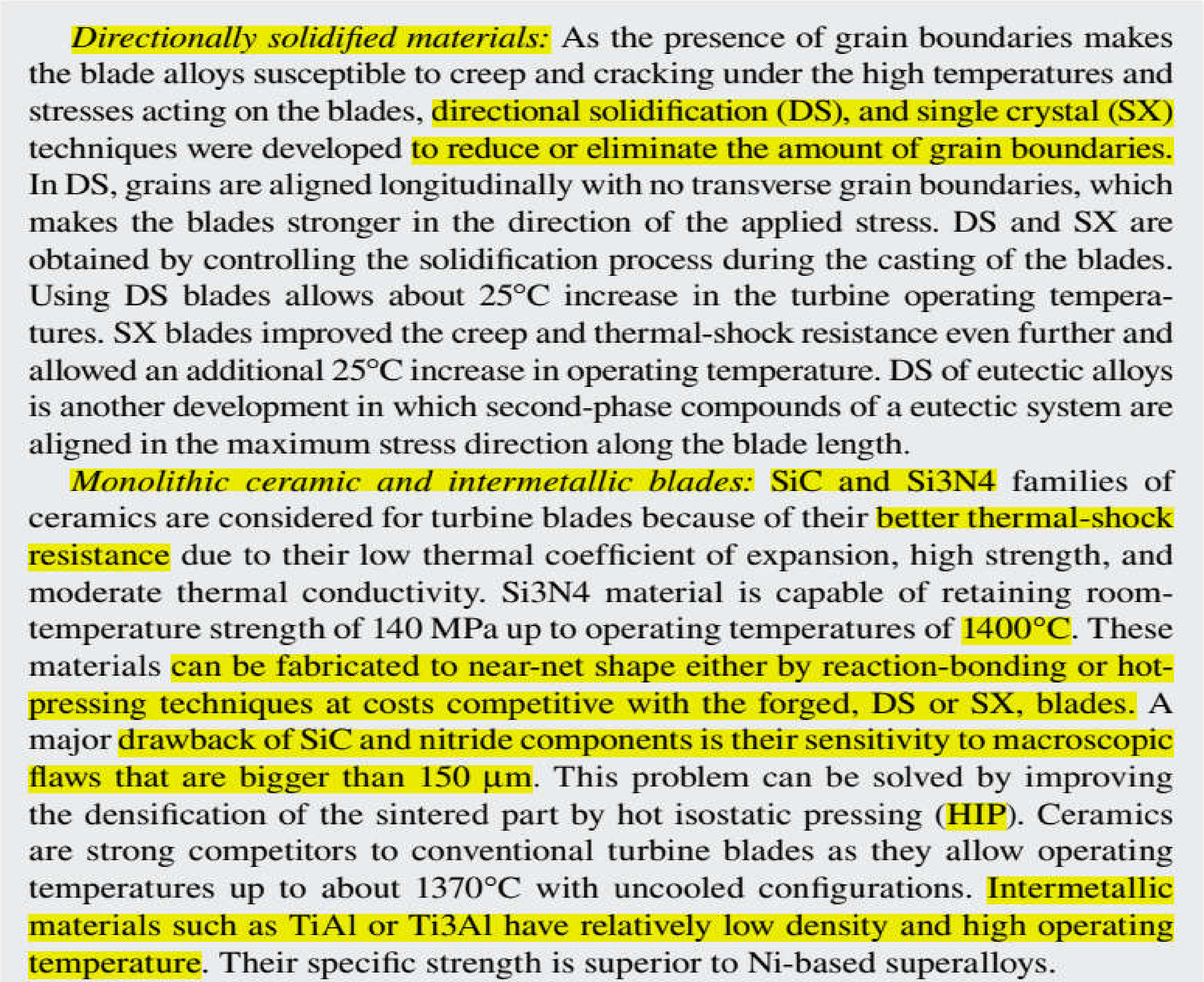
Analysis in Case Study 3.7 has shown that blades in the hot section of gas turbines are subject to the combined effects of mechanical loading at high temperature, which results in creep damage and thermal fatigue, and environmental attack, which causes oxidation, sulfidation, corrosion, and erosion.

ANALYSIS

The combined effect of high-temperature exposure and stress causes thermal overaging, which causes a decrease in strength and induces brittle behavior with a resulting accelerated creep rate and rupture. In addition, surface attack as a result of oxidation, sulfidation, corrosion, and erosion decreases the effective load-bearing area, which increases the effective stress and causes further acceleration of creep. Case Study 3.7 discussed blade cooling and thermal barrier coating that are used to extend the life of gas turbine blades. This case study illustrates how materials and processes can be improved to achieve the same objective.

SOLUTIONS

Attempts have been made to overcome the aforementioned material problems and have resulted in the development of several new material systems and manufacturing techniques. Some of these solutions are more developed and are being used on an industrial scale, while others are still in the development stage. Examples include the following:



Directionally solidified materials: As the presence of grain boundaries makes the blade alloys susceptible to creep and cracking under the high temperatures and stresses acting on the blades, directional solidification (DS), and single crystal (SX) techniques were developed to reduce or eliminate the amount of grain boundaries. In DS, grains are aligned longitudinally with no transverse grain boundaries, which makes the blades stronger in the direction of the applied stress. DS and SX are obtained by controlling the solidification process during the casting of the blades. Using DS blades allows about 25°C increase in the turbine operating temperatures. SX blades improved the creep and thermal-shock resistance even further and allowed an additional 25°C increase in operating temperature. DS of eutectic alloys is another development in which second-phase compounds of a eutectic system are aligned in the maximum stress direction along the blade length.

Monolithic ceramic and intermetallic blades: SiC and Si3N4 families of ceramics are considered for turbine blades because of their better thermal-shock resistance due to their low thermal coefficient of expansion, high strength, and moderate thermal conductivity. Si3N4 material is capable of retaining room-temperature strength of 140 MPa up to operating temperatures of 1400°C. These materials can be fabricated to near-net shape either by reaction-bonding or hot-pressing techniques at costs competitive with the forged, DS or SX, blades. A major drawback of SiC and nitride components is their sensitivity to macroscopic flaws that are bigger than 150 μm. This problem can be solved by improving the densification of the sintered part by hot isostatic pressing (HIP). Ceramics are strong competitors to conventional turbine blades as they allow operating temperatures up to about 1370°C with uncooled configurations. Intermetallic materials such as TiAl or Ti3Al have relatively low density and high operating temperature. Their specific strength is superior to Ni-based superalloys.

Metal–matrix composites (MMCs): High-strength Ti-based MMCs are suitable candidates for turbine blades, and they have the potential for weight reduction of up to 50% relative to conventional Ti alloys. High-modulus continuous fibers of SiC about 0.1 mm in diameter are used for the reinforcement of the Ti matrix. The SiC fibers are coated with a carbon layer, to prevent extensive reaction between the fiber and the matrix, and then coated with the Ti matrix using plasma or PVD. The coated fibers are consolidated using HIP.

Ceramic–matrix composites (CMCs): The relatively low fracture toughness of the monolithic ceramic materials can be improved by incorporating SiC or Al_2O_3 fibers in a matrix of SiC, Al_2O_3, or a mixture of both. A drawback of non-oxide fibers is their potential for chemical reaction with the ceramic–matrix at operating temperatures >1000°C for several hundred hours.

CONCLUSION

The solutions given in Case Study 3.7 and the aforementioned solutions can be combined to produce improved gas turbine blades for industrial applications. Case Study 9.4 compares the materials discussed here and selects the optimum candidates for use in aerospace and auxiliary power generation applications.

TABLE A.4
Composition and Properties of Selected Stainless Steels

	Nominal Composition (%)							Tensile Strength		Yield Strength			
AISI	C	Cr	Ni	Mn	Si	Others[a]		MPa	ksi	MPa	ksi	Elongation (%)	Hardness (BHN)
Austenitic													
201	0.15	17	4.5	6.50	1.0	—	—	805	117	385	56	55	185
301	0.15	17	7	2.0	1.0	—	—	770	112	280	41	60	162
302	0.15	18	9	2.0	1.0	—	—	630	91	280	41	50	162
304	0.08	19	9.5	2.0	1.0	—		588	85	294	43	55	150
316	0.08	17	12	2.0	1.0	2.5	Mo	588	85	294	43	50	145
330	0.08	18.5	35.5	2.0	1.0	—	—	630	91	266	39	45	150
Ferritic													
405	0.08	13	—	1.0	1.0	0.2	Al	490	71	280	41	30	150
430	0.12	17	—	1.0	1.0	—	—	525	76	315	46	30	155
442	0.2	21.5	—	1.0	1.0	—	—	560	81	315	46	20	185
Martensitic													
403	0.15	12.5	—	1.0	0.5	—	—	525	76	280	41	35	153
416	0.15	13	—	1.25	1.0	0.6	Mo	525	76	280	41	30	153
431	0.2	16	2.0	1.0	1.0	—	—	875	127	665	97	20	260
502	0.1	5	—	1.0	1.0	0.55	Mo	455	66	175	25	30	150
Precipitation hardening													
17—7 PH[b]	0.07	17	7	—	—	1.0	Al	1484	215	1346	195	9	465
PH 13—8Mo[b]	0.05	14	8.5	—	—	2.5	Mo	1552	225	1414	205	12	465
AM 350[c]	1.0	16.5	4.3	—	—	1.0 2.75	Al Mo	1518	220	1311	190	13	450

[a] Most steels contain 0.035 and 0.04–0.06 P except for type 416, which contains 0.15 S.

[b] Aged at 510°C.

[c] Aged at 450°C.

TABLE A.13
Chemical Composition of Selected Ni-Based and Co-Based Alloys

	Nominal Composition (wt%)										
Material	**C**	**Mn**	**Si**	**Cr**	**Ni**	**Co**	**W**	**Nb**	**Zr**	**Fe**	**Others**
Fe-Ni-based alloys											
Incoloy 80	0.05	0.8	0.5	21	32.5	—	—	—	—	45.7	0.38 Al, 0.38 Ti
Inconel 718	0.08	—	—	19	52.5	—	—	5.1	—	18.5	3 Mo, 0.9 Ti, 0.5 Al, 0.15 Cu
Nickel-based alloys											
DS-nickel	—	—	—	—	bal	—	—	—	—	—	2.1 ThO_2
Hastelloy X	0.1	1.0	1.0	21.8	bal	1.5	0.6	—	—	18.5	—
Inconel 600	0.08	0.5	0.2	15.5	76	—	—	—	—	8.0	—
Inconel 617	0.1	0.5	0.5	22.0	52	12.5	—	—	—	1.5	9 Mo, 0.3 Ti, 1.2 Al, 0.2 Cu
MAR-M200, c	0.15	—	—	9.0	bal	10	12.5	1.8	0.05	—	2Ti, 5 Al, 0.015 B
TRW VI A, c	0.13	—	—	6.0	bal	7.5	5.8	0.5	0.13	—	2 Mo, 1 Ti, 0.02 B, 5.4 Al, 9 Ta, 0.5 Re, 0.4 Hf
Cobalt-based alloys											
AiResist 13, c	0.45	0.5	—	21	1	bal	11	2	—	2.5	3.5 Al, 0.1 Y
X-40, c	0.5	0.5	0.5	25	10	bal	7.5	—	—	1.5	—
MAR-M302, c	0.85	0.1	0.2	21.5	—	bal	10	—	0.15	—	9 Ta, 0.005 B
MAR-M918	0.05	0.2	0.2	20	20	bal	—	—	0.1	0.5	7.5 Ta

Note: bal, balance; c, cast alloy.

TABLE A.14
Rupture Strength of Selected Nickel-Based and Cobalt-Based Alloys

	Rupture Strength (MPa) (ksi)					
	650°C (1200°F)		851°C (1500°F)		1093°C (2000°F)	
Material	**100 h**	**1000 h**	**100 h**	**1000 h**	**100 h**	**1000 h**
Nickel-based alloys						
DS-nickel	162	155	131	120.6	61.3	51
	(23.5)	(22.5)	(19)	(17.5)	(8.9)	(7.4)
Hastelloy X	330	234	96	69	8.2	4.1
	(48)	(34)	(14)	(10)	(1.2)	(0.6)
Inconel 600	—	—	55.2	38.6	9.6	6.2
			(8)	(5.6)	(1.4)	(0.9)
Inconel 617	414	324	145	96	18.6	10.3
	(60)	(47)	(21)	(14)	(2.7)	(1.5)
MAR-M200, c	—	—	524	414	75.8	44.8
	—	—	(76)	(60)	(11)	(6.5)
TRW VI A, c	1000	896	552	420.6	82.7	—
	(145)	(130)	(80)	(61)	(12)	—
Cobalt-based alloys						
AiResist 13, c	—	—	172.4	117.2	30.3	—
	—	—	(25)	(17)	(4.4)	—
X-40, c	390	339	179.3	137.9	27.6	—
	(57)	(49)	(26)	(20)	(4)	—
MAR-M302, c	—	—	276	206.9	41.4	27.6
	—	—	(40)	(30)	(6)	(4)
MAR-M918	462	—	206.9	137.9	17.2	—
	(67)	—	(30)	(20)	(2.5)	—

Note: c, cast alloy.

4.7 SELECTION OF MATERIALS FOR CORROSION RESISTANCE

Although corrosion resistance is usually the main factor in selecting corrosion-resistant materials, it is often difficult to assess this property for a specific application. This is because the behavior of a material in a corrosive environment can be dramatically changed by seemingly minor changes in the medium or the material itself. The main factors that can affect the behavior of the material can be classified as follows:

- Corrosive medium parameters
- Design parameters
- Material parameters

4.7.1 CORROSIVE MEDIUM PARAMETERS

Corrosive medium parameters include:

1. Chemical composition and presence of impurities
2. Physical state whether solid, liquid, gas, or combinations
3. Aeration, oxygen content, and ionization
4. Bacteria content

In the case of metallic materials, the most significant factor controlling the probability of atmospheric corrosion is whether or not an aqueous electrolyte is provided by condensation of moisture under prevailing climatic conditions. Hot and dry as well as cold and icy conditions give less attack than wet conditions. Clean atmosphere is less aggressive than industrial or marine atmospheres containing sulfur dioxide and salt, respectively. Direction of exposure to the sun, wind, and sources of pollution can also affect the rate of atmospheric corrosion.

In buried structures, increasing the porosity of the soil and the presence of water raises the rate of corrosion. In addition to allowing continuing access of oxygen to the corroding surface, porosity also encourages the activity of aerobic bacteria, which can lead to local variation in aeration, consumption of organic protection systems, and production of corrosive H_2S. In general, dry, sandy, or chalky soils of high electric resistance are the least corrosive, whereas heavy clays and saline soils are the most corrosive.

The rate of corrosion of underwater structures is affected by the amount of dissolved oxygen as well as the amount of dissolved salts and suspended matter. Since oxygen enters the water by dissolution from the air, its concentration can vary with depth and flow rate. Soft freshwater is generally more corrosive than hard water, which precipitates a protective carbonate on the corroding surface. In seawater, the presence of chloride ions increases the electric conductivity and, therefore, the rate of corrosion. The presence of organic matter, such as bacteria or algae, in water can decrease the rate of corrosion in the covered areas but produce regions of local deaeration where accelerated attack occurs. Increasing the water temperature generally increases the rate of attack. In chemical plants, the rate of attack depends on several factors including the temperature, concentration of chemicals, fluid velocity, degree of aeration, purity of the metal, and applied stresses. In general, the attack is severest where protective or oxide films are disrupted or become locally unstable.

4.7.2 DESIGN PARAMETERS

The design parameters that affect the rate of corrosive attack include the following:

1. Stresses acting on the material in service
2. Operating temperature
3. Relative motion of medium with respect to the material
4. Continuity of exposure of the material to the medium
5. Contact between the material and other materials
6. Possibility of stray currents
7. Geometry of the component

4.7.3 MATERIAL PARAMETERS

The main parameters that affect the corrosion resistance of materials include chemical composition and the presence of impurities, nature and distribution of microstructural constituents, surface condition and deposits, and processing history. Generally, the corrosion resistance improves in pure metals as their purity increases. An example is the localized attack in commercially pure aluminum due to the presence of iron impurities. Table 4.10 shows the relative corrosion resistance of some commonly used metallic materials under different service conditions.

TABLE 4.10
Relative Corrosion Resistance of Some Uncoated Metallic Materials

Material	Industrial Atmosphere	Fresh Water	Seawater	Acids H_2SO_4 5%–15% Concentration	Alkalis 8%
Low-carbon steel	1	1	1	1	5
Galvanized steel	4	2	4	1	1
GCI	4	1	1	1	4
4%–6% Cr steels	3	3	3	1	4
18–8 stainless steel	5	5	4	2	5
18–35 stainless steel	5	5	4	4	4
Monel (70% Ni–30% Cu)	4	5	5	4	5
Nickel	4	5	5	4	5
Copper	4	4	4	3	3
Red brass (85% Cu–15% Zn)	4	3	4	3	1
Aluminum bronze	4	4	4	3	3
Nickel silver (65% Cu–18% Ni–17% Zn)	4	4	4	4	4
Aluminum	4	2	1	3	1
Duralumin	3	1	1	2	1

Note: 1, poor: rapid attack; 2, fair: temporary use; 3, good: reasonable service; 4, very good: reliable service; 5, excellent: unlimited service.

4.7.4 CARBON STEELS AND CAST IRONS

Carbon steels and cast irons are used in large quantities because of their useful mechanical properties and low cost. These materials, however, are not highly corrosion resistant, with the exception of resistance to alkalis and concentrated sulfuric acid, as shown in Table 4.10. Low-carbon steels have adequate resistance to scaling in air up to about 500°C (ca. 930°F), but this temperature is reduced in the presence of sulfur in flue gases. The addition of chromium in amounts of about 3% increases the resistance to both oxidation and sulfide scaling. Chromium additions also improve resistance to atmospheric corrosion. Nickel is also added to improve the resistance to sodium hydroxide.

4.7.5 STAINLESS STEEL

Stainless steels represent a class of highly corrosion-resistant materials and have widespread applications in engineering. It should be remembered, however, that stainless steels do not resist all corrosive environments, as shown in Table 4.10. For example, when subjected to stresses in chloride-containing environments, stainless steels are less resistant than ordinary structural steels. Stainless steels, unless correctly fabricated and heat treated, can also be more susceptible to localized corrosion such as intergranular corrosion, SCC, crevice corrosion, and pitting than ordinary structural steels.

Increasing chromium content in stainless steels increases their resistance. This is because corrosion resistance of stainless steels can be attributed to the presence of a thin film of hydrous oxide on the surface of the metal. The condition of the film depends on the composition of the stainless steel and the treatment it receives. To give the necessary protection, the film must be continuous, nonporous, self-healing, and insoluble in the corrosive medium. In the presence of such an oxide film, the stainless steels are passive and have solution potentials approaching those of noble metals. When passivity is destroyed, the potential is similar to that of iron, as shown in Table 3.1.

TABLE 3.1
Position of Some Metallic Materials in the Galvanic Series Based on Seawater

Protected, Noble, or Cathodic End

Platinum
Gold
Graphite
Titanium
Silver
Chlorimet 3 (61 Ni, 18 Cr, 18 Mo)
Hastelloy C (62 Ni, 17 Cr, 15 Mo)
Inconel 625 (61 Ni, 21.5 Cr, 9 Mo, 3.6 Nb)
Incoloy 825 (21.5 Cr, 42 Ni, 3 Mo, 30 Fe)
Type 316 stainless steel (passive)
Type 304 stainless steel (passive)
Type 410 stainless steel (passive)
Monel alloy 400 (66.5 Ni, 31.5 Cu)
Inconel alloy 600 (passive) (76 Ni, 15.5 Cr, 8 Fe)
Nickel 200 (passive) (99.5 Ni)
Nickel 200 (passive) (99.5 Ni)
Leaded tin bronze G, 923, cast (87 Cu, 8 Sn, 4 Zn)
Silicon bronze C65500 (97 Cu, 5 Al)
Admiralty brass C44300, C44400, C44500 (71 Cu, 28 Zn, 1 Sn)
Chlorimet 2 (66 Ni, 32 Mo, 1 Fe)
Hastelloy B (60 Ni, 30 Mo, 6 Fe, 1 Mn)
Inconel 600 (active)
Nickel 200 (active)
Naval brass C46400 to C46700 (60 Cu, 39.25 Zn, 0.75 Sn)
Muntz metal C28000 (60 Cu, 40 Zn)
Tin
Lead
Type 316 stainless steel (active)
Type 304 stainless steel (active)
Lead tin solder (50 Sn, 50 Pb)
Cast irons
Low-carbon steels
Aluminum alloy 2117 (2.6 Cu, 0.35 Mg)
Aluminum alloy 2024 (4.5 Cu, 1.5 Mg, 0.6 Mn)
Aluminum alloy 5052 (2.5 Mg, 0.25 Cr)
Aluminum alloy 3004 (1.2 Mn, 1 Mg)
Aluminum 1100, commercial-purity aluminum (99% Al min, 0.12 Cu)
Galvanized steel
Zinc
Magnesium alloys
Magnesium
Corroded, anodic, least noble end

in Table 3.1. Exposing stainless steels to mildly oxidizing corrosive agents causes them to become active, and increasing the oxygen concentration causes them to regain passivity. When the passive film is destroyed locally, stainless steels can fail catastrophically by localized mechanisms such as pitting, crevice corrosion, intergranular corrosion, or SCC, as shown in Example 3.3 and Case Study 4.6.

Chromium plays an important role in forming the passive film on the stainless steel surface. The presence of nickel in high-chromium steels greatly improves their resistance to some nonoxygenating media. It is also an austenite stabilizer. Manganese can be used as a substitute for part of the nickel as an austenite stabilizer, although it does not significantly alter the corrosion resistance of high-chromium steels.

Molybdenum strengthens the passive film and improves resistance to pitting in seawater. Other elements such as copper, aluminum, and silicon also increase corrosion resistance of stainless steels.

CASE STUDY 4.6: CORROSION OF WELDED 304 STAINLESS STEEL TANK

PROBLEM

A food processing welded 304 stainless steel tank exhibited considerable pitting corrosion near the welded joints after 6 months of service.

ANALYSIS

Microscopic examination showed extensive precipitates in the affected areas. It is assumed that the precipitates are chromium carbides, which precipitated in the areas that were heated to the sensitizing temperature range (650°C–750°C). Precipitation of the carbides depleted the neighboring areas from chromium.

SOLUTION

It is recommended that 304L stainless steel be used. With its carbon content of <0.03%, there is less opportunity for chromium carbides to form during welding. Other possible solutions include using stabilized stainless steels, for example, 347 or 321.

4.7.6 NICKEL

Nickel has a relatively high corrosion resistance and is particularly useful for handling caustic alkalis. Nickel resists stress corrosion cracking (SCC) in chloride environments but may be susceptible in caustic environments if highly stressed and if it contains impurities in solution.

Inconel, 78/16/6 Ni–Cr–Fe, is resistant to many acids and has outstanding resistance to nitriding at high temperatures. Nimonic alloys, based on the 80/20 Ni–Cr basic composition, have particularly good combination of high strength and oxidation resistance at high temperatures. As shown in Table 4.10, Monel alloys, which are based on the 70/30 Ni–Cu composition, have similar resistance to pure nickel with the additional advantage of being less expensive and being able to handle seawater and brackish waters at high fluid velocities. Monel alloys present an economic means of handling hydrofluoric acid and are also resistant to other nonoxidizing acids. Monel alloys are not, however, resistant to oxidizing media such as nitric acid, ferric chloride, sulfur dioxide, and ammonia.

4.7.7 COPPER

Pure copper is a noble metal and is, therefore, highly corrosion resistant. It is especially compatible with most industrial, marine, and urban atmospheres, in addition to water and seawater, as shown in Table 4.10. When copper is alloyed with zinc in concentrations more than 15%, dezincification may occur in some environments. An addition of about 1% tin can reduce this problem. Tin bronzes are resistant to a variety of atmospheres, waters, and soils. Phosphorus is added to impart oxidation resistance. Aluminum bronzes, containing about 10% Al, are resistant to corrosion from chloride–potash solutions, nonoxidizing mineral acids, and many organic acids. Cupronickels are widely used in saltwater; they have excellent resistance to biofouling and SCC.

Key types are 90/10 (90% Cu, 10% Ni) for general marine use and 70/30 (70% Cu, 30% Ni) for high-corrosion naval applications.

4.7.8 TIN

Over half of the tin production is used as protective coatings of steels and other metals. In addition to its corrosion resistance, tin is nontoxic and it provides a good base for organic coatings. This explains its wide use in coating the steel cans, tin cans, used for the storage of food products and beverages. Tin is normally cathodic to iron, but the potential reverses in most sealed cans containing food products and the tin acts as a sacrificial coating, thus protecting steel. Tin is also resistant to relatively pure water and dilute mineral acids in the absence of air. This makes it suitable for coating copper pipes and sheets in contact with distilled water and medicaments. Tin is attacked by strong mineral acids and alkalis.

4.7.9 LEAD

A large proportion of lead production goes into applications where corrosion resistance is important, especially those involving sulfuric acid. The corrosion resistance of lead is due to the protective sulfates, oxides, and phosphates that form on its surface as a result of reaction with corrosive environments. Lead containing about 0.06% copper is usually specified for process equipment in contact with sulfuric, chromic, hydrofluoric, and phosphoric acids. It is also used for neutral solutions, seawater, and soils. Lead is attacked by acetic, nitric, hydrochloric, and organic acids.

4.7.10 ALUMINUM

Aluminum is a reactive metal, but it develops an aluminum oxide film that protects it from corrosion in many environments. The film is quite stable in neutral and many acid solutions but is attacked by alkalis. The aluminum oxide film is also resistant to a variety of organic compounds, including fatty acids. This oxide film forms in many environments, but it can be artificially produced by anodization.

Pure aluminum and nonheat-treatable aluminum alloys exhibit high resistance to general corrosion but, because of their dependence on the surface oxide film, are liable to suffer local attack under deposits and in crevices. Heat-treatable alloys in the 2000 series and those in the 7000 series contain copper and exhibit lower resistance to general corrosion, as shown in Table 4.10. Such alloys are used in applications where corrosion resistance is secondary to strength. The role played by crevice corrosion in causing failure of an aircraft is discussed in more detail in a reflection paper in Chapter 3.

4.7.11 TITANIUM

Titanium exhibits excellent corrosion resistance because of its stable, protective, strongly adherent surface oxide film. Titanium is immune to all forms of corrosive attack in seawater and chloride salt solutions at ambient temperatures and to hot, strong oxidizing solutions. It also has very high resistance to erosion corrosion in seawater.

4.7.12 PLASTICS AND FIBER-REINFORCED PLASTICS

Because of their corrosion resistance, plastics and composites have replaced metals in many applications. Examples from the automotive industry include fenders, hoods, and other body components. However, there are several environmental effects that should be considered when selecting plastics and FRP.

Several plastics absorb moisture, which causes swelling and distortion in addition to degrading their strength and electric resistance. Polymers can also be attacked by organic solvents, as discussed in Section 3.5 and as shown in Table 3.2. Generally, crystalline thermoplastics, such as fluorocarbons, Teflon, and nylon, have superior chemical stability than amorphous types like polycarbonate. Fluorocarbons, for example, PTFE, are among the most chemically inert materials available to the engineer. They are inert to all industrial chemicals, and they resist the attack of boiling aqua regia, fuming nitric acids, hydrofluoric acid, and most organic solvents. Other thermoplastics like polyketones and polyphenylene sulfide provide excellent chemical resistance, even at relatively elevated temperatures. Among thermosetting plastics, epoxies represent the best combination of corrosion resistance and mechanical properties.

4.7.13 CERAMIC MATERIALS

Most ceramic materials exhibit good resistance to chemicals, with the main exception of hydrofluoric acid. Glasses are among the most chemically stable materials, and they have exceptionally good resistance to attack by water, aqueous solutions of most acids, alkalis, and salts. Enamels, which are made of silicate and borosilicate glass with the addition of fluxes to promote adhesion, are highly resistant to corrosion and are widely used to protect steels and cast irons.

4.7.14 OTHER MEANS OF RESISTING CORROSION

Occasionally, no material may offer an economical combination of corrosion resistance and other performance requirements. In such cases, a low-cost base material that satisfies the mechanical and physical requirements can be selected provided that it is adequately protected against corrosion. Protection can take the form of sacrificial coatings, passivation, corrosion inhibitors, barrier coatings, or cathodic protection, as discussed in Section 3.7. Barrier coatings are also commonly used for protection against corrosion, and their selection is discussed in Section 4.8.

4.8 COATINGS FOR PROTECTION AGAINST CORROSION

Coatings are usually applied for one or more of the following purposes:

1. To modify the surface quality of color, brightness, reflectivity, or opacity
2. To provide protection against corrosion or oxidation
3. To provide protection against abrasion and wear
4. To provide electric and thermal conductivity or insulation

The following discussion is mainly concerned with the use of coatings for protection against corrosion. In such cases, protection against corrosion can be achieved in two ways:

1. Isolation of the surface from the environment
2. Electrochemical action

Isolation of the surface is usually performed by nonmetallic coatings, and in such cases, the thickness, soundness, and strength of the coating will control its effectiveness as an isolator. Nonmetallic coatings can be either inorganic, as in the case of vitreous enamels, or organic, as in the case of varnishes and lacquers. Electrochemical action is achieved with metallic coatings.

4.8.1 METALLIC COATINGS

4.8.2 ORGANIC COATINGS

4.8.3 VITREOUS ENAMELS

4.9 SELECTION OF MATERIALS FOR WEAR RESISTANCE

The main factors that influence the wear behavior of a material can be grouped as:

1. Metallurgical variables, including hardness, toughness, chemical composition, and microstructure
2. Service variables, including contacting materials, contact pressure, sliding speed, operating temperature, surface finish, lubrication, and corrosion

In general, hardness values provide an approximate guide to relative wear behavior among different materials. This is particularly true for applications involving metal-to-metal sliding. In such cases, increasing the hardness increases wear resistance as a result of decreasing penetration, scratching, and deformation. Increasing toughness also increases wear resistance by making it more difficult to tear off small particles of deformed metal.

4.9.1 WEAR-RESISTANT ALLOYS

Austenitic manganese steels are usually selected for applications where good abrasion resistance is important. An example is Hadfield steel, which contains 1.2% C and 12% Mn. These steels have superior toughness at moderate cost. They have excellent resistance to metal-to-metal wear, as in sheave wheels, rails, and castings for railway track work. Manganese steels are also valuable in conveyors and chains subjected to abrasion and used for carrying heavy loads.

Gray cast iron (GCI) has adequate wear resistance for applications such as slideways of machine tools and similar sliding members. Better wear resistance is achieved with white pearlitic and martensitic irons, which are used in chilled iron rolls and grinding balls.

A World War I M1917, made from Hadfield steel

Alpha aluminum bronzes, with about 7% aluminum, are soft and ductile and are used for press guides and wear plates. Increasing the aluminum content increases the hardness and abrasion resistance but lowers conformability and embeddability of these alloys when used as sleeves for sliding bearings. This subject is discussed in more detail in Chapter 11, case study on material selection for lubricated journal bearing. Beryllium–copper alloys are among the hardest and strongest of all copper alloys. Properly lubricated, they have better wear resistance than other copper alloys and many ferrous alloys. An alloy containing 1.9% Be, 0.2% Co, and rest Cu is usually specified for wear applications, and it has better load-carrying capacity than all other copper-based alloys. In addition, beryllium coppers exhibit excellent corrosion resistance in industrial and marine atmospheres.

Wrought cobalt-based wear-resistant alloys, such *as* Stellite and Haynes alloys, have excellent resistance to most types of wear in addition to good resistance to impact and thermal shock, heat and oxidation, corrosion, and high hot hardness.

4.9.2 WEAR-RESISTANT PLASTICS

Wear-resistant, self-lubricating plastics are favorably competing with metals in many applications including bearings, cams, and gears. In addition to ease of manufacture, these plastics have better lubricating properties and need less maintenance. Wear-resistant plastics are formulated with internal lubricating agents and are available in both unreinforced and reinforced versions. A combination of lubricating additives is usually employed to achieve optimum wear resistance. For example, silicone and PTFE are usually added to thermoplastics to improve their performance at high speeds and pressures. Carbon and aramid fibers, which are usually added for mechanical reinforcement, are also known to improve wear resistance.

4.9.3 WEAR-RESISTANT CERAMICS

Ceramics can be used in a variety of applications where wear resistance is required. The wear behavior of ceramics is determined by the nature of the mating surfaces and the presence of surface films. In general, as the grain size and porosity of the ceramic material increases, wear increases. The presence of surface films, such as water and oils, can affect adhesion and wear. For example, wear of partially stabilized zirconia increases in aqueous environments but decreases in fatty acids such as stearic acid. For engines and similar applications, SiC against lubricated steel has lower friction and less scuffing than chilled cast iron, which makes it suitable for engine valves, train components, and bearings.

4.9.4 SURFACE TREATMENTS AND WEAR-RESISTANT COATINGS

Because wear is a surface phenomenon, surface treatments and coatings play an important role in combating it. Surface treatment avoids having to make the entire part of a wear-resistant material, which may not provide all the other functional requirements or may be more expensive. Surface treatments include the following:

- Surface heat treatment, as in the case of flame and induction heating, allows hardening of the surface without affecting the bulk of the material (Table 4.11).
- Surface alloying, as in the case of carburizing, cyaniding, nitriding, and carbonitriding, increases the hardness of the surface by increasing its carbon and nitrogen content (Table 4.11).

TABLE 4.11
Surface Hardening Treatments for Steels

Process	Treatment	Applications
Flame hardening	Heat the surface using torch, then quench	Hardened depth is 0.5–6 mm. Used for gear teeth, crankshafts, and axles
Induction hardening	Heat the surface using high-frequency induction current, then quench	
Carburizing: Increasing carbon content of the surface	Heat component at 850°C–950°C in a carbon-rich gas or solid, then quench	Hardened depth is 0.5–1.5 mm. Used for gear teeth, cams, shafts, bolts, and nuts
Cyaniding: Increasing carbon and nitrogen content of the surface	Heat component at 700°C–850°C in a cyanide-rich salt bath, for example, sodium cyanide, then quench	Hardened depth is 0.02–0.3 mm. Used for small gears, bolts, and nuts
Nitriding: Increasing nitrogen content of the surface	Heat component at 500°C–650°C in ammonia gas	Hardened depth is 0.05–0.6 mm. Used for gears, shafts, and tools
Carbonitriding: Increasing carbon and nitrogen content of the surface	Heat component at 700°C–850°C in a mixture of carbon-rich and ammonia gases, then quench	Hardened depth is 0.05–0.6 mm. Used for gears, tools, and nuts

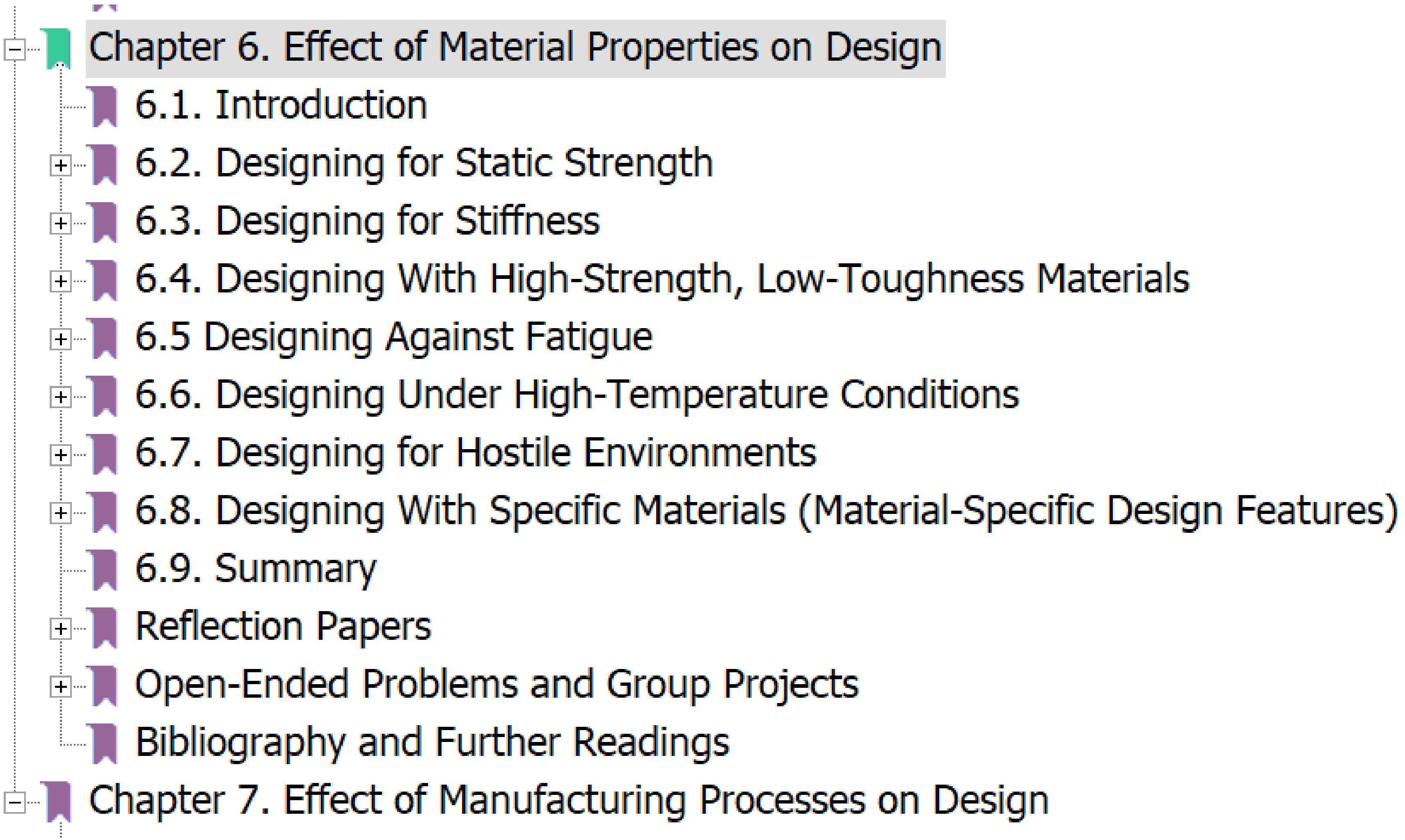
Surface coatings consist of wear-resistant materials that are applied to the surface for protection against wear. These coats may be applied to new parts made of soft materials to improve their resistance to wear or to worn parts to restore them to serviceable condition. The selection of hard-facing alloys for a given application is guided primarily by wear and cost considerations. However, other factors, such as impact resistance, corrosion and oxidation resistance, and thermal requirements, should also be considered. Most hard-facing alloys are marketed as proprietary materials and are classified as follows:

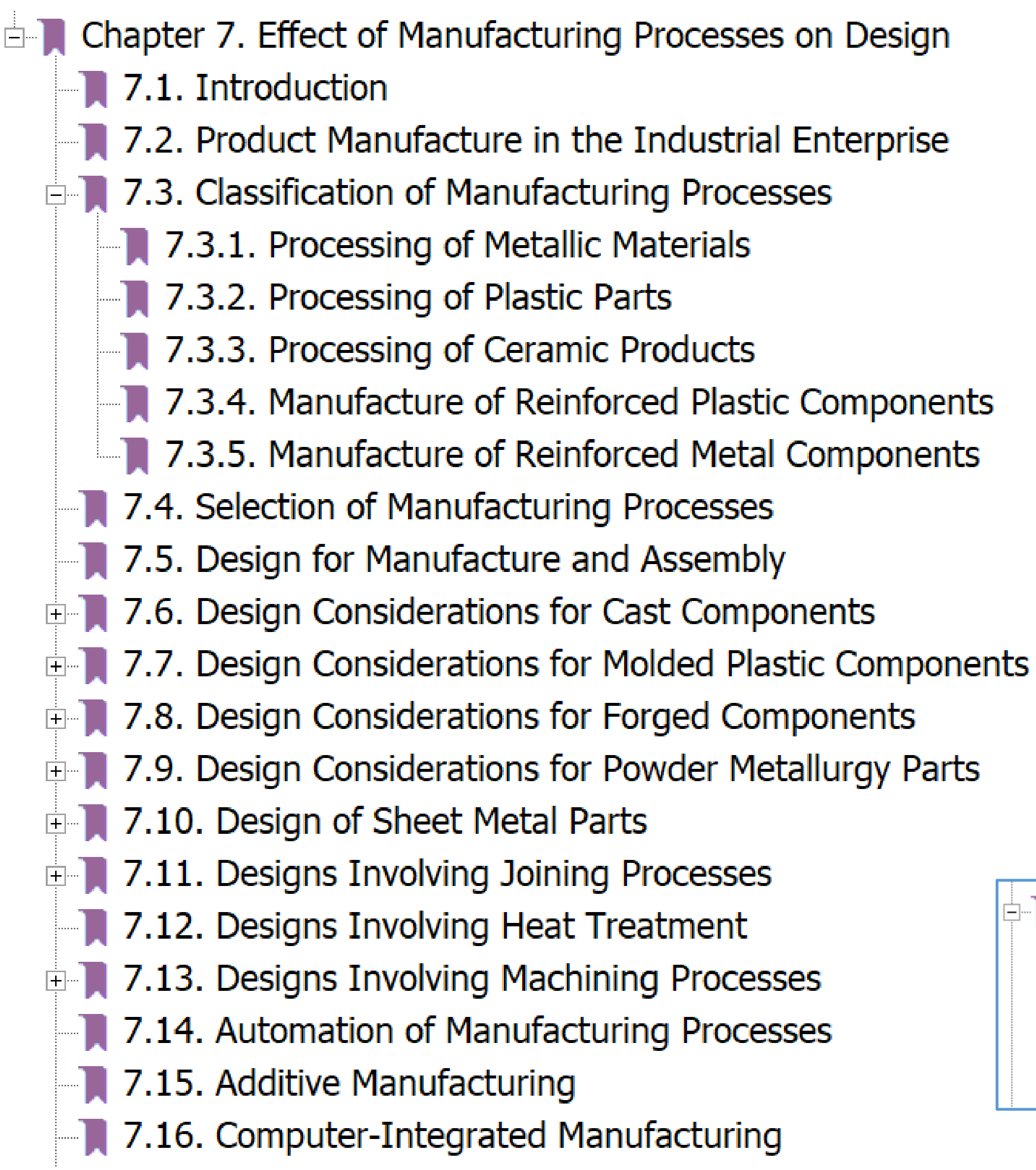
- Low-alloy steels (group 1)
- High-alloy ferrous materials (groups 2 and 3)
- Nickel-based and cobalt-based alloys (group 4)
- Carbides (group 5)

Generally, both wear resistance and cost increase as the group number increases.

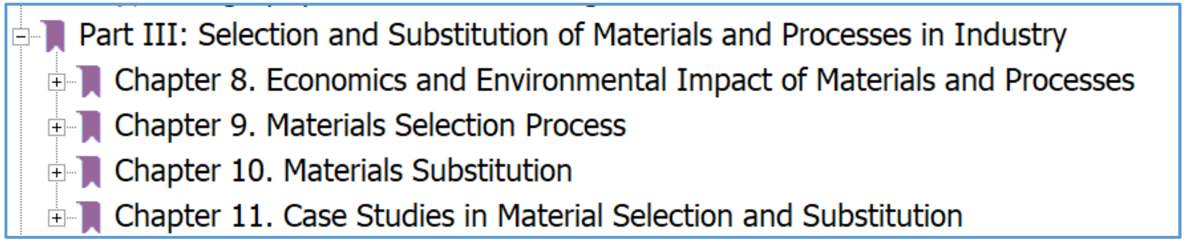
In spite of the widespread use of surface treatments and surface coatings to combat wear, these solutions are not without problems. Not all materials or parts can be surface treated, and surface coatings can fail by spalling. In many applications, wear problems are solved, wholly or in part, by the proper selection of materials, as discussed in the following sections.

- Part II: Relationships between Design, Materials, and Manufacturing Processes
  - Chapter 5. Nature of Engineering Design
    - 5.1. Introduction
    - 5.2. General Considerations in Engineering Design
    - 5.3. Design for Six Sigma
    - 5.4. Major Phases of Design
    - 5.5. Environmentally Responsible Design
    - 5.6. Design Codes and Standards
    - 5.7. Effect of Component Geometry
    - 5.8. Factor of Safety
    - 5.9. Reliability of Components
    - 5.10. Product Liability
    - 5.11. Summary
    - Reflection Papers
    - Open-Ended Problems and Group Projects
    - Bibliography and Further Readings
    - Websites
  - Chapter 6. Effect of Material Properties on Design





- Chapter 7. Effect of Manufacturing Processes on Design
  - 7.1. Introduction
  - 7.2. Product Manufacture in the Industrial Enterprise
  - 7.3. Classification of Manufacturing Processes
    - 7.3.1. Processing of Metallic Materials
    - 7.3.2. Processing of Plastic Parts
    - 7.3.3. Processing of Ceramic Products
    - 7.3.4. Manufacture of Reinforced Plastic Components
    - 7.3.5. Manufacture of Reinforced Metal Components
  - 7.4. Selection of Manufacturing Processes
  - 7.5. Design for Manufacture and Assembly
  - 7.6. Design Considerations for Cast Components
  - 7.7. Design Considerations for Molded Plastic Components
  - 7.8. Design Considerations for Forged Components
  - 7.9. Design Considerations for Powder Metallurgy Parts
  - 7.10. Design of Sheet Metal Parts
  - 7.11. Designs Involving Joining Processes
  - 7.12. Designs Involving Heat Treatment
  - 7.13. Designs Involving Machining Processes
  - 7.14. Automation of Manufacturing Processes
  - 7.15. Additive Manufacturing
  - 7.16. Computer-Integrated Manufacturing



- Part III: Selection and Substitution of Materials and Processes in Industry
  - Chapter 8. Economics and Environmental Impact of Materials and Processes
  - Chapter 9. Materials Selection Process
  - Chapter 10. Materials Substitution
  - Chapter 11. Case Studies in Material Selection and Substitution

7 Effect of Manufacturing Processes on Design

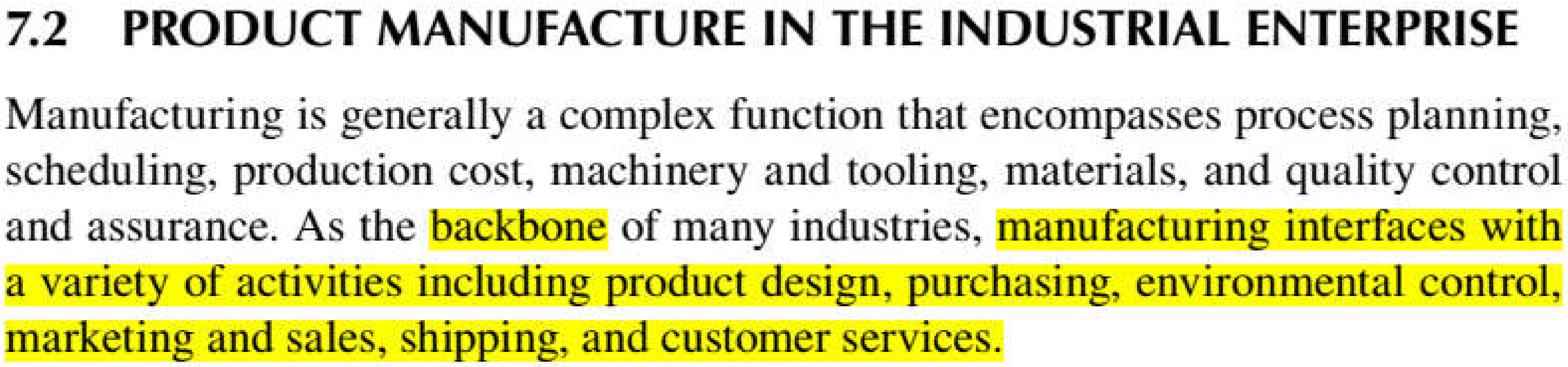
7.1 INTRODUCTION

Manufacturing can be defined as the act of transforming materials into usable and saleable end products. This means that the products must function satisfactorily and provide value for money. The cost, rate of production, availability, and quality of product are important criteria that should be considered when selecting a manufacturing process. With the increasing sophistication of many products and the increasing range of available materials, new manufacturing technologies have been developed to produce more sound and accurate components economically.

The introduction of automation, computers, robots, and 3D printing in manufacturing processes has been of great help to industry in producing better products more economically as they improve productivity, increase product quality and uniformity, and reduce labor cost. The integration of these elements in computer-integrated manufacturing (CIM) allows manufacturers to respond rapidly to market demand and product modification and to exercise better control of production operations, as well as better utilization of materials, machines, and human resources.

The goal of this chapter is to illustrate how the manufacturing processes influence the design of components, with emphasis on the following topics:

1. Types of available manufacturing processes and their selection
2. Design for manufacture and assembly (DFMA)
3. Design considerations for cast components
4. Design considerations for molded plastic components
5. Design considerations for forged components
6. Design considerations for P/M parts
7. Designs involving welding processes
8. Designs involving machining processes
9. Additive manufacturing (AM)
10. Automation of manufacturing processes and CIM



7.2 PRODUCT MANUFACTURE IN THE INDUSTRIAL ENTERPRISE

Manufacturing is generally a complex function that encompasses process planning, scheduling, production cost, machinery and tooling, materials, and quality control and assurance. As the backbone of many industries, manufacturing interfaces with a variety of activities including product design, purchasing, environmental control, marketing and sales, shipping, and customer services.

It is now widely recognized that **design, material selection, and manufacturing** are intimately related activities that cannot be performed in isolation of one another.

7.3 CLASSIFICATION OF MANUFACTURING PROCESSES

7.3.1 PROCESSING OF METALLIC MATERIALS

The relationship between the different manufacturing processes that are normally used in processing metallic materials can generally be presented as shown in Figure 7.1. Most metallic materials are found in nature in the form of ores, which have to be reduced or refined and then cast as ingots of convenient size and shape for further processing. Casting processes involve pouring the liquid metal, or alloy, into a mold cavity and allowing it to solidify. Powdered materials can be shaped by pressing in suitably shaped dies and then sintering, heating, to achieve the required properties. An important advantage of casting and P/M processes is that parts of complex shapes can be obtained in one step.

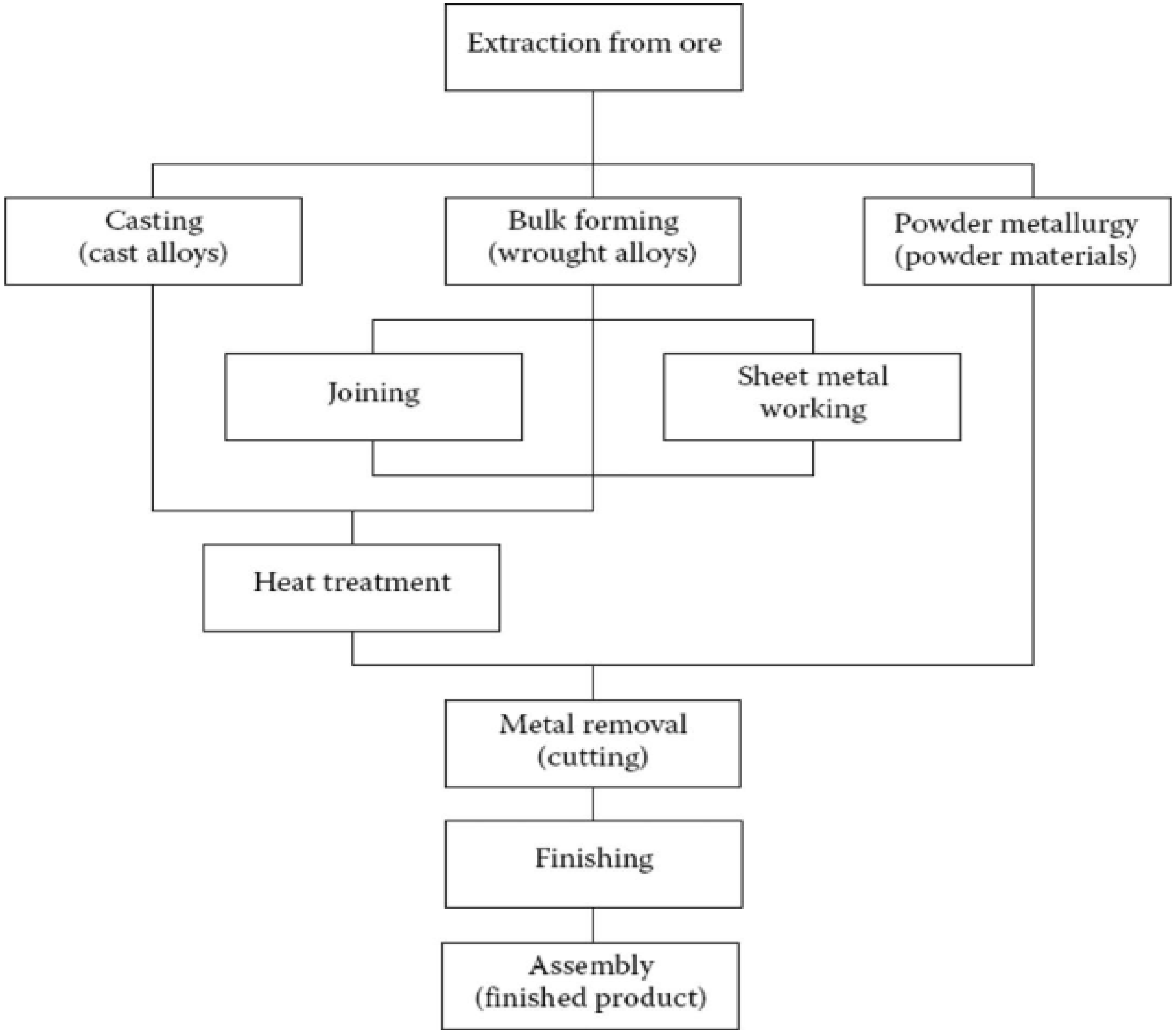


FIGURE 7.1 Types and usual sequence of manufacturing processes that are normally used in processing metallic materials.

Bulk forming processes are generally used to change the shape of metallic materials by plastic deformation. The deformation can be carried out at relatively high temperatures, as in the case of hot working processes, or at relatively low temperatures, as in the case of cold working processes. The basic bulk deformation processes are forging; rolling; extrusion; swaging; and drawing of rod, wire, and tube. These processes are called primary working when applied to ingots to break down their cast structure into wrought structure and to change their shape to slabs, plates, or billets. Secondary working involves further processing of the products from primary working into final or semifinal shapes.

Sheet metal working processes are normally carried out at room temperature and usually involve the change of sheet form without greatly affecting its thickness. The basic sheet metal working processes include shearing, bending, stretch forming, bulging, deep drawing, spinning, and press forming. Other sheet metal forming operations have been developed for the manufacture of certain components and special materials.

Heat treatment is normally carried out to control the structure and properties of the material. By proper control of temperature and cooling rate, the material can be softened to permit further processing or hardened to increase its mechanical strength. Heat treatment can also be used to remove internal stresses, control grain size, or produce a hard surface on a ductile interior. With the proper heat treatment, a less expensive material could replace a more expensive material or a less costly processing could be employed.

Material removal or cutting processes are normally used to remove unwanted material in the form of chips by using cutting tools, which are mounted in machine tools. The traditional, basic machine tools are lathes, boring machines, shapers and planers, milling machines, drill presses, saws, broaches, and grinding machines. The productivity in cutting processes can be improved by using machining centers, which are single machines that can perform the functions of several basic machine tools. When cutting very hard metals or when machining intricate shapes and delicate parts, nontraditional or chipless processes can be used. These cutting methods include ultrasonic, electric discharge, electrochemical, chemical milling, abrasive jet, electro arc, plasma arc, electron beam, and laser cutting.

AM, sometimes called 3D printing, is a relatively newcomer to the manufacturing industry and covers a wide range of technologies that build 3D objects by adding successive layers of the material. With appropriate computer control, complex shapes can be created without the need for dies or molds, which makes it possible to tailor-make each manufactured part separately.

In many cases, products are manufactured as separate units and then assembled either by fastening, as in the case of temporary or semipermanent joints, or by joining, as in the case of permanent joints. Examples of fastening methods include screws, bolts, and rivets, whereas joining methods include welding, brazing, soldering, and adhesive bonding. Assembling by press and shrink fitting is also used in some applications. Finishing processes are normally used to control the quality of the surface and to make it ready for service. Cleaning, deburring and polishing, anodizing, tinning, galvanizing, plating, and painting are among the frequently used finishing processes. In addition to controlling the appearance of the surface, many of the finishing processes provide some protection against corrosion.

7.3.2 PROCESSING OF PLASTIC PARTS

There are many methods of manufacturing plastic parts, which can be considered as molding processes. These processes usually employ the following sequence of steps:

1. Plastics in the form of powder, pellets, or granules are usually heated above the softening point.
2. The molten plastic is forced or placed into a mold that determines the dimensions of the molded part.
3. The material is then allowed to harden, by curing or freezing, and is then ejected from the mold.
4. In some molding processes, the ejected part is ready for use. With others, trimming and other finishing processes are necessary to make it ready for use.

Pressure-molding processes cover compression molding, transfer molding, and injection molding. These processes are similar in some ways to die-casting processes used for metals. It should be noted, however, that molten plastics are more viscous and much less conducting to heat than metals. These differences are reflected in the design and operation of the plastic-molding machines.

7.3.3 PROCESSING OF CERAMIC PRODUCTS

The raw materials used for making ceramic parts are usually in the form of particles or powder. After mixing and blending the appropriate ingredients, processing is carried out either in a dry, semidry, or liquid state and either cold or hot condition. Forming processes include slip casting, molding, jiggering, extrusion, and pressing. After forming the plastic ceramic mass into the required shape, it is dried to remove the water and then fired to sinter the ceramic powder into a final product.

7.3.4 MANUFACTURE OF REINFORCED PLASTIC COMPONENTS

Thermoplastics that are reinforced with short-chopped, randomly oriented fibers are easily fabricated using conventional techniques of injection molding and extrusion.

Composites based on thermosetting plastics are processed using specially developed methods like

1. Contact molding, which employs single-surface molds as in the case of hand layup, spray-up, and filament winding.
2. Compression-type molding, as in the case of sheet molding, bulk molding, preform molding, and cold molding.
3. Resin-injection molding, which is similar to the process used for nonreinforced materials and reinforced thermoplastics.
4. Pultrusion, which is a modification of the extrusion process.

7.3.5 MANUFACTURE OF REINFORCED METAL COMPONENTS

MMCs can be prepared in a variety of ways, which can be broadly classified into the following:

1. Processes based on solid-state diffusion
2. Liquid-phase infiltration
3. *In situ* processes

Selection of the appropriate process is a function not only of the required shape and properties of the composite but also of the fiber–matrix combination.

7.4 SELECTION OF MANUFACTURING PROCESSES

Figure 5.1 shows that in addition to having a direct influence on the design of components, manufacturing processes are also closely related to the material out of which the component is made and to its function and shape. The importance of manufacturing processes is further emphasized in Figure 6.1, where it is shown that the behavior of the material in the component is not only a function of the stock material properties but is also strongly influenced by the fabrication method. Such intimate relations between manufacturing processes, material properties, and design have led to widely used practice of concurrent, or simultaneous, engineering in product development. As the design progresses from concept to configuration and the material choices get narrower, manufacturing processes, which have initially been broadly defined, also need to be better identified. Successful product development requires a good match between the capabilities and limitation of the manufacturing process and the component attributes, which include its size, geometrical features, number required, and the type of material used.

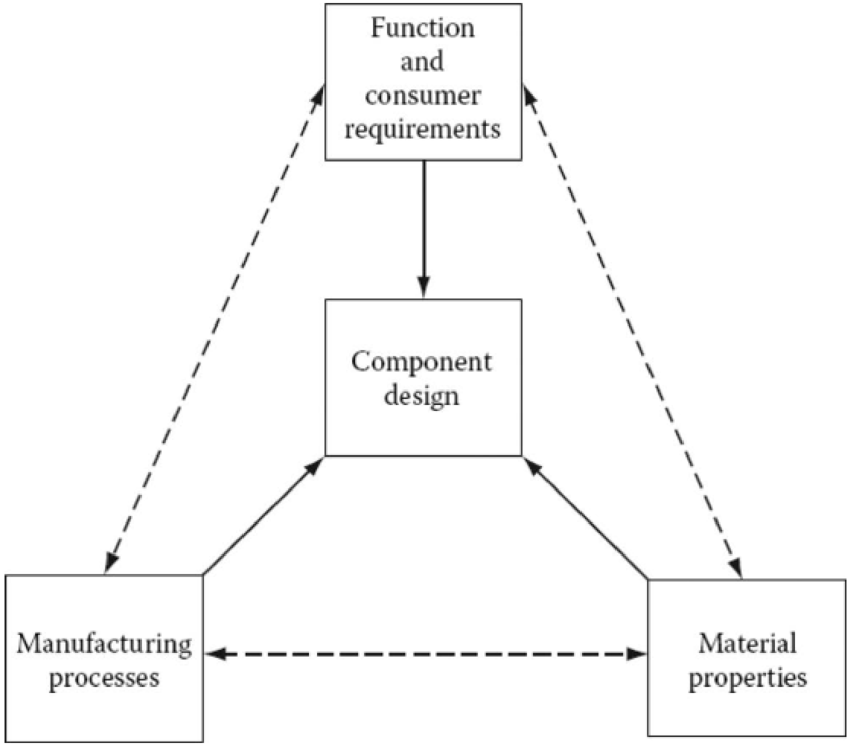


FIGURE 5.1 Factors that should be considered in component design.

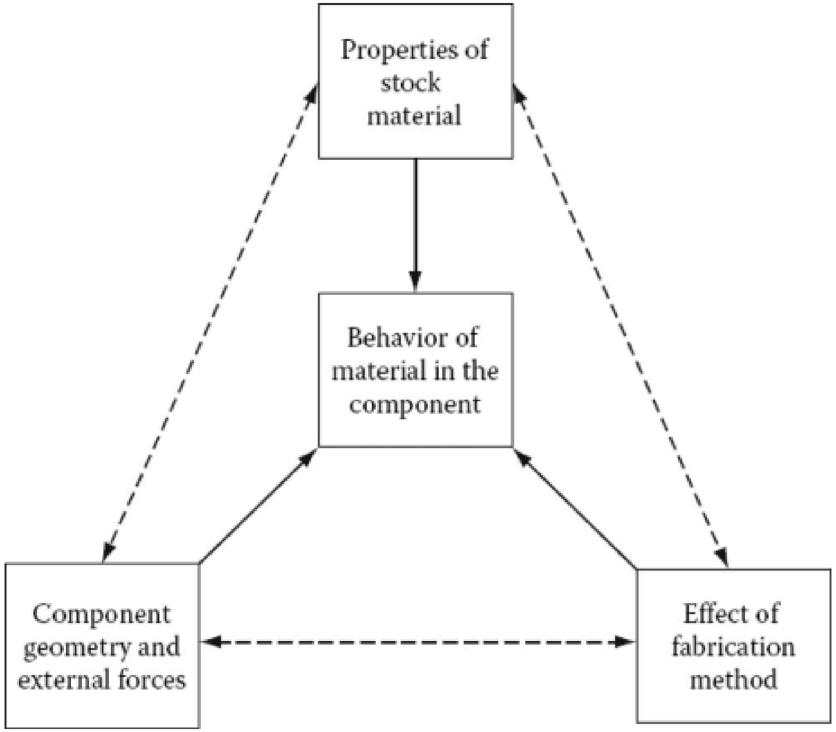


FIGURE 6.1 Factors that should be considered in anticipating the behavior of a material in the component.

As most components require a sequence of processes for their manufacture, there will be hundreds of possible process combinations, which can be used to make a given part. The choices can be narrowed down based on the following:

1. Screening based on component material group because not all processes are suitable for all materials. For example, cast iron cannot be forged and P/M is uneconomical for a limited production run. Table 7.1 outlines the compatibility between some widely used metallic materials and processes; further details appear throughout this chapter.
2. Screening based on component shape because manufacturing processes also have limitations on the shapes they can produce. For example, wires and sheets cannot be produced by casting and 3D shapes cannot be produced by rolling or extrusion. Table 7.2 shows the compatibility between shapes and manufacturing processes.
3. Screening based on the required number of components because the most economical batch size varies from one manufacturing process to another. For example, the number of components produced by P/M or die casting has to be large enough to justify the high cost of dies. Table 7.2 gives the economic batch sizes for some manufacturing processes.

TABLE 7.1
Compatibility between Some Widely Used Metallic Materials and Processes

	Carbon Steel	Stainless Steel	Cast Iron	Aluminum Alloys	Copper and Alloys	Magnesium and Alloys	Zinc and Alloys	Titanium and Alloys	Superalloys
Sand casting	XX	XX	XX	XX	XX	XX	X	Nr	XX
Investment casting	XX	XX	Nr	XX	XX	X	Nr	X	XX
Die casting	Nr	Nr	Nr	XX	X	XX	XX	Nr	Nr
P/M	XX	XX	Nr	XX	XX	Nr	Nr	X	XX
Forging	XX	XX	Nr	XX	XX	XX	Nr	X	X
Rolling	XX	XX	Nr	XX	XX	XX	X	X	XX
Extrusion	X	X	Nr	XX	XX	XX	X	X	X
Sheet metal work	XX	XX	Nr	XX	XX	X	X	X	X
Cold heading	XX	XX	Nr	XX	XX	Nr	Nr	Nr	X
Metal cutting	XX	XX	XX	XX	XX	XX	XX	X	X
Fusion welding	XX	XX	X	XX	XX	XX	Nr	XX	XX

Note: XX = common practice, X = less common or performed with difficulty, and Nr = not recommended.

TABLE 7.2

Economic Batch Size and Compatibility between Product Shape and Manufacturing Processes

		3D (Similar Dimensions in All Directions)		Prismatic (1D Much Longer than the Other 2Ds)		Sheet (1D Much Shorter than the Other 2Ds)	
	Economic Batch Size	**Solid**	**Hollow**	**Circular Cross Section**	**Noncircular Cross Section**	**Flat**	**Cupped**
Sand casting	1–1000	XX	XX	XX	XX	Nr	Nr
Investment casting	50–1000	XX	XX	XX	XX	Nr	Nr
Die casting	>10,000	XX	XX	XX	XX	Nr	Nr
P/M	>5000	XX	XX	XX	XX	Nr	Nr
Forging	1–10,000	XX	Nr	XX	XX	Nr	Nr
Rolling	N/A	Nr	Nr	XX	XX	XX	Nr
Extrusion	N/A	Nr	Nr	XX	XX	Nr	Nr
Sheet metal work	>50,000	Nr	Nr	XX	XX	XX	XX
Cold heading	1–10,000	XX	Nr	XX	XX	X	X
Metal cutting	N/A	XX	XX	XX	XX	XX	XX
Fusion welding	N/A	XX	XX	XX	XX	XX	XX
Injection molding	>10,000	XX	XX	Nr	Nr	Nr	Nr
Blow molding	>100,000	Nr	XX	Nr	Nr		
Compression molding	>5000						

Note: N/A = does not apply, XX = common practice, X = less common or performed with difficulty, Nr = not recommended.

4. Many processes form a natural sequence for shape generation, surface finish or dimensional accuracy. For example, casting and forging are normally followed by machining and then surface finishing, if needed, as shown in Figure 7.1. From this point of view, processes can be grouped as follows:

   a. Primary processes, including casting (sand casting, investment casting and die casting, etc.), bulk forming (forging, rolling, extrusion, etc.).
   b. Primary/secondary processes, including joining and welding, sheet metal work, heat treatment, and metal cutting.
   c. Tertiary processes or finishing processes, including surface treatment, grinding, and coating.

CASE STUDY 7.1: PROCESS SELECTION FOR A CONNECTING ROD

PROBLEM

It is required to select the optimum sequence of manufacturing processes for a connecting rod for an internal combustion engine for use in a motorcar, as shown in Figure 7.2. The distance between centers of the big end and small end normally ranges between 140 and 180 mm and the weight can range from 600 to 900 g for steel connecting rods. The numbers produced in connecting rod batches are normally in the tens of thousands.

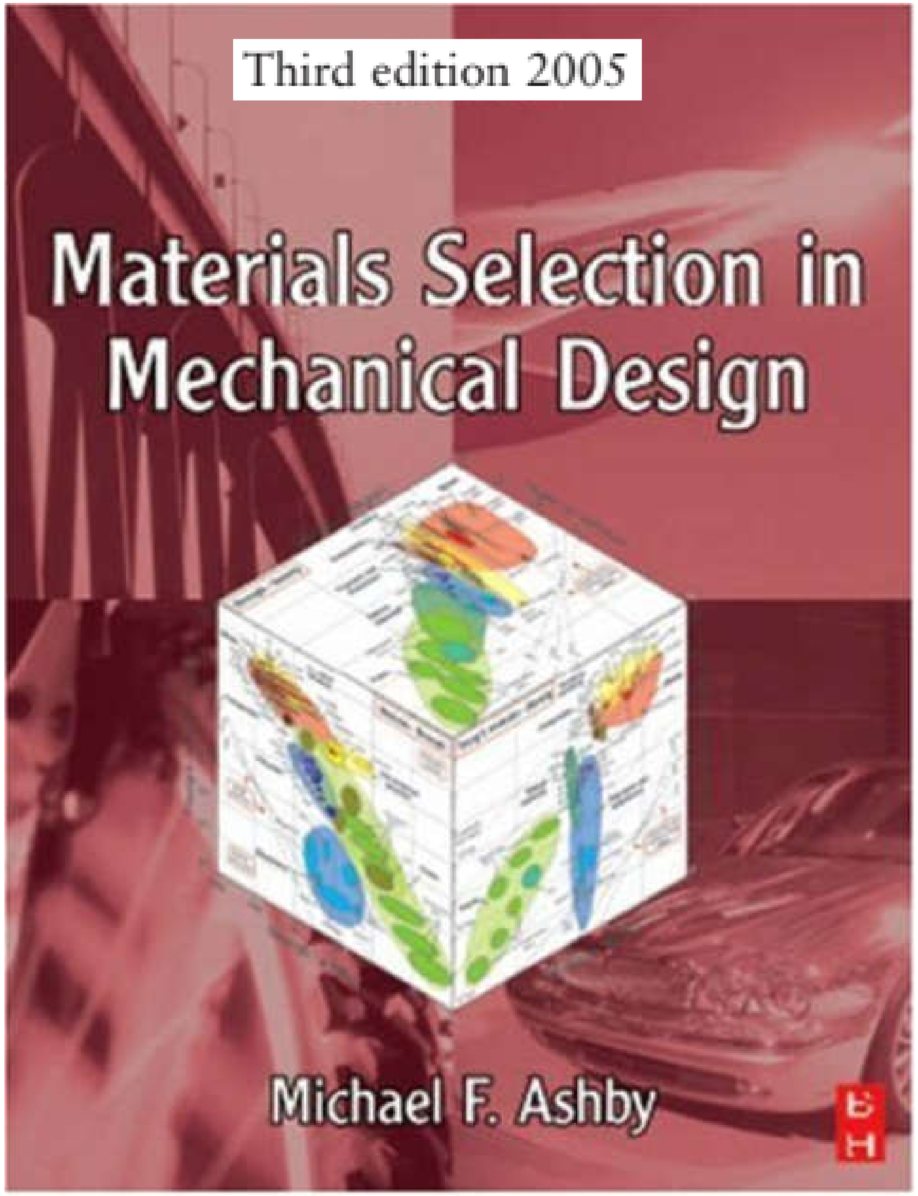
ANALYSIS

The most important mechanical property for the connecting rod material is fatigue resistance. Experience has shown that wrought components have better fatigue properties than cast components. Normally steels, such as AISI 4340 and C-70, are used for making motorcar connecting rods. Cast irons, such as

ductile irons, were used in the past, but steels give better fatigue resistance and are lighter. Aluminum alloys, titanium and magnesium alloys are used in high performance and racing cars where weight reduction is at a premium. The current practice for splitting the big end to allow insertion around the crank pin is to make a groove and fracture the rod. The halves are then easily assembled and the hole of the big end remains circular. Using a cutting process to split the big end results in a noncircular hole due to loss of material at the cut surfaces. Also the parting surfaces have to be finished to a high degree to allow accurate assembly.

PRIMARY PROCESS SELECTION

From Tables 7.1 and 7.2, the most suited primary processes for making 3D solid components, such as the connecting rod, are casting, P/M, and forging. Since cast irons are no longer used in making connecting rods, casting processes will be eliminated. Both P/M and forging processes are suitable for steel connecting rods and are used in practice. The powder process is competitive in spite of the higher cost of material, as it has less waste, requires less machining, and consumes less energy in manufacture.



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Materials Selection in Mechanical Design

Michael F. Ashby

A *process* is a method of shaping, joining, or finishing a material. *Sand casting*, *injection molding*, *fusion welding*, and *electro-polishing* are all processes; there are hundreds of them. It is important to choose the right process-route at an early stage in the design before the cost-penalty of making changes becomes large. The choice, for a given component, depends on the material of which it is to be made, on its size, shape and precision, and on how many are to be made — in short, on the *design requirements*. A change in design requirements may demand a change in process route.

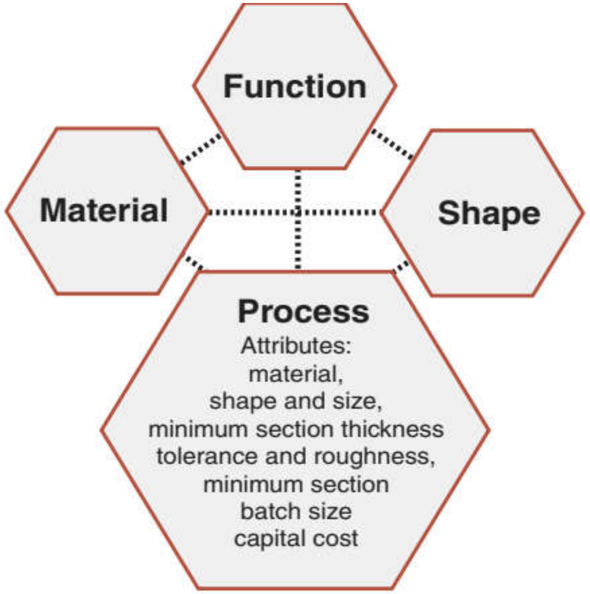


Figure 7.1 Processing selection depends on material and shape. The "process attributes" are used as criteria for selection.

7.2 Classifying processes

Manufacturing processes can be classified under the headings shown in Figure 7.2. *Primary processes* create *shapes*. The first row lists seven primary forming processes: casting, molding, deformation, powder methods, methods for forming composites, special methods, and rapid prototyping. *Secondary processes* modify shapes or properties; here they are shown as "machining", which adds features to an already shaped body, and "heat treatment, which enhances surface or bulk properties. Below these comes *joining*, and, finally, *finishing*.

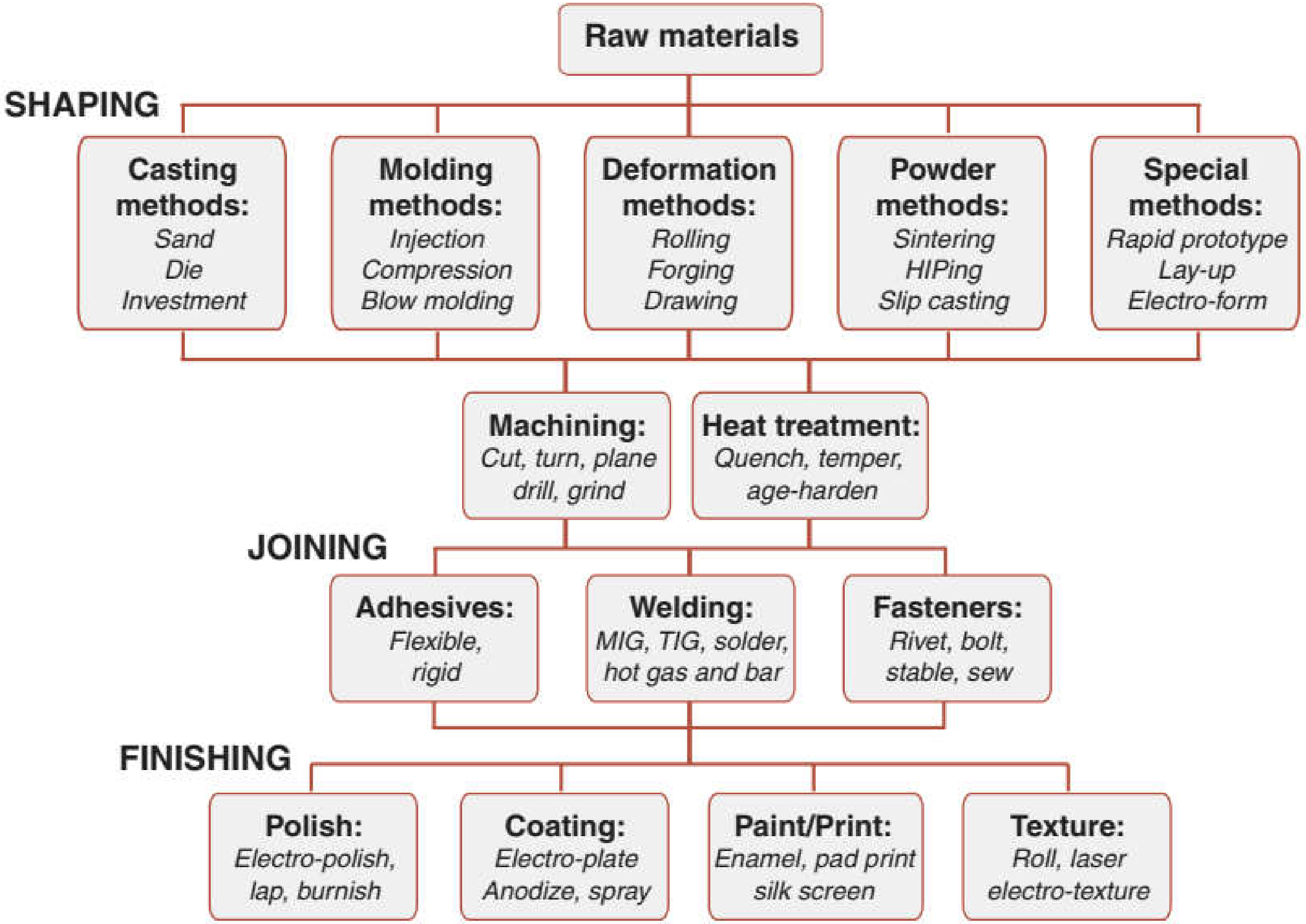


Figure 7.2 The classes of process. The first row contains the primary shaping processes; below lie the secondary processes of machining and heat treatment, followed by the families of joining and finishing processes.

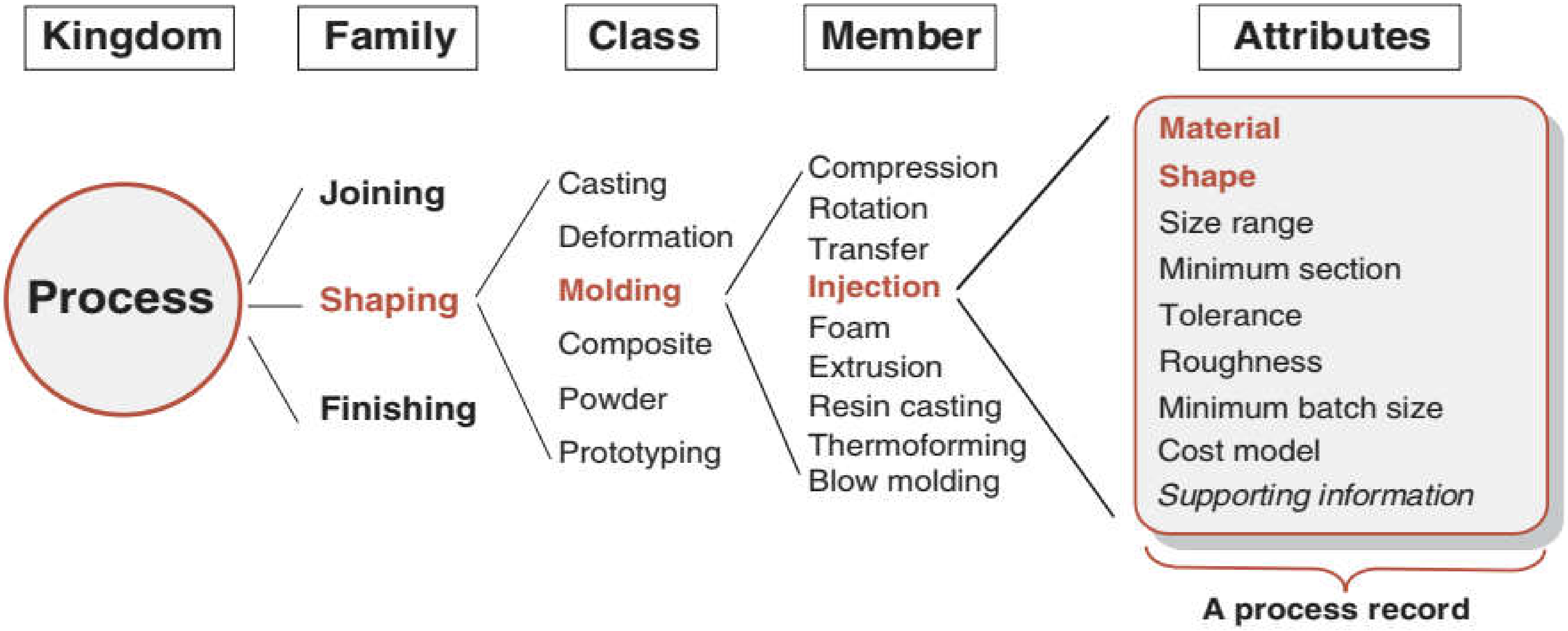


Figure 7.3 The taxonomy of the kingdom of process with part of the *shaping* family expanded. Each member is characterized by a set of attributes. Process selection involves matching these to the requirements of the design.

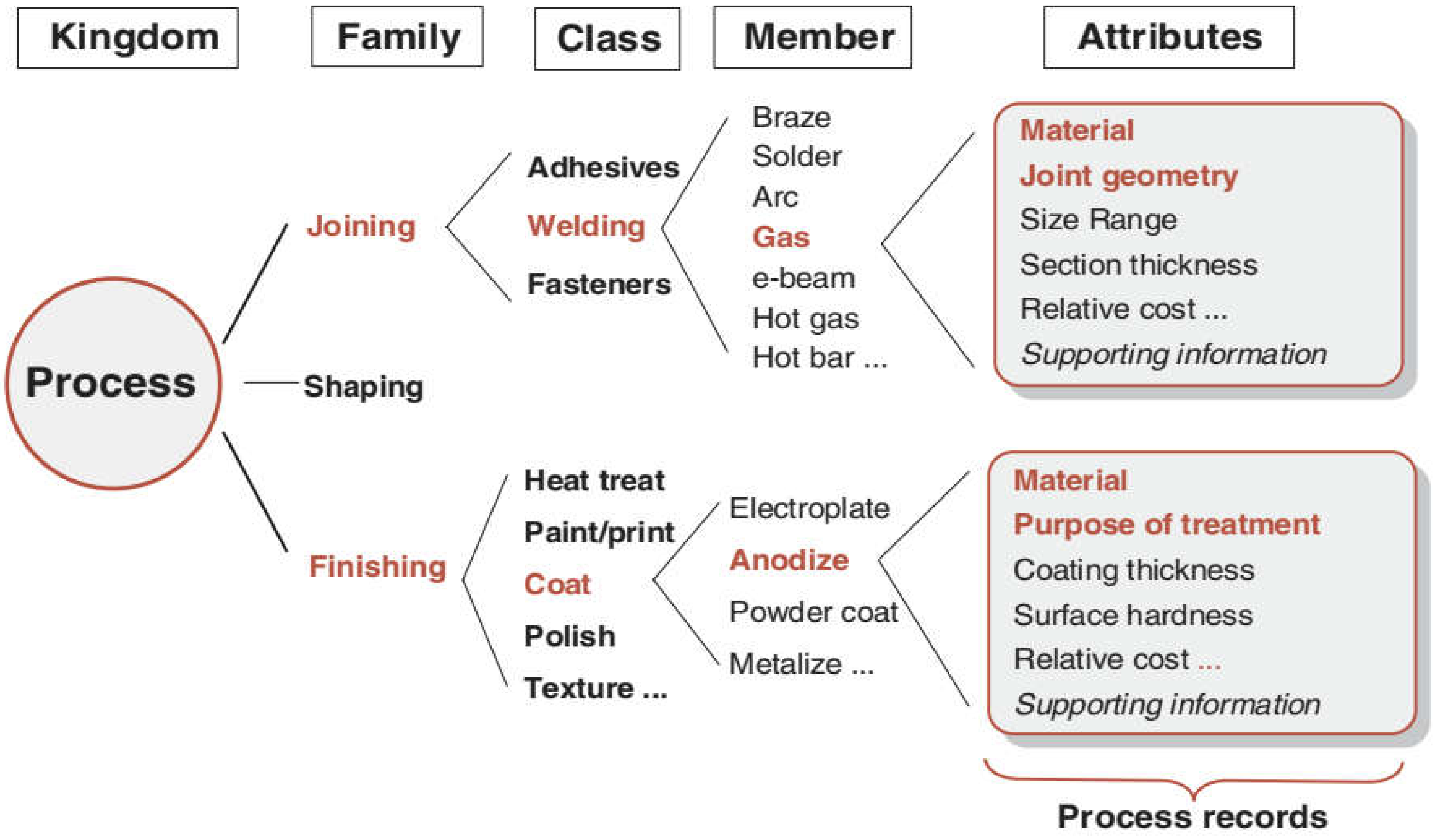
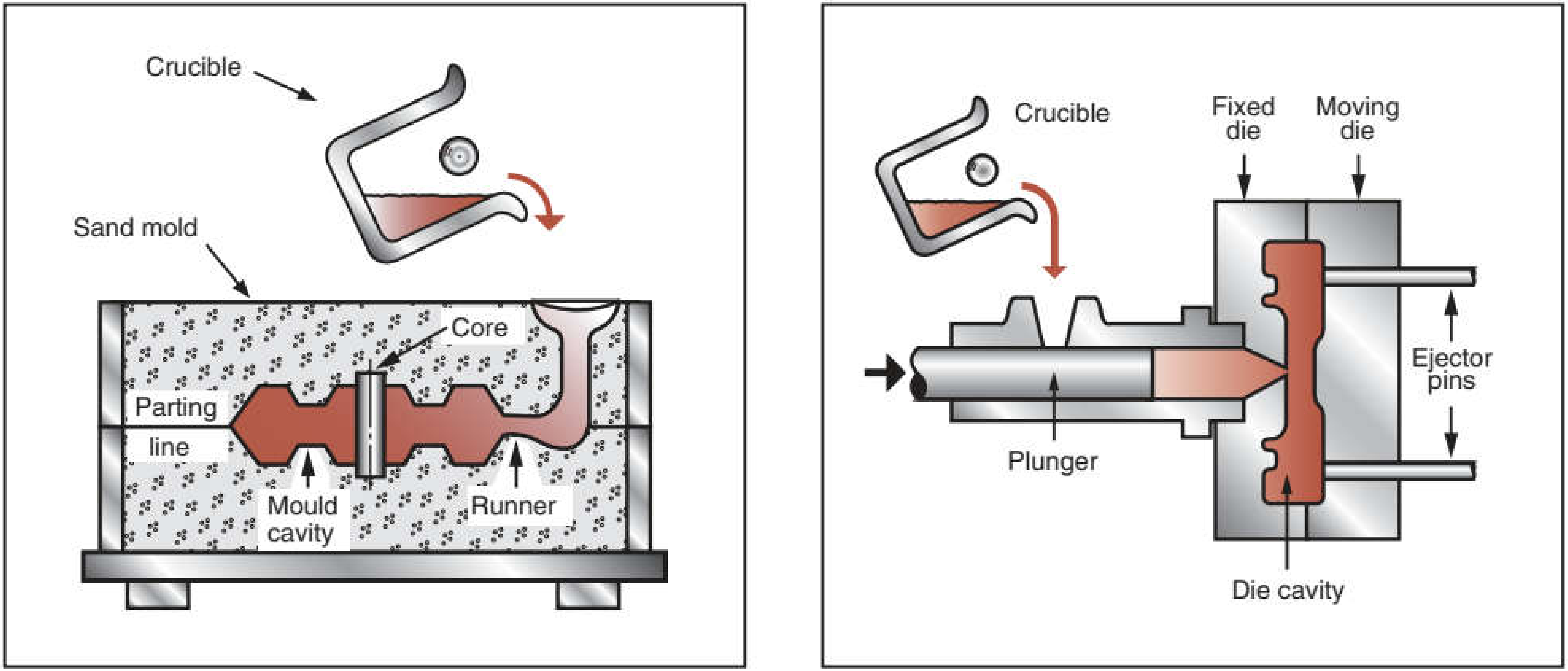


Figure 7.4 The taxonomy of the process kingdom again, with the families of *joining* and *finishing* partly expanded.

7.3 The processes: shaping, joining, and finishing

Shaping processes

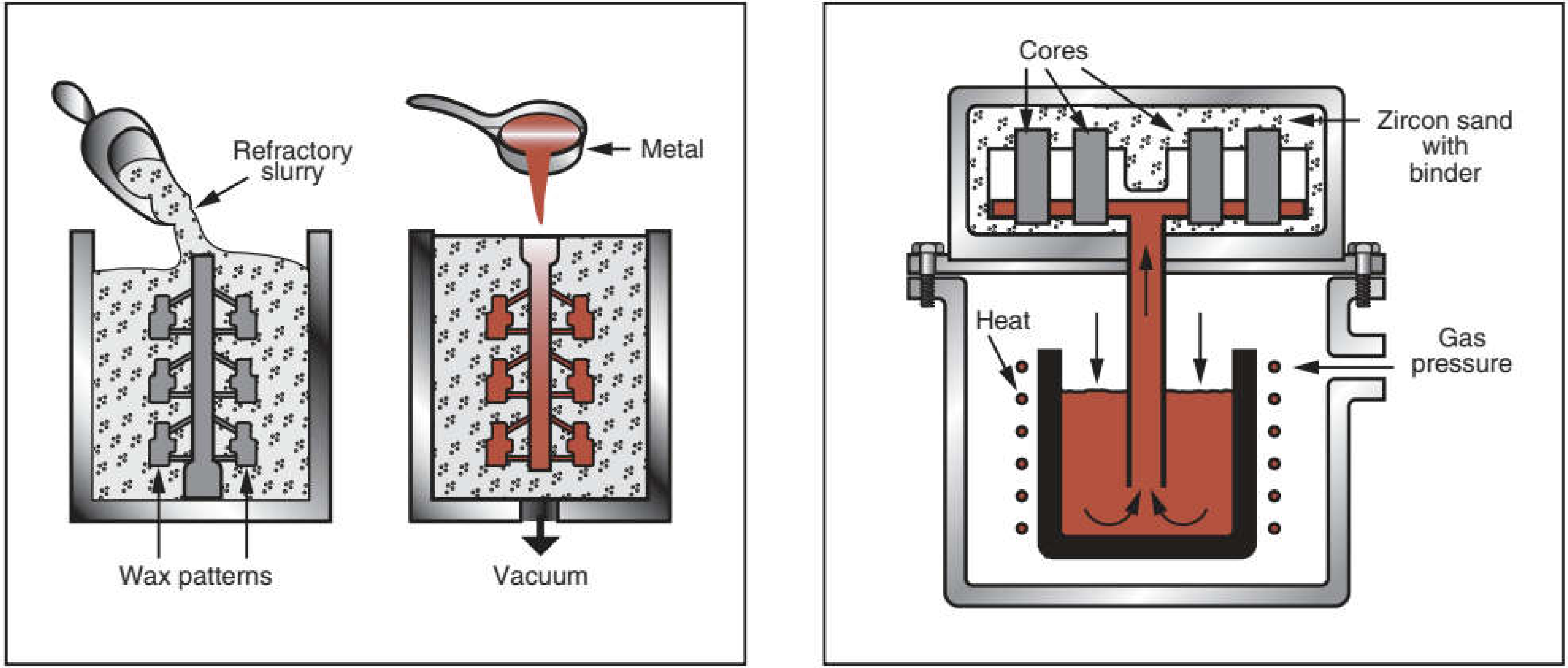
In *casting* (Figure 7.5), a liquid is poured or forced into a mold where it solidifies by cooling. Casting is distinguished from molding, which comes next, by the low viscosity of the liquid: it fills the mold by flow under its own weight (as in gravity sand and investment casting) or under a modest pressure (as in die casting and pressure sand casting). Sand molds for one-off castings are cheap; metal dies for die-casting large batches can be expensive. Between these extremes lie a number of other casting methods: shell, investment, plaster-mold and so forth.



Sand casting

Die casting

Figure 7.5 Casting processes. In *sand casting*, liquid metal is poured into a split sand mold. In *die casting*, liquid is forced under pressure into a metal mold. In *investment casting*, a wax pattern in embedded in refractory, melted out, and the cavity filled with metal. In *pressure casting*, a die is filled from below, giving control of atmosphere and of the flow of metal into the die.

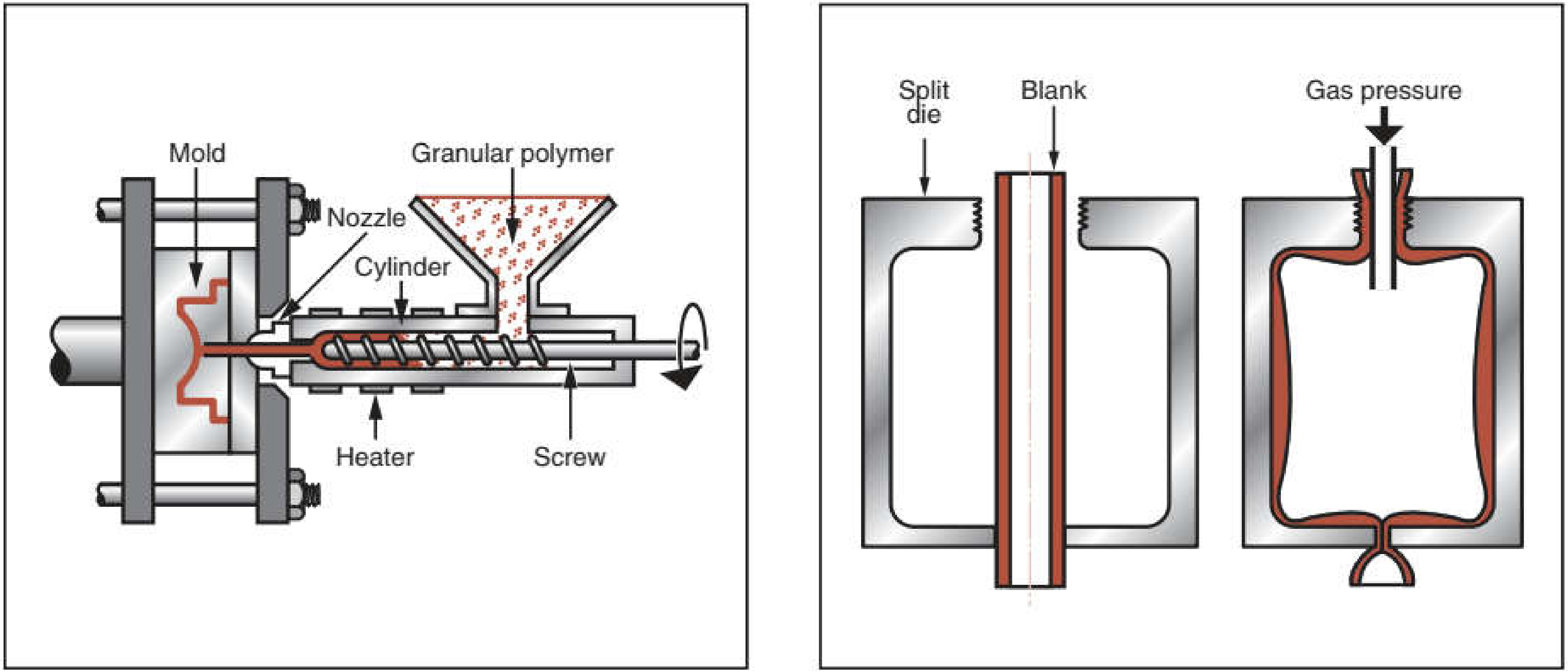


Investment casting

Low pressure casting

Figure 7.5 Casting processes. In *sand casting*, liquid metal is poured into a split sand mold. In *die casting*, liquid is forced under pressure into a metal mold. In *investment casting*, a wax pattern in embedded in refractory, melted out, and the cavity filled with metal. In *pressure casting*, a die is filled from below, giving control of atmosphere and of the flow of metal into the die.

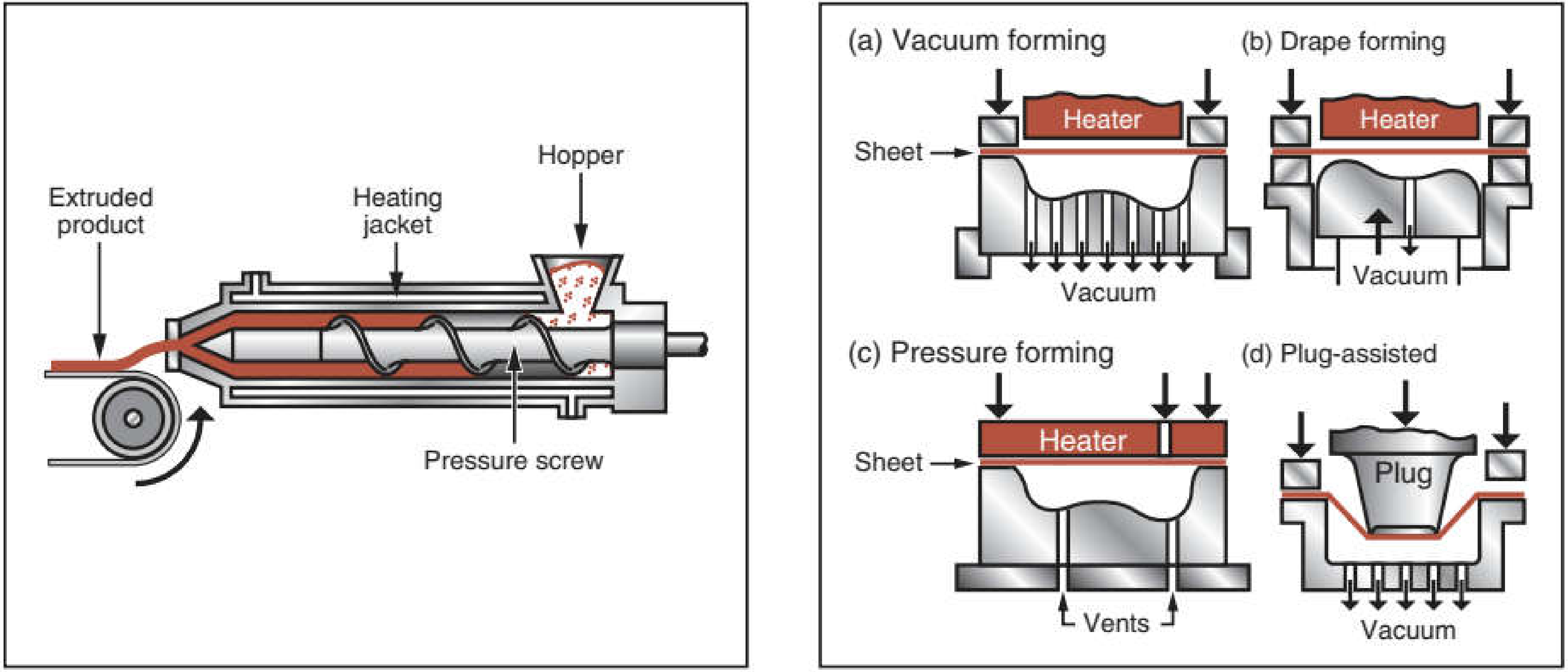
Molding (Figure 7.6). Molding is casting, adapted to materials that are very viscous when molten, particularly thermoplastics and glasses. The hot, viscous fluid is pressed or injected into a die under considerable pressure, where it cools and solidifies. The die must withstand repeated application of pressure, temperature and the wear involved in separating and removing the part, and therefore is expensive. Elaborate shapes can be molded, but at the penalty of complexity in die shape and in the way it separates to allow removal. The molds for thermo-forming, by contrast, are cheap. Variants of the process use gas pressure or vacuum to mold form a heated polymer sheet onto a single-part mold. Blow-molding, too, uses a gas pressure to expand a polymer or glass blank into a split outer-die. It is a rapid, low-cost process well suited for mass-production of cheap parts like milk bottles. Polymers, like metals, can be extruded; virtually all rods, tubes and other prismatic sections are made in this way.



Injection-molding

Blow-molding

Figure 7.6 Molding processes. In *injection-molding*, a granular polymer (or filled polymer) is heated, compressed and sheared by a screw feeder, forcing it into the mold cavity. In *blow-molding*, a tubular blank of hot polymer or glass is expanded by gas pressure against the inner wall of a split die. In *polymer extrusion*, shaped sections are formed by extrusion through a shaped die. In *thermo-forming*, a sheet of thermoplastic is heated and deformed into a female die by vacuum or gas pressure.



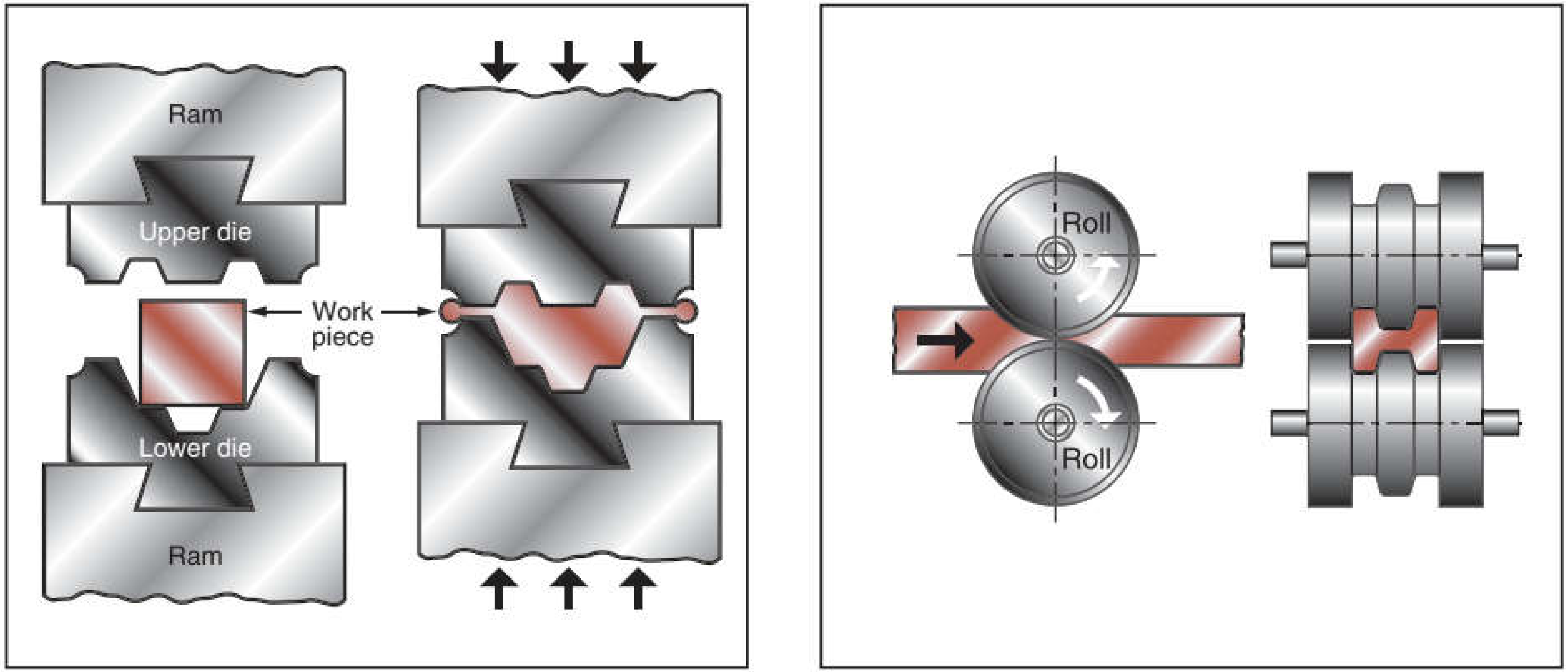
Polymer extrusion

Thermo-forming

Figure 7.6 Molding processes. In *injection-molding*, a granular polymer (or filled polymer) is heated, compressed and sheared by a screw feeder, forcing it into the mold cavity. In *blow-molding*, a tubular blank of hot polymer or glass is expanded by gas pressure against the inner wall of a split die. In *polymer extrusion*, shaped sections are formed by extrusion through a shaped die. In *thermo-forming*, a sheet of thermoplastic is heated and deformed into a female die by vacuum or gas pressure.

Deformation processing (Figure 7.7). This process can be hot, warm or cold—cold, that is, relative to the melting point of the T_m material being processed. Extrusion, hot forging and hot rolling ($T > 0.55\ T_m$) have much in common with molding, though the material is a true solid not a viscous liquid. The high temperature lowers the yield strength and allows simultaneous recrystallization, both of which lower the forming pressures. Warm working ($0.35T_m < T < 0.55T_m$) allows recovery but not recrystallization. Cold forging, rolling, and drawing ($T < 0.35T_m$) exploit work hardening to increase the strength of the final product, but at the penalty of higher forming pressures.

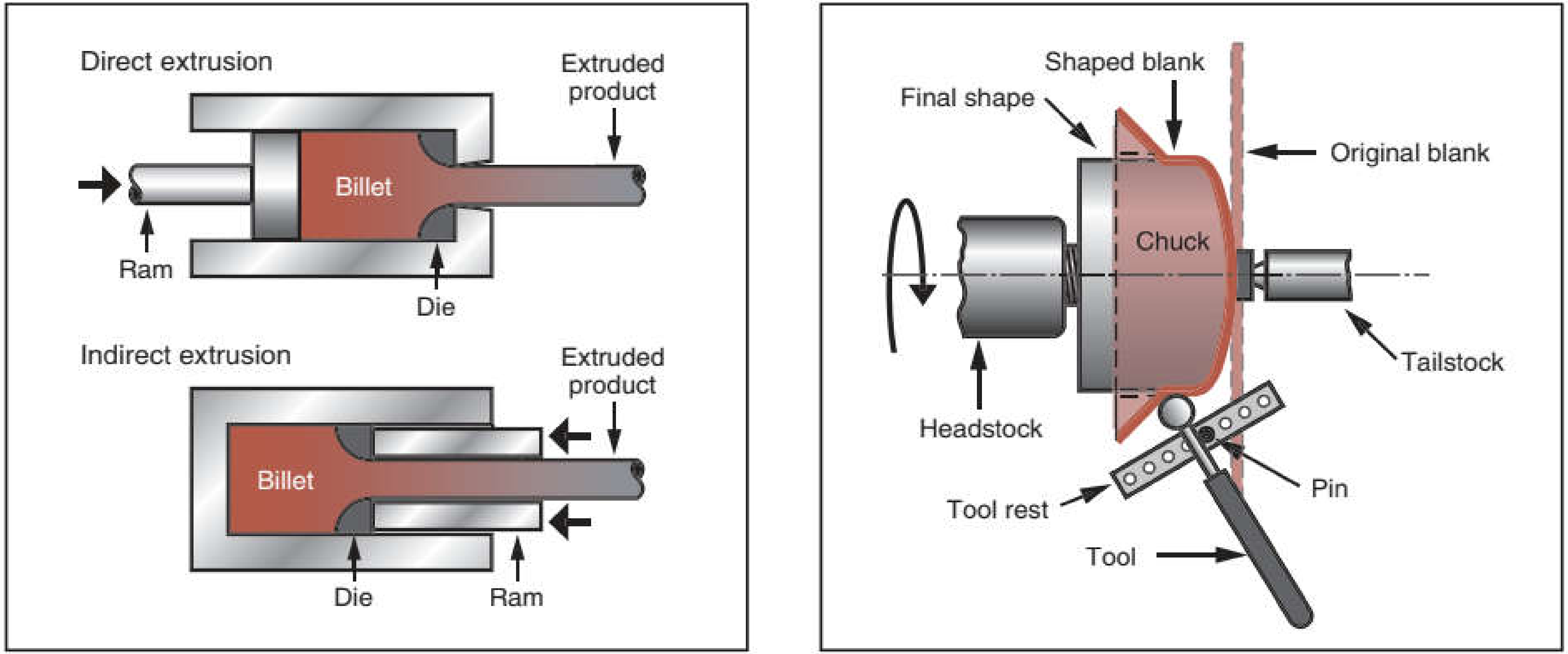
Forged parts are designed to avoid rapid changes in thickness and sharp radii of curvature since both require large local strains that can cause the material to tear or to fold back on itself ("lapping"). Hot forging of metals allows larger changes of shape but generally gives a poor surface and tolerance because of oxidation and warpage. Cold forging gives greater precision and finish, but forging pressures are higher and the deformations are limited by work hardening.



Forging

Rolling

Figure 7.7 Deformation processes. In *forging*, a slug of metal is shaped between two dies held in the jaws of a press. In *rolling*, a billet or bar is reduced in section by compressive deformation between the rolls. In *extrusion*, metal is forced to flow through a die aperture to give a continuous prismatic shape. All three process can be hot ($T > 0.85T_m$), warm ($0.55T_m < T < 0.85T_m$) or cold ($T < 0.35T_m$). In *spinning*, a spinning disk of ductile metal is shaped over a wooden pattern by repeated sweeps of the smooth, rounded, tool.



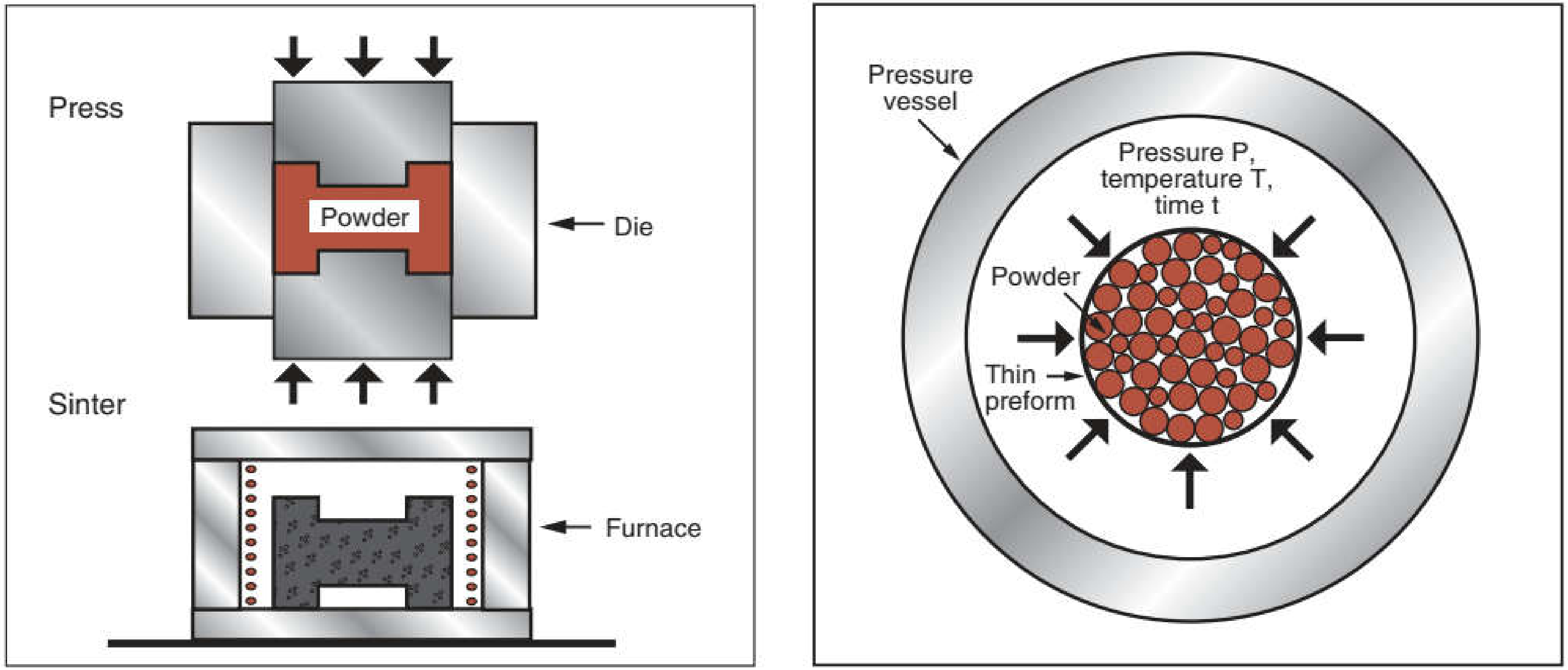
Extrusion

Spinning

Figure 7.7 Deformation processes. In *forging*, a slug of metal is shaped between two dies held in the jaws of a press. In *rolling*, a billet or bar is reduced in section by compressive deformation between the rolls. In *extrusion*, metal is forced to flow through a die aperture to give a continuous prismatic shape. All three process can be hot ($T > 0.85T_m$), warm ($0.55T_m < T < 0.85T_m$) or cold ($T < 0.35T_m$). In *spinning*, a spinning disk of ductile metal is shaped over a wooden pattern by repeated sweeps of the smooth, rounded, tool.

Powder methods (Figure 7.8). These methods create the shape by pressing and then sintering fine particles of the material. The powder can be cold-pressed and then sintered (heated at up to 0.8 T_m to give bonding); it can be pressed in a heated die ("die-pressing"); or, contained in a thin preform, it can be heated under a hydrostatic pressure ("hot isostatic pressing" or "HIPing"). Metals that are too high-melting to cast and too strong to deform, can be made (by chemical methods) into powders and then shaped in this way. But the processes are not limited to "difficult" materials; almost any material can be shaped by subjecting it, as a powder, to pressure and heat.

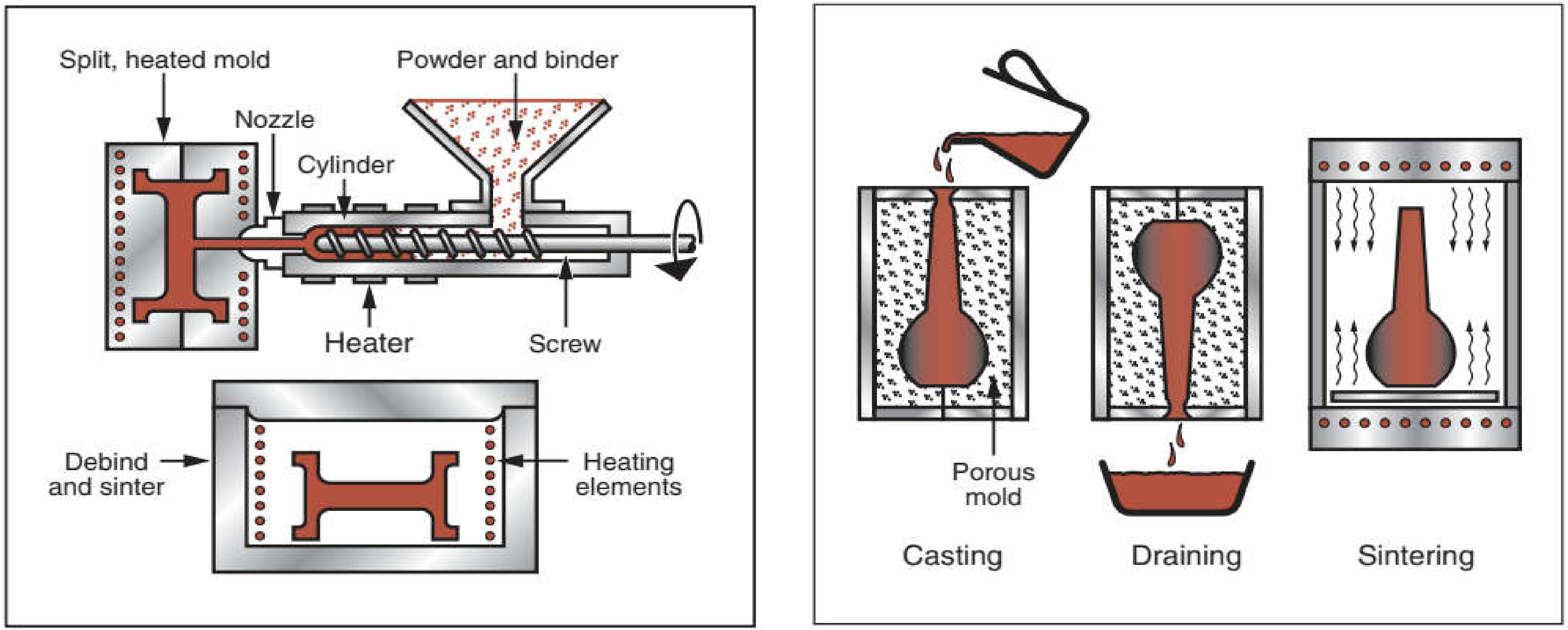
Powder processing is most widely used for small metallic parts like gears and bearings for cars and appliances. It is economic in its use of material, it allows parts to be fabricated from materials that cannot be cast, deformed or machined, and it can give a product that requires little or no finishing. Since pressure is not transmitted uniformly through a bed of powder, the length of a die-pressed powder part should not exceed 2.5 times its diameter. Sections must be near-uniform because the powder will not flow easily around corners. And the shape must be simple and easily extracted from the die.



Die-pressing and sintering

Hot isostatic pressing

Figure 7.8 Powder processing. In *die-pressing and sintering* the powder is compacted in a die, often with a binder, and the green compact is then fired to give a more or less dense product. In *hot isostatic pressing*, powder in a thin, shaped, shell or pre-form is heated and compressed by an external gas pressure. In *powder injection molding*, powder and binder are forced into a die to give a green blank that is then fired. In *slip casting*, a water-based powder slurry is poured into a porous plaster mold that absorbs the water, leaving a powder shell that is subsequently fired.



Powder injection molding

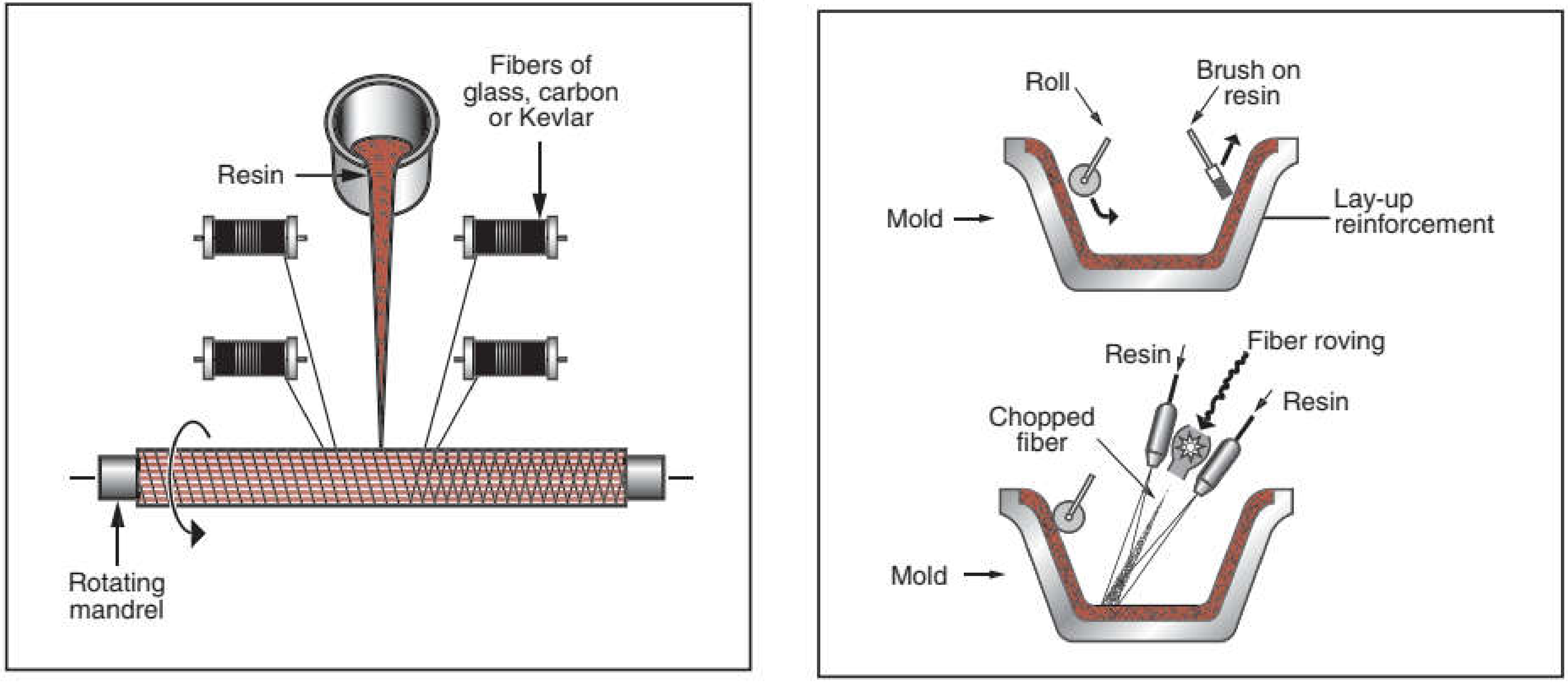
Slip casting

Figure 7.8 Powder processing. In *die-pressing and sintering* the powder is compacted in a die, often with a binder, and the green compact is then fired to give a more or less dense product. In *hot isostatic pressing*, powder in a thin, shaped, shell or pre-form is heated and compressed by an external gas pressure. In *powder injection molding*, powder and binder are forced into a die to give a green blank that is then fired. In *slip casting*, a water-based powder slurry is poured into a porous plaster mold that absorbs the water, leaving a powder shell that is subsequently fired.

Optional

Composite fabrication methods (Figure 7.9). These make polymer–matrix composites reinforced with continuous or chopped fibers. Large components are fabricated by filament winding or by laying-up pre-impregnated mats of carbon, glass or Kevlar fiber ("pre-preg") to the required thickness, pressing and curing. Parts of the process can be automated, but it remains a slow manufacturing route; and, if the component is a critical one, extensive ultrasonic testing may be necessary to confirm its integrity. Higher integrity is given by vacuum- or pressure-bag molding, which squeezes bubbles out of the matrix before it polymerizes. Lay-up methods are best suited to a small number of high-performance, tailor-made, components. More routine components (car bumpers, tennis racquets) are made from chopped-fiber composites by pressing and heating a "dough" of resin containing the fibers, known as bulk molding compound (BMC) or sheet molding compound (SMC), in a mold, or by injection molding a rather more fluid mixture into a die. The flow pattern is critical in aligning the fibers, so that the designer must work closely with the manufacturer to exploit the composite properties fully.

Optional

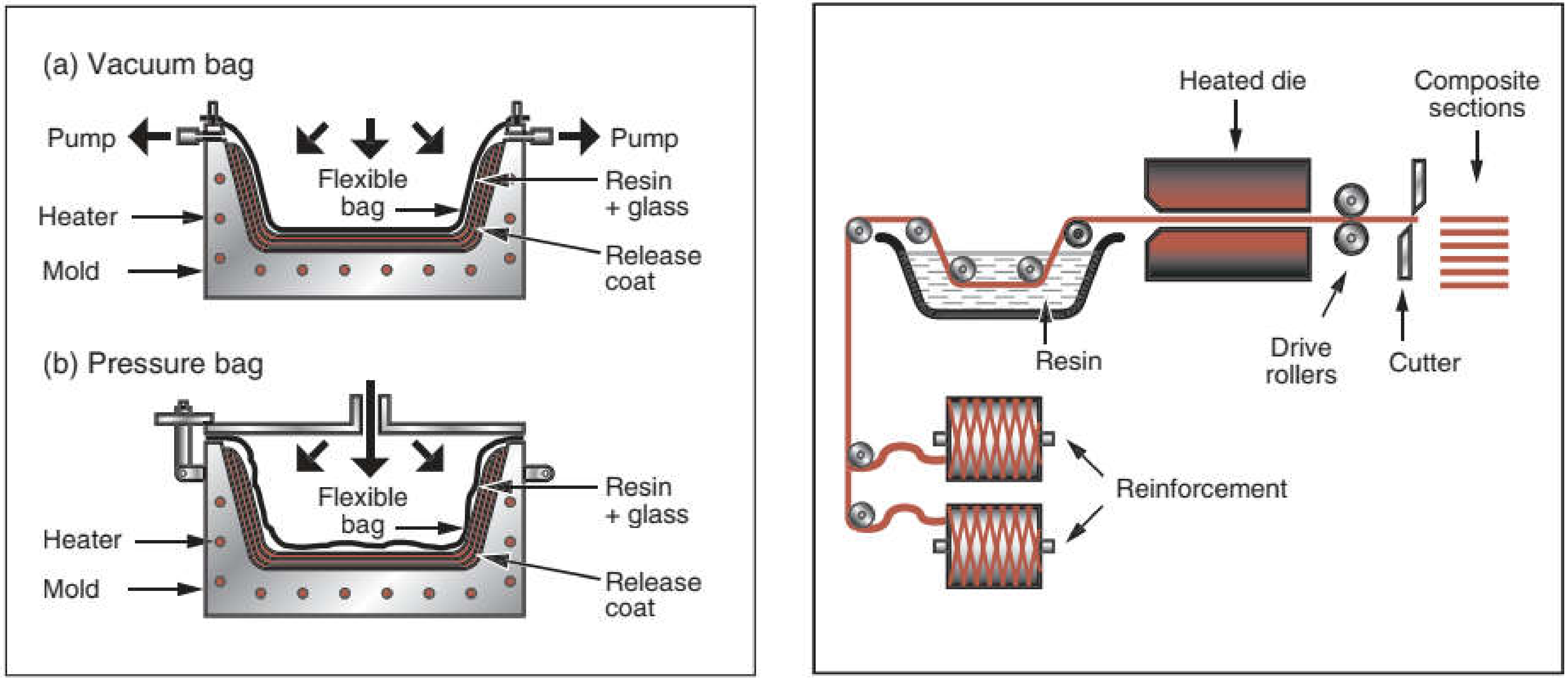


Filament winding

Roll and spray lay-up

Figure 7.9 Composite forming methods. In *filament winding*, fibers of glass, Kevlar or carbon are wound onto a former and impregnated with a resin-hardener mix. In *roll and spray lay-up*, fiber reinforcement is laid up in a mold onto which the resin-hardener mix is rolled or sprayed. In *vacuum- and pressure-bag molding*, laid-up fiber reinforcement, impregnated with resin-hardener mix, is compressed and heated to cause polymerization. In *pultrusion*, fibers are fed through a resin bath into a heated die to form continuous prismatic sections.

Optional



Vacuum- and pressure-bag molding

Pultrusion

Figure 7.9 Composite forming methods. In *filament winding*, fibers of glass, Kevlar or carbon are wound onto a former and impregnated with a resin-hardener mix. In *roll and spray lay-up*, fiber reinforcement is laid up in a mold onto which the resin-hardener mix is rolled or sprayed. In *vacuum- and pressure-bag molding*, laid-up fiber reinforcement, impregnated with resin-hardener mix, is compressed and heated to cause polymerization. In *pultrusion*, fibers are fed through a resin bath into a heated die to form continuous prismatic sections.

Optional

Rapid prototyping systems (RPS — Figure 7.10). The RPS allow single examples of complex shapes to be made from numerical data generated by CAD solid-modeling software. The motive may be that of visualization: the aesthetics of an object may be evident only when viewed as a prototype.

It may be that of pattern-making: the prototype becomes the master from which molds for conventional processing, such as casting, can be made or — in complex assemblies — it may be that of validating intricate geometry, ensuring that parts fit, can be assembled, and are accessible. All RPS can create shapes of great complexity with internal cavities, overhangs and transverse features, though the precision, at present, is limited to ±0.3 mm at best.

All RP methods build shapes layer-by-layer, rather like three-dimensional (3D) printing, and are slow (typically 4–40 h per unit). There are at least six broad classes of RPS:

Optional

(i) The shape is built up from a thermoplastic fed to a single scanning head that extrudes it like a thin layer of toothpaste ("fused deposition modelling" or FDM), exudes it as tiny droplets ("ballistic particle manufacture", BPM), or ejects it in a patterned array like a bubble-jet printer ("3D printing").

(ii) Scanned-laser induced polymerization of a photo-sensitive monomer ("stereo-lithography" or SLA). After each scan, the work piece is incrementally lowered, allowing fresh monomer to cover the surface. Selected laser sintering (SLS) uses similar laser-based technology to sinter polymeric powders to give a final product. Systems that extend this to the sintering of metals are under development.

(iii) Scanned laser cutting of bondable paper elements. Each paper-thin layer is cut by a laser beam and heat bonded to the one below.

Optional

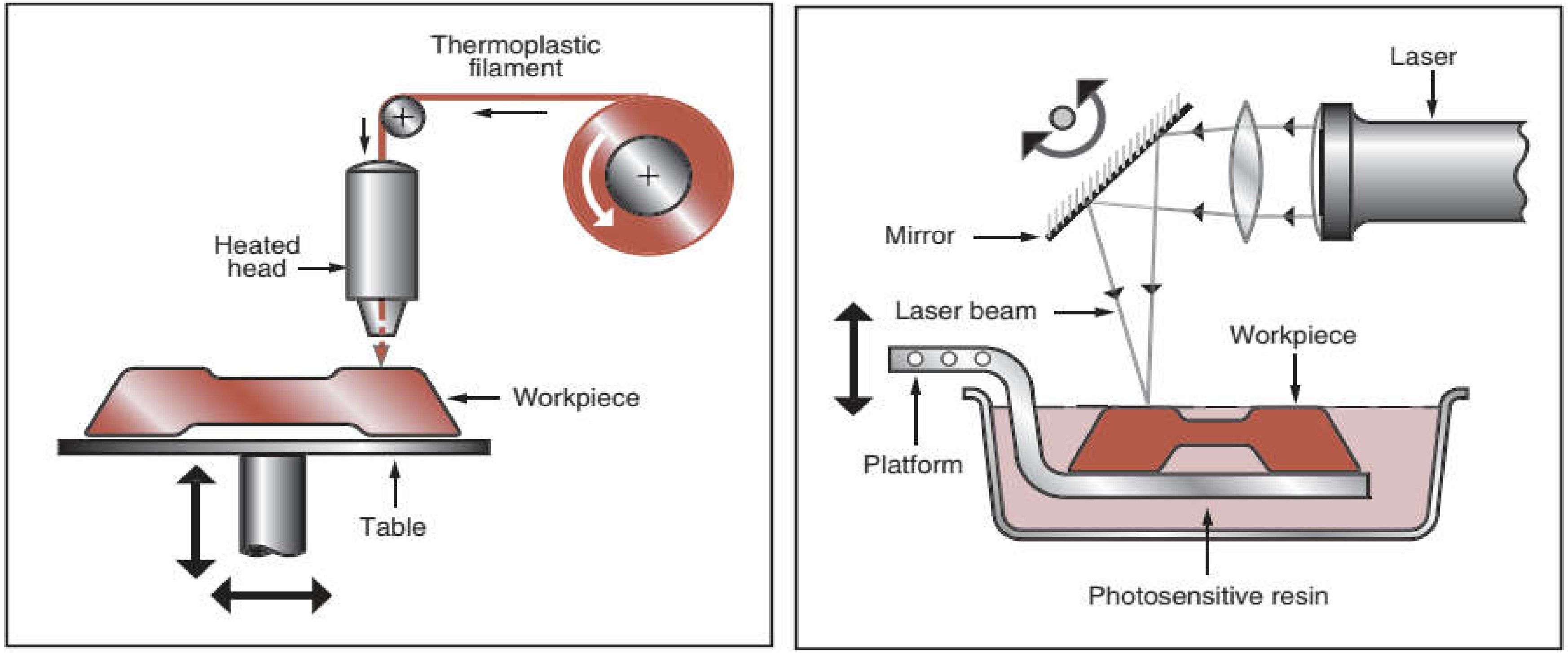
(iv) Screen-based technology like that used to produce microcircuits ("solid ground curing" or SGC). A succession of screens admits UV light to polymerize a photo-sensitive monomer, building shapes layer by layer.

(v) SLS allows components to be fabricated directly in thermoplastic, metal or ceramic. A laser, as in SLA, scans a bed of particles, sintering a thin surface layer where the beam strikes. A new layer of particles is swept across the surface and the laser-sintering step is repeated, building up a 3-dimensional body.

(vi) Bonded sand molding offers the ability to make large complex metal parts easily. Here a multi-jet print-head squirts a binder onto a bed of loose casting sand, building up the mold shape much as selected laser sintering does, but more quickly. When complete the mold is lifted from the remaining loose sand and used in a conventional casting process.

To be useful, the prototypes made by RPS are used as masters for silicone molding, allowing a number of replicas to be cast using high-temperature resins or metals.

Optional

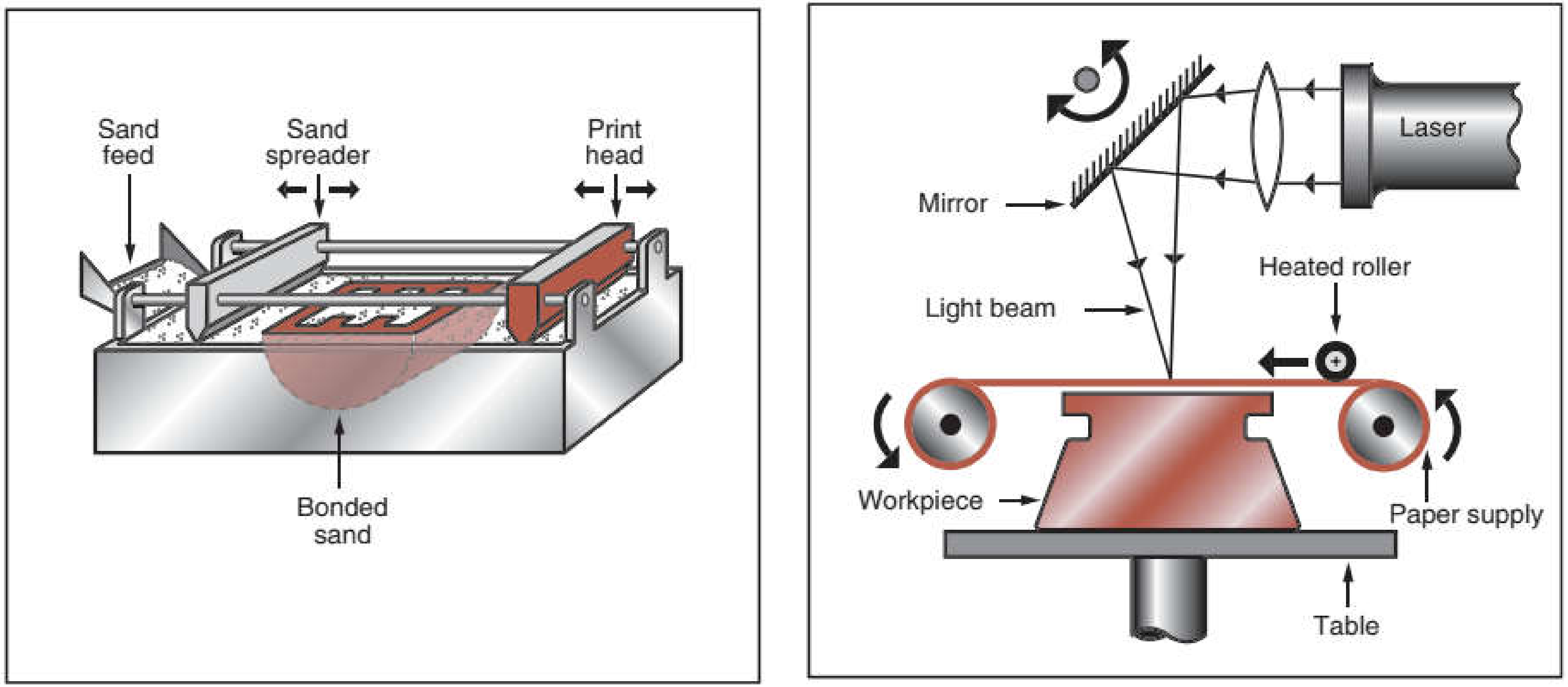


Deposition modeling

Stereo-lithography, SLA

Figure 7.10 Rapid prototyping. In *deposition modeling* and *ballistic particle manufacture* (BPM), a solid body is created by the layer-by-layer deposition of polymer droplets. In *stereo-lithography* (SLA), a solid shape is created layer-by-layer by laser-induced polymerization of a resin. In *direct mold modeling*, a sand mold is built up layer-by-layer by selective spraying of a binder from a scanning print-head. In *laminated object manufacture* (LOM), a solid body is created from layers of paper, cut by a scanning laser beam and bonded with a heat-sensitive polymer.

Optional

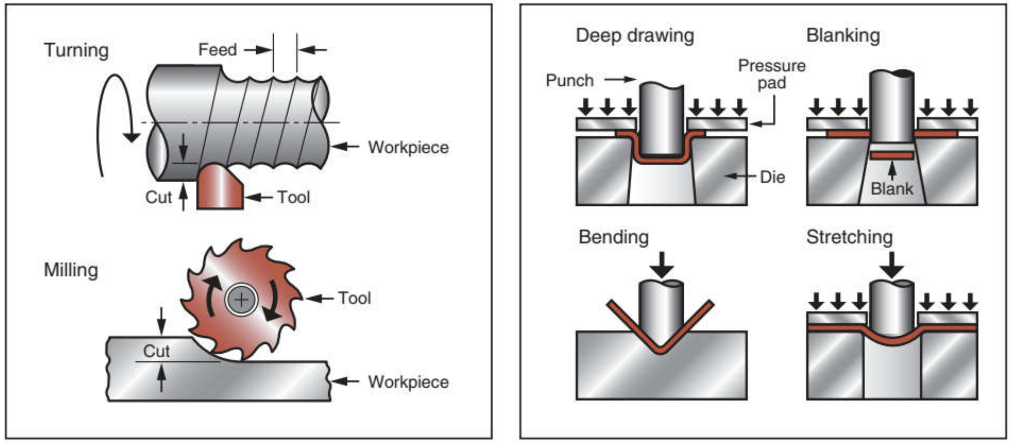


Direct mold modeling

Laminated object manufacture, LOM

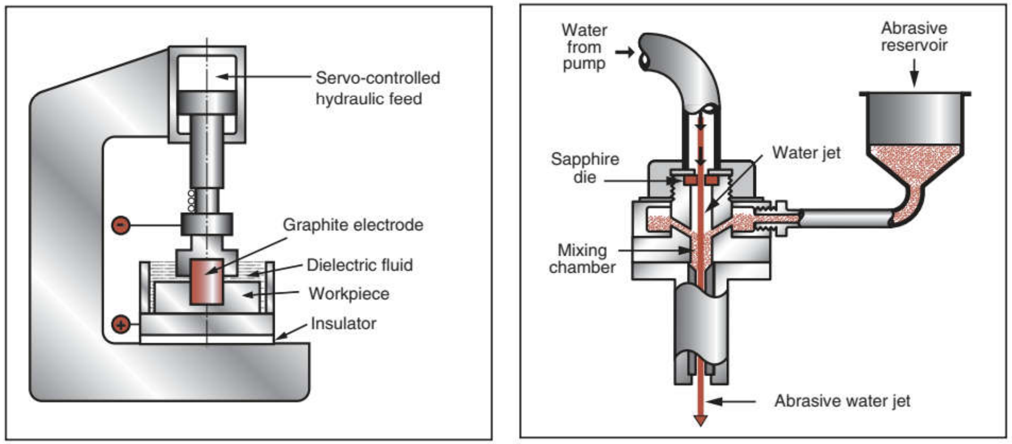
Figure 7.10 Rapid prototyping. In *deposition modeling* and *ballistic particle manufacture* (BPM), a solid body is created by the layer-by-layer deposition of polymer droplets. In *stereo-lithography* (SLA), a solid shape is created layer-by-layer by laser-induced polymerization of a resin. In *direct mold modeling*, a sand mold is built up layer-by-layer by selective spraying of a binder from a scanning print-head. In *laminated object manufacture* (LOM), a solid body is created from layers of paper, cut by a scanning laser beam and bonded with a heat-sensitive polymer.

Optional



Turning and milling

Drawing, blanking, bending and stretching

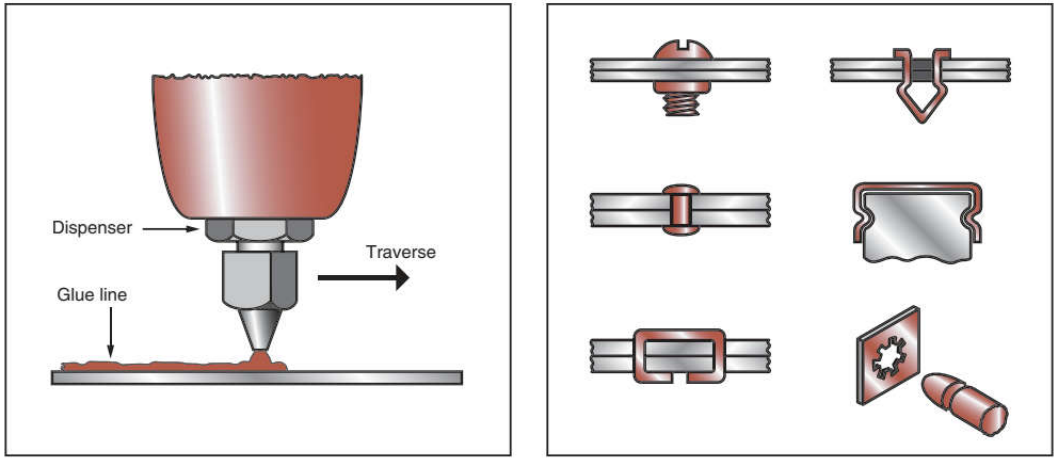


Electro-discharge machining

Water-jet cutting

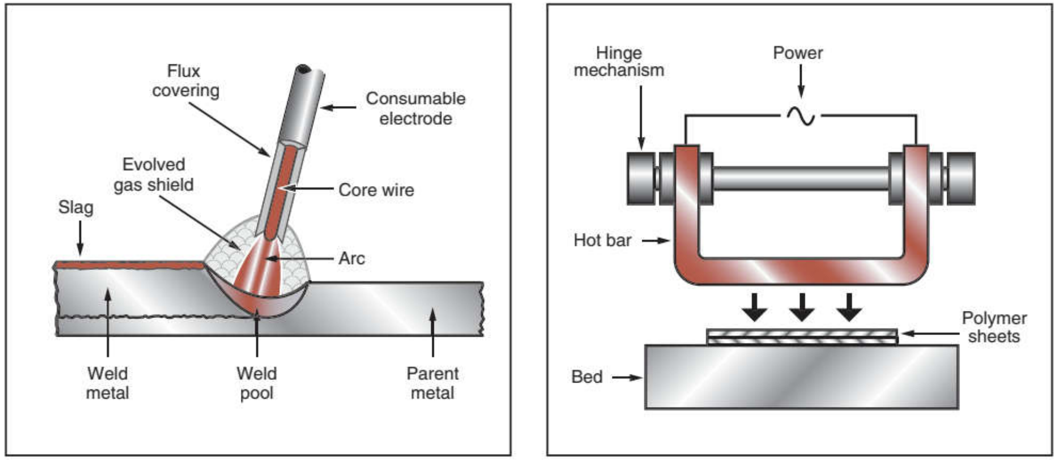
Figure 7.11 Machining operations. In *turning* and *milling*, the sharp, hardened tip of a tool cuts a chip from the workpiece surface. In *drawing, blanking, bending* and *stretching*, a sheet is shaped and cut to give flat and dished shapes. In *electro-discharge machining*, electric discharge between a graphite electrode and the workpiece, submerged in a dielectric such as paraffin, erodes the workpiece to the desired shape. In water-jet cutting, an abrasive entrained in a high speed water-jet erodes the material in its path.

Optional



Adhesives

Fasteners

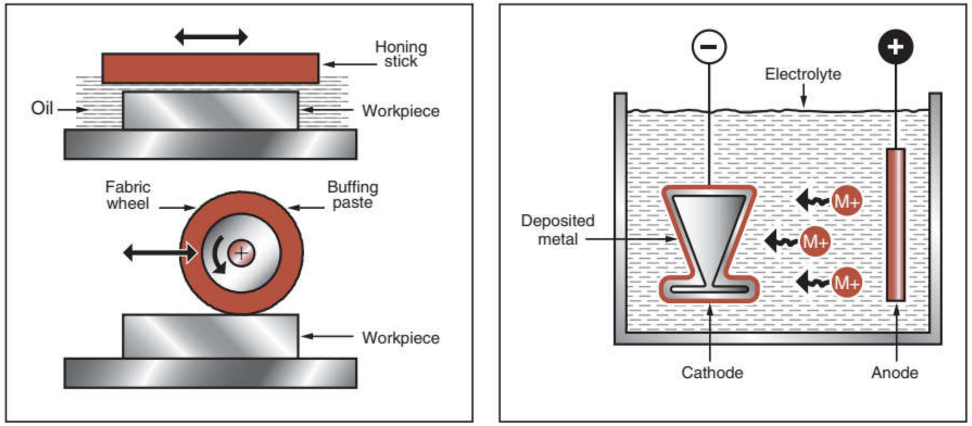


Welding: manual metal arc

Welding: hot bar polymer welding

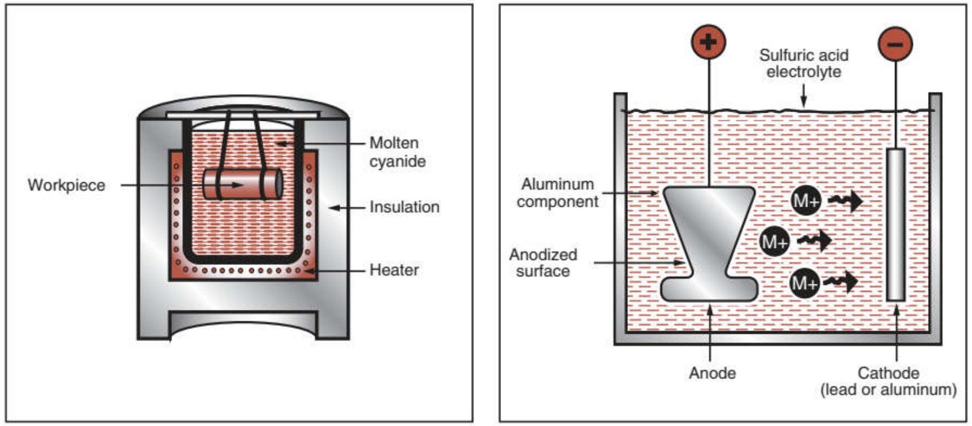
Figure 7.12 Joining operations. In *adhesive bonding*, a film of adhesive is applied to one surface, which is then pressed onto the mating one. *Fastening* is achieved by bolting, riveting, stapling, push-through snap fastener, push-on snap fastener or rod-to-sheet snap fastener. In *metal fusion-welding*, metal is melted, and more added from a filler rod, to give a bond or coating. In *thermoplastic polymer welding*, heat is applied to the polymer components, which are simultaneously pressed together to form a bond.

Optional



Mechanial polishing

Electro-plating

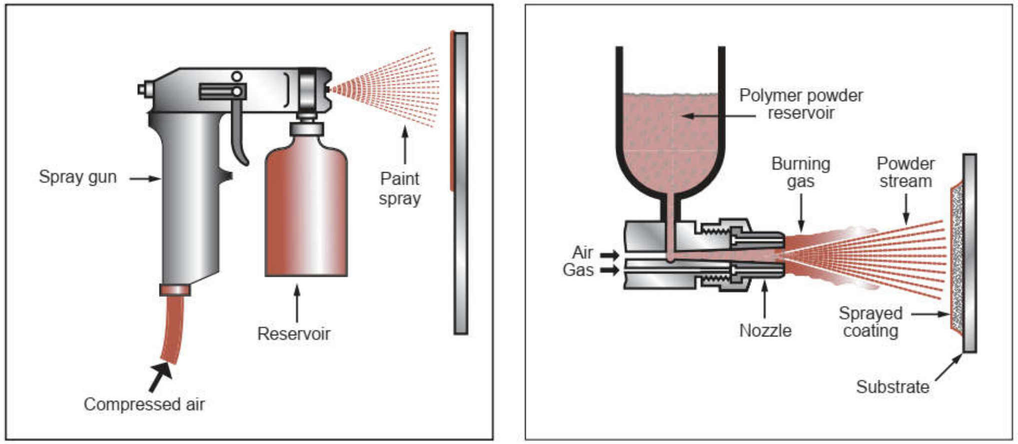


Heat treatment: carburizing

Anodizing

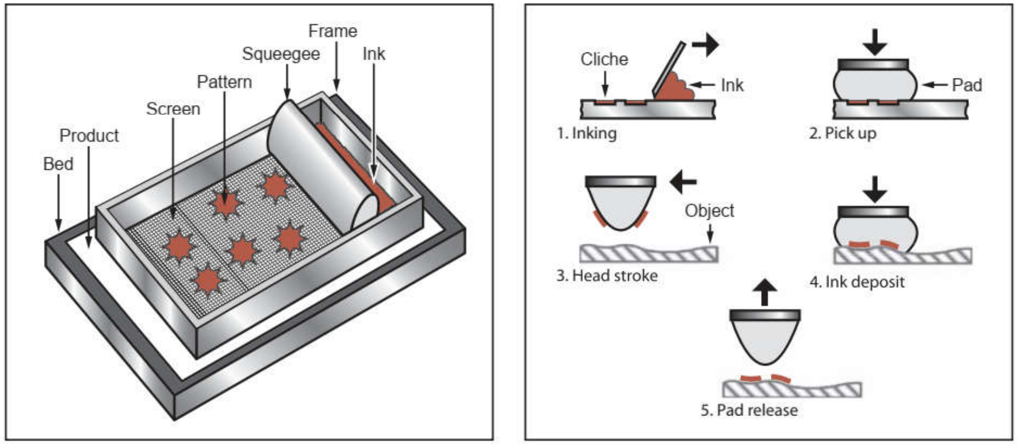
Figure 7.13 Finishing processes to protect and enhance properties. In *mechanical polishing*, the roughness of a surface is reduced, and its precision increased, by material removal using finely ground abrasives. In *electro-plating*, metal is plated onto a conducting workpiece by electro-deposition in a plating bath. In *heat treatment*, a surface layer of the workpiece is hardened, and made more corrosion resistant, by the inward diffusion of carbon, nitrogen, phosphorous or aluminum from a powder bed or molten bath. In *anodizing*, a surface oxide layer is built up on the workpiece (which must be aluminum, magnesium, titanium, or zinc) by a potential gradient in an oxidizing bath.

Optional



Paint spraying

Polymer powder spraying



Silk-screen printing

Pad printing

Figure 7.14 Finishing processes to enhance appearance. In *paint spraying*, a pigment in an organic or water-based solvent is sprayed onto the surface to be decorated. In *polymer powder-coating* a layer of thermoplastic is deposited on the surface by direct spraying in a gas flame, or by immersing the hot workpiece in a bed of powder. In *silk-screen printing*, ink is wiped onto the surface through a screen onto which a blocking-pattern has been deposited, allowing ink to pass in selected areas only. In *pad printing*, an inked pattern is picked up on a rubber pad and applied to the surface, which can be curved or irregular.

« و اینکه برای انسان بهره‌ای جز سعی [و کوشش] او، نیست » (سوره مبارکه نجم، آیه ۳۹)

اَللّٰهُمَّ ما بِنا مِنْ نِعْمَةٍ فَمِنْكَ

بارالها؛ هر نعمتی که بر ماست، از آن توست

با آرزوی سلامتی و موفقیت روز افزون برای شما عزیزان

❋ دکتر محمود سمیع زاده ❋