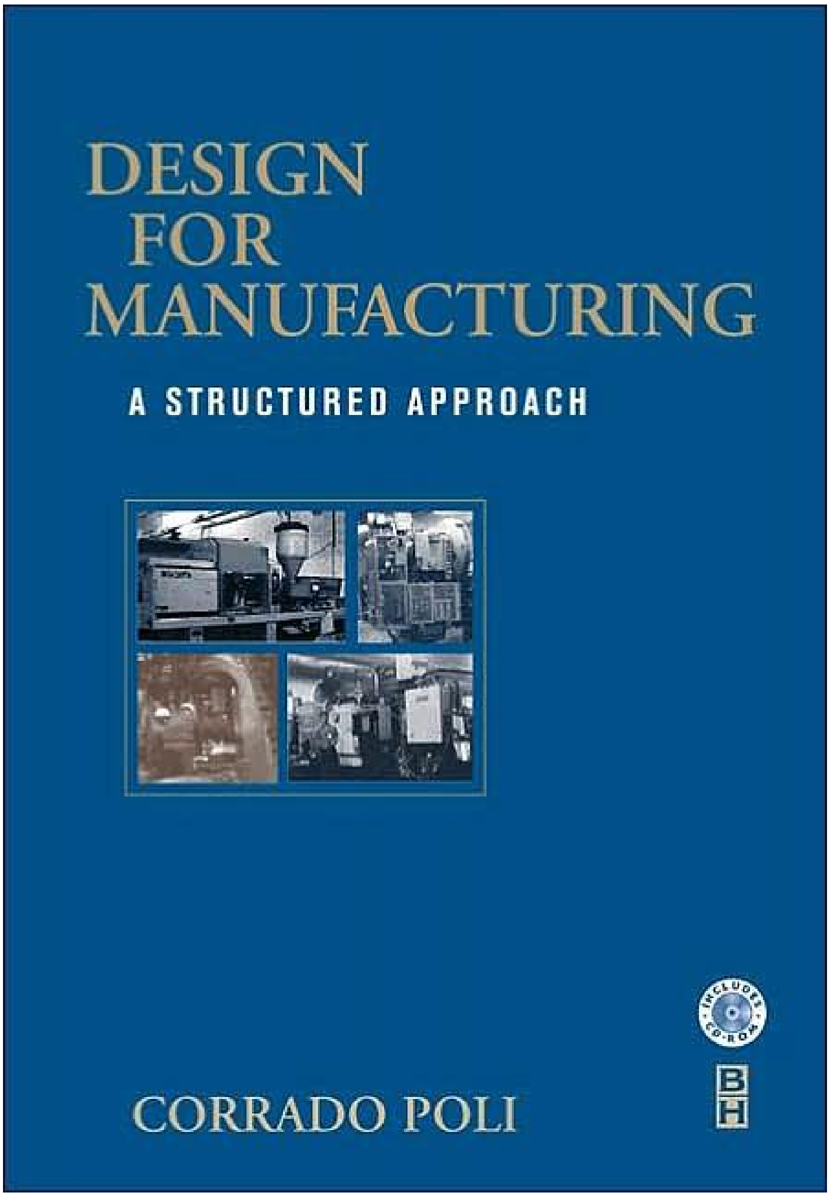
Design for Manufacturing: A Structured Approach

by Corrado Poli



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Preface

Design for Manufacturing: A Structured Approach is intended as a text for mechanical, industrial, and manufacturing engineering students at the junior level or higher, and as a continuing education text for manufacturing engineers and engineering design practitioners in industry. Unlike many books on design for manufacturing that provide only broad qualitative guidelines to designers, this book uses a combination of both qualitative and quantitative information to assist readers in making informed decisions concerning alternative competing designs.

The quantitative methods presented here inherently require considerably more attention to geometric detail, more than required by conceptual or even configuration design. If students are to do quantitative DFM (design for manufacturing) evaluations, they simply must take the time and trouble to learn to do them. Although engineering design can be considerably more abstract than DFM, the transition from the abstraction of engineering design to the concrete detail of DFM simply goes with the territory if one wants to perform quantitative DFM evaluations in a concurrent fashion. The part-coding systems that are the basis for some of the DFM methodologies may initially appear cumbersome (there are a lot of new terms to learn), but they are in fact easy to learn. The reward is not only the ability to estimate relative tooling and processing costs, but also a good sense of the design issues that drive part costs.

This book is based on material that first appeared in *Engineering Design and Design for Manufacturing: A Structured Approach*, a book I co-authored with John R. Dixon and published in 1995. *Design for Manufacturing: A Structured Approach* is an updated, revised, reorganized, and stand-alone version of the chapters in the earlier book that dealt primarily with design for manufacturing and materials and process selection. The greatest changes occur in the chapters dealing with stamping. The coding system originally used to estimate the number of active stations required to produce a stamped part has been dropped. Instead, a more accurate and user-friendly algorithm based on the concept of process planning and strip-layout development is used to determine the number of active stations required to produce the tooling for a stamped part.

Another change that has been made in this book occurs when estimating the total relative part cost, that is, the cost of the part relative to a reference part. The original approach allowed the cost of the reference part to vary with production volume. This, in turn, often resulted in increases in the total relative cost of the designed part with increases in production volume. This counterintuitive result appeared to cause confusion among students. The approach used here, as suggested by Professor Larry Murch of the University of Massachusetts Amherst, is to fix the cost of the reference part to $1 and the production volume of the reference part to the production volume that results in a part cost of $1.00. This approach, which results in an increase in relative part cost with increases in production volume, appears to be favored by students, and allows them to use the DFM systems to roughly estimate the production cost of a proposed design.

To assist students in better visualizing and understanding the many orthographic views that appear in the book, isometric views have also been included where it was deemed advantageous. Many new homework problems have also been added.

To help students better envisage and comprehend the rationale behind the DFM methodologies described here, a series of Power Point presentations has been developed, which are on a CD-ROM that is available for use by faculty in courses that require the use of this book. These presentations contain both video clips and quick-times movies of processes such as injection molding, stamping, die casting, forging, rolling, rod drawing, and aluminum extrusion.

Readers of this book may also be interested in visiting the design for manufacturing Web site hosted by the Mechanical and Industrial Engineering Department at the University of Massachusetts Amherst.

Design for Manufacturing: A Structured Approach can be used to support a one-semester course in Design for Manufacturing (or Manufacturing for Design) at the level of the junior or senior year in college. Such a course could be taught independently of a design course, or the two courses could be taught simultaneously. It is strongly recommended that this course include a design for manufacturing project. Although it is true that DFM can be taught without the use of a supplementary DFM project, my experience is that student interest in manufacturing and how parts are made increases significantly when a project is included.

Acknowledgments

The methodologies described in this book rely on the prior work, assistance, support, encouragement, and dedication of many colleagues and students. The development of these methodologies in turn depends on the knowledge base and data made available by various collaborating companies and the financial support provided by both private industry and state and federal funding agencies. Although there are too many individuals, companies, and funding agencies to mention here I do want to mention a few.

Among faculty colleagues at the University of Massachusetts Amherst who have helped are J. Edward Sunderland and Robert Graves (now at Rensselaer), who participated in much of the DFM work described here, and Larry Murch, who suggested the total relative part cost model used in Chapters 5, 7, and 10 and who made many valuable suggestions while reading the manuscript. I am especially appreciative of the many useful discussions and suggestions provided by my good friend and colleague John R. Dixon to the original version of this manuscript, which first appeared in our book *Engineering Design and Design for Manufacturing: A Structured Approach.*

Although many graduate students participated and contributed to the ongoing research in design for manufacturing (DFM), among the students who have contributed the most were Jiten Divgi, Sheng-Ming Kuo, Ricardo Fernandez, Lee Fredette, Ferruccio Fenoglio, Juan Escodero, Shyam Shanmugasundaram, Pratip Dastidar, Prashant Mahajan, and Shrinivasan Chandrasrkran.

The contributions of these students would not have been possible without the financial support of the former Digital Equipment Corporation, Xerox, the National Science Foundation, and the Massachusetts Center of Excellence Corporation.

Most of the knowledge base and data base upon which the DFM methodologies in die casting and stamping are based was acquired with the cooperation of the following New England-based companies, namely, Cambridge Tool and Manufacturing Company, North Billerica, MA; Kennedy Die Castings, Worcester, MA; Larson Tool and Stamping Company, Attleboro, MA; K. F. Bassler Company, Attleboro, MA; Leicester Die and Tool Inc., Leicester, MA; Metropolitan Machine and Stamping Company, Medfield, MA; Thomas Smith Company Inc., Worcester, MA; Hobson and Motzer, Inc., Wallingford, CT; Newton New Haven Co., North Haven, CT. The knowledge base and data base for injection molding was obtained with the cooperation of the following companies: Jada Precision Plastics, Rochester, NY; Sajar Plastics, Midfield, OH; Colonial Machine Company, Kent, OH; Tremont Tool and Gage, Cleveland, OH; Woldring Plastic Mold Technology, Grand Rapids, MI; Sinicon Plastics, Pittsfield, MA; and Tog Mold, Pittsfield, MA. I am deeply indebted to all of these companies, as well as to those companies whom I have forgotten to mention, for their invaluable help and for their willingness to work closely with the students mentioned above.

To help in better visualizing and understanding the logic behind the methodologies described in this book, a series of Power Point presentations have been

developed to accompany the book. These presentations make heavy use of animations developed by students from the Center for Knowledge Communication in the Computer Science Department at the University of Massachusetts Amherst. Although many students contributed to the development of these animations I want to especially thank Ryan Moore and Nick Steglich for their work on the stamping and die-casting animations.

Finally, I also want to express my indebtedness to both Geoffrey Boothroyd and Beverly Woolf. It was Geoffrey Boothroyd who introduced me to the entire design for manufacturing mindset, and it is his work in design for assembly that opened the frontier to all the "design-fors." Chapter 12, "Assembly," borrows a great deal from his prior work on manual assembly. Beverly Woolf introduced me to the fascinating world of multimedia and pointed out its usefulness in education, especially in the area of design for manufacturing.

Lastly, to those who contributed but whom I have failed to acknowledge here, I apologize. There just isn't space for you all, but I do sincerely appreciate your help.

To the extent that the book is correct and useful, I owe much to all of you; to the extent that it is not, I am solely responsible.

Responsibilities of Users

What do I say to people who use the information and methods described here and something goes wrong? THEY are responsible, not me.

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Chapter 1

Introduction

1.1 MANUFACTURING, DESIGN, AND DESIGN FOR MANUFACTURING

Different uses of the word *manufacturing* create an unfortunate confusion. Sometimes the word is used to refer to the entire product realization process, that is, to the entire spectrum of product-related activities in a firm that makes products for sale, including marketing (e.g., customer desires), design, production, sales, and so on. This complete process is sometimes referred to as "big-M Manufacturing."

But the word manufacturing is also used as a synonym for production, that is, to refer only to the portion of the product realization process that involves the actual physical processing of materials and the assembly of parts. This is sometimes referred to as "little-m manufacturing."

We will use the little-m meaning for manufacturing in this book. In other words, manufacturing here consists of physical processes that modify materials in form, state, or properties. Thus in this book, manufacturing and production have the same meaning. When we wish to refer to big-M Manufacturing, we will call it the product realization process.

Design (as in a design process) is the series of activities by which the information known and recorded about a designed object is added to, refined (i.e., made more detailed), modified, or made more or less certain. In other words, the process of design changes the state of information that exists about a designed object. During successful design, the amount of information available about the designed object increases, and it becomes less abstract. Thus, as design proceeds the information becomes more complete and more detailed until finally there is sufficient information to perform manufacturing. Design, therefore, is a process that modifies the information we have about an artifact or designed object, whereas manufacturing (i.e., production) modifies its physical state.

A *design problem* is created when there is a desire for a change in the state of information about a designed object. Consequently, a design problem exists when there is a desire to generate more (or better) information about the designed object, when we want to develop a new (but presently unknown) state of information. For a simple example, we may know from the present state of information that a designed object is to be a beam, and we desire to know whether it is to be an I-beam, a box beam, an angle beam, or some other shape. Our desire to know more about the designed object defines a new design problem—in this example, determining the beam's shape. Later, once we know the shape (say it is to be an I-beam), another design problem is defined when we want also to know the dimensions. There are many kinds of design problems defined by the present and desired future states of information.

Design for manufacturing (DFM) is a philosophy and mind-set in which manufacturing input is used at the earliest stages of design in order to design parts and products that can be produced more easily and more economically. Design for manufacturing is any aspect of the design process in which the issues involved in manufacturing the designed object are considered explicitly with a view to influencing the design. Examples are considerations of tooling costs or time required, processing costs or controllability, assembly time or costs, human concerns during manufacturing (e.g., worker safety or quality of work required), availability of materials or equipment, and so on. Design for manufacturing occurs—or should occur—throughout the design process.

1.2 FUNCTIONAL DESIGNED OBJECTS

We distinguish among the following types of functional designed objects, though not all of them are mutually exclusive: parts, assemblies, subassemblies, components, products, and machines.

Parts

A *part* is a designed object that has no assembly operations in its manufacture. (Welding, gluing, and the like are considered assembly operations for the purposes of this definition.) Parts may be made by a sequence of manufacturing processes (e.g., casting followed by milling), but parts are not assembled.

Parts are either *standard* or *special purpose*. A standard part is a member of a class of parts that has a generic function and is manufactured routinely without reference to its use in any particular product. Examples of standard parts are screws, bolts, rivets, jar tops, buttons, most beams, gears, springs, and washers. Tooling for standard parts is usually on hand and ready for use by manufacturers. Manufacturers, distributors, or vendors often carry standard parts themselves in stock. Standard parts are most frequently selected by designers from catalogs, often with help from vendors.

Special purpose parts are designed and manufactured for a specific purpose in a specific product or product line rather than for a generic purpose in several different products. Special purpose parts that are incorporated into the subassemblies and assemblies of products and machines are often referred to as piece parts. Special purpose parts that stand alone as products (e.g., paper clips, Styrofoam cups) are referred to as single-part products.

Even though screws, springs, gears, and the like, are generally manufactured as standard parts, a special or unique screw, spring, gear, and any other part that is specially designed and manufactured for a special rather than a general purpose is considered a special purpose part. This is not often done, however, because it is usually less expensive to use an available standard part if one will serve the purpose.

Assemblies and Subassemblies

An assembly is a collection of two or more parts. A subassembly is an assembly that is included within an assembly or other subassembly.

A standard module or standard assembly is an assembly or subassembly that—like a standard part—has a generic function and is manufactured routinely for general use or for inclusion in other subassemblies or assemblies. Examples of standard modules are electric motors, electronic power supplies or amplifiers, heat exchangers, pumps, gear boxes, v-belt drive systems, batteries, light bulbs, switches, and thermostats. Standard modules, like standard parts, are generally selected from catalogs.

Products and Machines

A product is a functional designed object that is made to be sold and/or used as a unit. Products that are marketed through retailing to the general public are called consumer products. Many manufactured products are designed for and sold to other businesses for use in the business; this is sometimes called the trade (or commercial, or industrial) market. For example, a manufacturer may buy a pump to circulate cooling water to a machine tool already purchased. In addition, there are products, including especially standard parts and standard modules, that are sold to other manufacturers for use in products being manufactured; this is called the original equipment manufacturer (or OEM) market. An example is the purchase of a small motor for use in an electric fan. Trade marketing is usually done through a system of regional manufacturer's representatives and distributors.

A machine is a product whose function is to contribute to the manufacture of products and other machines.

1.3 THE PRODUCT REALIZATION PROCESS

Product Realization is the set of cognitive and physical processes by which new and modified products are conceived, designed, produced, brought to market, serviced, and disposed of. That is to say, product realization is the entire "cradle to grave" cycle of all aspects of a product.

Product realization includes determining customers' needs, relating those needs to company strategies and products, developing the product's marketing concept, developing engineering specifications, designing both the product and the production tools and processes, operating those processes to make the product, and distributing, selling, repairing, and finally disposing of or recycling the product and the production facilities.

Product realization also includes those management, communication, and decision-making processes that organize and integrate all of the above, including marketing, finance, strategic planning, design (industrial, engineering, detail, and production), manufacturing, accounting, research and development, distribution and sales, service, and legal operations.

Product realization consists of several overlapping stages including product development, industrial design, engineering design, and production design. These are defined in the paragraphs below. Figure 1.1 also provides a supporting illustration for the definitions of these terms.

Product development is the portion of the product realization process from inception to the point of manufacturing or production. Though product development does not, by this definition, include activities beyond the beginning of production, it does require the use of feedback from all the various downstream product realization activities for use in designing, evaluating, redesigning parts and assemblies, and planning production. This feedback especially includes information about manufacturing issues—that is, information about design for manufacturing. Thus product development (including product improvement and redevelopment) is an ongoing activity even after production has begun.

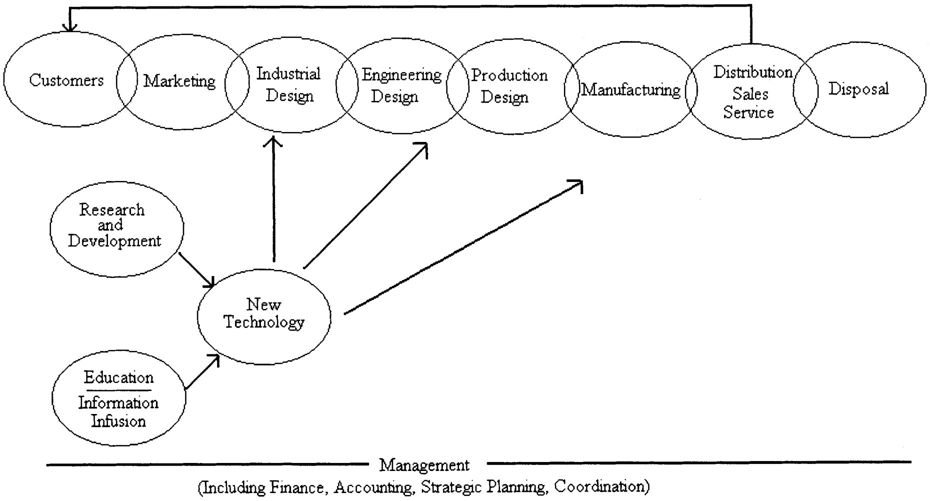

FIGURE 1.1 *View of the product realization process.*

1.4 INDUSTRIAL (OR PRODUCT) DESIGN

The process of *industrial design* (sometimes the phrase *product design* is used) creates the first broadly functional description of a product together with its essential visual conception. Artistic renderings of proposed new products are made, and almost always physical models of one kind or another are developed. The models are often merely very rough, nonfunctional ones showing external form, color, and texture only, but some models at this stage may also have a few moving parts.

There is great variability in the way industrial design is organized and utilized within different firms. In one firm, for example, a very small number of industrial designers are employed who work constantly to generate new or revised product concepts. These industrial designers are essentially a separate department but keep in close communication with colleagues in both marketing and engineering design. When a product concept has been approved by management for further development, then outside consultants in industrial design are brought in to work with the in-house industrial designers and with the firm's engineering designers and manufacturing people to refine and complete the industrial design phase. Marketing remains involved during this phase.

In another firm, no industrial designers per se are employed. In this firm, creative engineering designers working with marketing develop initial product concepts. Once a concept has approval, then outside industrial design consultants are brought in to perform the work described above.

An example of the kinds of issues that must be resolved by cooperation among industrial and engineering designers at this early stage is determination of the basic size and shape of the product. Industrial designers will have aesthetics, company image, and style primarily in mind in creating a proposed size and shape for a product. Engineering designers, on the other hand, will be concerned with how to get all the required functional parts into the (usually) small space proposed. Another issue requiring cooperation may be choices of materials for those parts that can be seen or handled by consumers. And, of course, both design engineers and manufacturing engineers are concerned about how the product is to be made within the required cost and time constraints.

It is helpful to use the phrase *product-marketing concept* to describe the results of industrial design. Sometimes the product-marketing concept is written into a formal (or at least informal) product-marketing specification. Whether written or not, the information available about the product after industrial design includes any and all information about the product that is essential to its marketing. Thus it will include qualitative or fuzzy statements of the marketing rationale and the in-use function of an artifact as perceived by potential customers, including any special in-use features the product is to have. It will certainly include any visual or other physical characteristics that are considered essential to marketing the product.

The product marketing concept or specification should, however, contain as little information as possible about the engineering design and manufacture of the product. This is to allow as much freedom as possible to the engineering design and production phases that follow. Such a policy is called *least commitment*, and it is a good policy at all stages of product realization. The idea is to allow as much freedom as possible for downstream decisions so that designers are free to develop the best possible solutions unconstrained by unnecessary commitments made at previous stages.

Some engineers who like things to be quite precise will fret over the fact that the definition of the product marketing concept, and any associated product marketing specification, is fuzzy. However, the activity of industrial design that produces the product marketing concept is creative, involves aesthetics and psychology, and naturally produces somewhat imprecise results. Industrial design is, nevertheless, extremely important to the product realization process. Engineers should respect it, and learn to live and work cooperatively with it—frustrating though it may be on occasion.

The use of the terms *industrial design* or *product design* to describe this phase of product development is clearly misleading. Both terms are nevertheless in customary use—and there is no hope of changing the custom. Logically, the whole product development process, including engineering design, could be accurately called product design. More accurate terms for industrial or product design would be preliminary product concept design or marketing product concept design, but we will generally adhere to the more commonly used industrial design in this book.

1.5 ENGINEERING DESIGN

Engineering design generally follows but overlaps industrial design, as illustrated in Figure 1.1. Engineering design consists of four roughly sequential but also overlapping stages or subprocesses, each corresponding to a design problem type:

engineering conceptual design;
configuration design of parts;
parametric design; and
detail design.

The first three of these basic engineering design problem types are introduced very briefly below.

Engineering Conceptual Design

Several variations of the engineering conceptual design problem are encountered in the course of engineering design. The variations are slight and depend on whether the object being designed is

(1) a new product (usually an assembly),
(2) a subassembly within a product, or
(3) a part within a product or subassembly.

The desired state of information that is to result from the engineering conceptual design process is called the physical concept. It includes information about the physical principles by which the object will function. In addition, in the case of products and their subassemblies, the physical concept also includes identification of the principal functional subassemblies and components of which the product will be composed, including particular functions and couplings within the product. By "couplings" we mean their important interrelationships, such as physical connections, or the sharing of energy or other resources.

Engineering conceptual design problems, like all major engineering design problem types, are solved by guided iteration. The first step in the guided iteration process is problem formulation. In engineering conceptual design, this means preparation of an Engineering Design Specification. This Specification records the product's quantitative functional requirements as well as specific information on requirements for such factors as weight, cost, size, required reliability, and so on.

Generating alternatives in engineering conceptual design requires a creative process called *conceptual decomposition*, or just decomposition. We might, for example, decompose a wheelbarrow into a wheel subassembly, the tub, and the carrying handle subassembly. The subsidiary subassemblies and components that make up a product or subassembly are created during the decomposition process for a product or other subassembly. There are many options open to designers in this creative decomposition process, and many opportunities for innovation. The decomposition process is very important because the physical concepts chosen have a tremendous impact on the final cost and quality of the designed object.

For evaluating competing conceptual solutions, a number of methods are available, as discussed in, among other places, Dixon and Poli. The conceptual design of parts is a bit different from the issues in the design of products and subassemblies, and it is discussed separately in Dixon and Poli.

An activity that permeates the engineering design process is the selection of the materials of which the parts are to be made, as well as the processes by which they are to be manufactured. Because there are literally thousand of materials and hundred of processes, these problems of choice are complex. Moreover, materials, processes, and the functional requirements of parts must all be compatible. Though most often it is only necessary at the conceptual design stage to select the broad class of material and process (e.g., plastic or thermoplastic injection molded, or aluminum die cast), we will cover the subject of materials and process selection rather fully in Chapter 13, "Selecting Materials and Processes for Special Purpose Parts."

Configuration Design of Parts and Components

During the conceptual design of products and their subassemblies, a number of components (that is, standard modules, standard parts, and special purpose parts) are created as concepts.

In the case of standard modules and standard parts, configuration design involves identifying and selecting their type or class. For example, if a standard module is a pump, then configuration design involves deciding whether it is to be a centrifugal pump, a reciprocating pump, a peristaltic pump, or some other type. Another example: if a standard part is to be a spring, then configuration design involves deciding whether it is to be a helical spring, a leaf spring, a beam spring, or another type.

For special purpose parts, configuration design includes determining the geometric features (e.g., walls, holes, ribs, intersections, etc.) and how these features are connected or related physically; that is, how the features are arranged or configured to make up the whole part. In the case of a beam, for example, configuration design makes the choice between I-beam or box beam and all the other possible beam cross-section configurations. The features in an I-beam are the walls (called *flanges* and *web*), and they are configured as in the letter "I."

At the configuration design stage, exact dimensions are not decided, though approximate sizes are generally quite obvious from the requirements of the Engineering Design Specification.

More information about material classes and manufacturing processes may be added at the configuration stage if the information is relevant to evaluating the configuration during the guided iteration process. For example, it may be necessary for evaluation to know that a high-strength engineering plastic is to be used, or that an aluminum extrusion is to be heat-treated to a high level of strength. However, this more detailed information should be generated only if it is really needed; least commitment is always the basic policy.

Configuration design of special purpose parts begins with problem formulation, usually in the form of a part requirements' sketch. Once the requirements are established in a sketch, then alternative configurations are sketched and evaluated with important help from qualitative reasoning based on physical principles and, it is hoped, DFM concepts.

Parametric Design

In the parametric design stage, the initial state of information is the configuration. In other words, just about everything is known about the designed object except its exact dimensions and tolerances. It may also be in some cases that the exact material choice is also unknown, though the basic class of material will usually be included in the configuration information.

The goal of parametric design, therefore, is to add the dimensions and any other specific information needed for functionality and manufacturability. The specific material is also selected if it has not previously been designated. In other words, parametric design supplies all the dimensions, tolerances, and detailed materials information critical to the design consistent with both the marketing concept and the Engineering Design Specification.

In the spirit of least commitment design, parametric design need not and should not specify information to any degree of precision that is not actually required by the Specifications, but most dimensions are in fact usually determined at the parametric stage.

Detail Design

Detail design supplies any remaining dimensions, tolerances, and material information needed to describe the designed object fully and accurately in preparation for manufacturing. As every manufacturing engineer knows, in a large complex product, the result seldom provides all the dimensions and tolerances that exist. The rest of the details, if needed, are established in the manufacturing design phase.

1.6 PRODUCTION DESIGN

Production design overlaps with detailed design. It involves, for example, finishing any of the design details left undone by detailed design, detailed design of the tooling, planning the manufacturing process, planning for quality control, "ramping up" the actual production, planning for quality and process control, and supporting the initial production runs. It is a substantial design task, though it is usually referred to as a part of the overall manufacturing or production process.

1.7 SCOPE OF THE BOOK

1.7.1 Mode of Operation in Industry

The sequential mode of operation depicted in Figure 1.2 is still the prevalent mode of operation found in industry today. Although changes are taking place, "old habits are hard to break," and the linear sequence displayed still seems to prevail.

As shown in Figure 1.2, the sequence begins with the conception of an idea for a new or revised product. These ideas for new and improved products commonly come from customers, employees, and new technology.

Customers

Competitive manufacturing businesses require constant feedback from the customers who buy, sell, repair, or use the company's products. Getting such feedback cannot be left to chance or to mail surveys, or even to formal complaint records, though such mechanisms are certainly a part of the process. There are marketing professionals who know how to get this information. But in addition, if a design engineer is looking for positive new ideas as well as for shortcomings

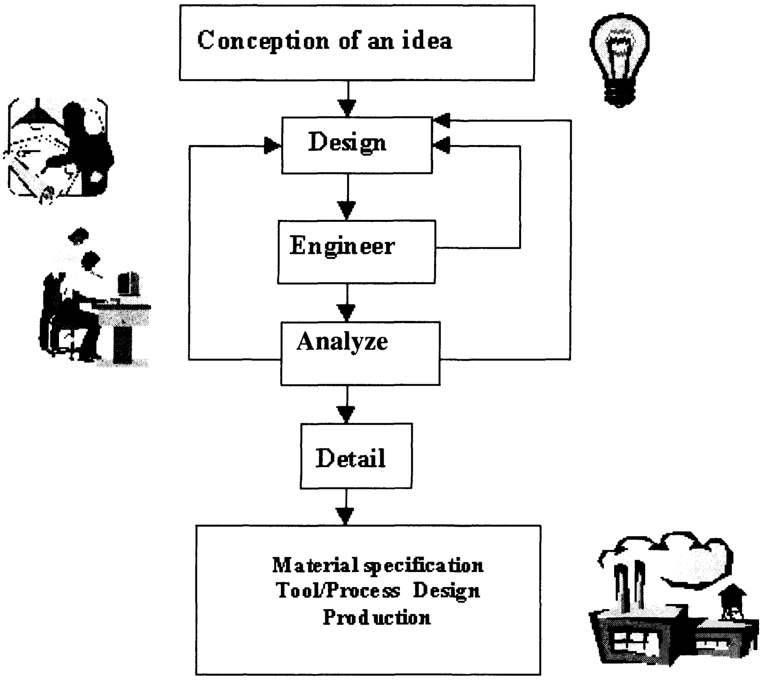

FIGURE 1.2 *Sequence of events prevalent in industry for the design and manufacture of products.*

of current products, then he or she must get out personally and talk to the customers.

A famous example is the Japanese automaker who sent design engineers to talk to a large number of American shoppers in supermarket parking lots discovering, among other things, that making it easy to get heavy grocery bags into and out of car trunks was a convenience valued by many potential customers.

Design and product development engineers must also get out and talk to their "customers" within the company. These include not only marketing people, but also manufacturing engineers, analysts, draftsmen, accountants, and others.

Employees

Employees in the factory, shops, and offices are also an extremely valuable source of new ideas for products and product improvements. Good practice requires that there must be a believable, financially rewarding, well understood, and low threshold (i.e., easy) mechanism for employees to get their new product, product improvement, and process improvement ideas heard and seriously considered.

Employees must also get rapid feedback on what happens to their ideas (good and bad), and why.

New Technology

Keeping abreast of new technologies and methodologies in materials, manufacturing, design, engineering, and management is another important source of ideas for new and improved products. Coupling new technological information with the search for new or improved product ideas is an essential part of the product development process that is not, strictly speaking, engineering design as we have defined it. But it is important for engineering designers to be able to contribute for best results within a company.

Upon approval of the idea, the new or improved product is then designed, engineered, and analyzed for function and performance. The design phases in this case consist of (a) an industrial or product design phase in which artistic renderings or nonfunctional models are produced, and (b) an engineering design phase. In the engineering phase of the design the decision of whether to use standard or special purpose parts is made. In the case of special purpose parts, the overall geometric configuration of the parts is first determined (box-shaped, flat, etc.), as well as the presence and location of various features such as ribs, holes, and bosses. Following this configuration design, a parametric design phase takes place in which more detailed dimensions and tolerances are added.

Next an analysis of the design from the point of view of function and performance takes place. Subsequently the design is detailed as the remaining dimensions and tolerances are added, the material is specified, and production drawings are produced. Finally, the product is turned over to manufacturing where both production design and process design takes place.

1.7.2 Goals of This Book

According to high-ranking representatives from industry, there are two main problems with the sequential approach depicted in Figure 1.2:

1. Decisions made during the early conceptual stages of design have a great effect on subsequent stages. In fact, quite often more than 70% of the manufacturing cost of a product is determined at this conceptual stage, yet manufacturing is not involved.

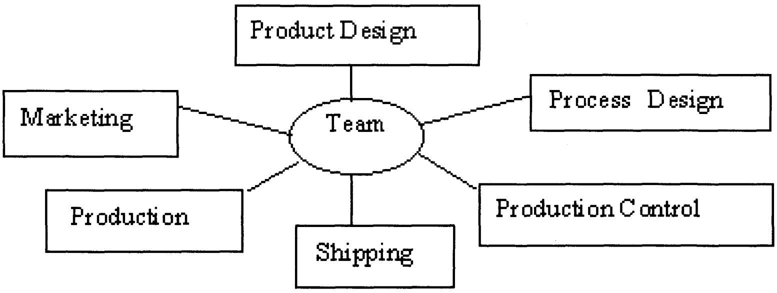

FIGURE 1.3 *The team approach often used in industry.*

2. No single person or group is in charge. Each group blames the other for problems. Subsequently, difficulties and delays occur and the design and manufacturing process goes out of control.

Two possible solutions that have been proposed are:

1. Form teams (Figure 1.3) that involve everyone from the beginning to the end of the entire life cycle. In the team approach, product design and process design take place concurrently. With the team approach, an approach often used with success in industry, the team is in charge of the product from cradle to grave.
2. Educate designers about manufacturing. In other words, make designers more manufacturing literate.

The overall goals of this book are centered on this latter solution, namely to educate students as to how parts are manufactured and to train them to recognize costly-to-produce features (cost-drivers) so that they can be avoided.

1.7.3 Manufacturing Processes Considered

The vast majority of consumer products today consist of both standard parts and special purpose parts. Many of the special purpose parts are thin-walled parts produced by injection molding, die casting, and stamping. Occasionally a forged component is present as well. For this reason, and in order to best meet the goal of making designers more manufacturing literate, the emphasis in this book is on the study of these four processes. In particular, we will study the effect of part geometry on the ease or difficulty of creating the tooling required to produce the part and the effect that geometry and production volume have on both processing costs and overall part costs.

There are obviously other important manufacturing processes. For example, *machining* is used to create the dies and molds needed to produce parts by the processes mentioned above and one-of-a-kind parts. *Rolling* is used to produce structural shapes, rails, sheets, large diameter tubes, strips, and plates, and drawing is used to produce bars, wires, and small diameter tubes. *Extrusion* plays an important role in the production of long metal objects whose cross-sectional shapes are constant. And, of course, there are also a whole host of other casting processes (*sand casting, investment casting,* etc.) and polymer processing methods (*extrusion, compression molding, transfer molding*, etc.) used to produce thin-walled parts. Since these processes are adequately treated elsewhere (*American Society of Metals Handbook*, Vols. 14, 15, and 16), their treatment here will be limited.

The emphasis, as indicated above, will be on those processes used to produce the vast majority of special purpose parts found in consumer products today.

1.8 SUMMARY

This chapter has described the product realization process and to the three main stages of engineering design, namely, engineering conceptual design, part configuration design, and parametric design. All of these design stages use guided iteration, a method discussed in greater detail in Dixon and Poli, 1995, as a problem solving methodology and all involve design for manufacturing (DFM).

In the chapters that follow, a number of common manufacturing processes and their associated qualitative DFM guidelines are described. Of course, whole books are written that describe each of these processes in much more detail. The purpose of this book is limited, however, thus, we need only present sufficient information for a reasonable understanding of the rationale for the DFM guidelines.

Before beginning our discussion of DFM, we review, in the next chapter, tolerances, mechanical properties, and physical properties.

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QUESTIONS AND PROBLEMS

1.1 What is the smallest functional designed object you have heard of? The largest?

1.2 In a bicycle (or thermostat or other product of your choice), give an example of a standard part, a special purpose part, a special purpose subassembly, a standard module, and a component.

1.3 Have you ever used the basic guided iteration process to solve a design problem? If so, describe your experience, noting especially how you implemented each of the steps.

1.4 Have you ever used the basic guided iteration process to solve a problem other than a design problem? If so, describe your experience, noting especially how you implemented each of the steps.

1.5 Go to your library and find at least one book on design for manufacturing and read its introductory chapter and the preface. Report back to the class on how it is the same and how it is different from this chapter.

1.6 In Figure 1.1, identify the stages that constitute "product development" as defined in this chapter.

1.7 What are the disadvantages to the sequential mode of operation depicted in Figure 1.2?

1.8 Can you think of any disadvantages to the mode of operation depicted in Figure 1.3?

Chapter 2

Tolerances, Mechanical Properties, Physical Properties—A Review

2.1 INTERCHANGEABILITY OF PARTS

At first glance it might appear that a car's fuel pump, a laser jet printer cartridge, and an ordinary lightbulb have nothing in common. This is because what they do have in common we simply take for granted. For example, when our fuel pump goes we assume that we can go to our local auto parts supplier, and that, upon supplying the make, model, and year of our car, we can pick up a pump and "easily" replace the old pump with the new one. The same is true of our printer cartridge and lightbulb. We assume that we can purchase a replacement part and that it will fit—we assume that the parts will be interchangeable.

It has not always been possible to interchange parts. In the early days of manufacturing, each assembly operator was responsible for producing every individual piece-part and then making adjustments to the parts in order to complete the final assembly. Components on one assembly could not be interchanged with those on another assembly. For example, during the Revolutionary War, components from one musket would not be interchangeable with "identical" components from another musket.

Modern manufacturing, be it the high-volume mass production of cars, pens, or watches, or the low-volume batch production of computers, copy machines, or printers, depends on the interchangeability of parts.

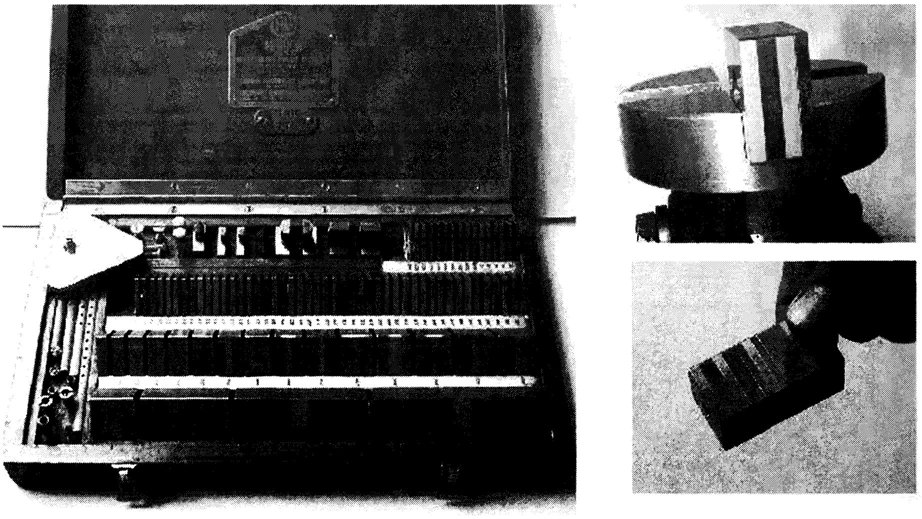
2.1.1 Size Control

Interchangeability depends on size control, and size control depends upon the existence of a standard unit of length and suitable measuring equipment such as *gage blocks*, *dial gages*, *calipers*, *steel rules*, and other measuring instruments (Figures 2.1 and 2.2). Size control also depends upon the inspection of parts and quality control.

2.2 TOLERANCES

2.2.1 Introduction

A tolerance is a designer-specified allowed variation in a dimension or other geometric characteristic of a part. Proper tolerances are crucial to the proper



Developed by Carl Johansson of Sweden around 1900, gage blocks saw limited use in World War I. Henry Ford brought him to the U.S. after WWI and was responsible for the large scale production and use of gage blocks. Gage blocks are end-standards and can be used for direct measurement, as in measuring the width of a groove or keyway (top right), or for calibrating line standard measuring instruments (Fig. 2.2). The insert on the bottom right shows several gages blocks wrung together in order to produce a special purpose gage block dimension.

FIGURE 2.1 *Gage blocks.*

FIGURE 2.2 *Some line standard measuring instruments (micrometer on left, vernier caliper on the right) used for size control.*

functioning of products. However, the most common cause of excessive manufacturing cost is the specification by designers of too many tolerances or tolerances that are tighter than necessary.

On part drawings, simple dimensional tolerances are usually attached to dimensions, as shown in Figures 2.3 and 2.4.

The issue of tolerances may be found at the intersection between the requirements of functionality and the capabilities of manufacturing processes. Mass-produced parts cannot all be produced to any exact dimensions specified by designers. In a production run, regardless of the process used, there will always be variations in dimensions, from the nominal; that is, not all parts produced will have the same dimensions. Some of the reasons are: tools and dies wear; processing conditions change slightly during production; and raw materials vary in composition and purity. Modern methods for controlling processes are achieving

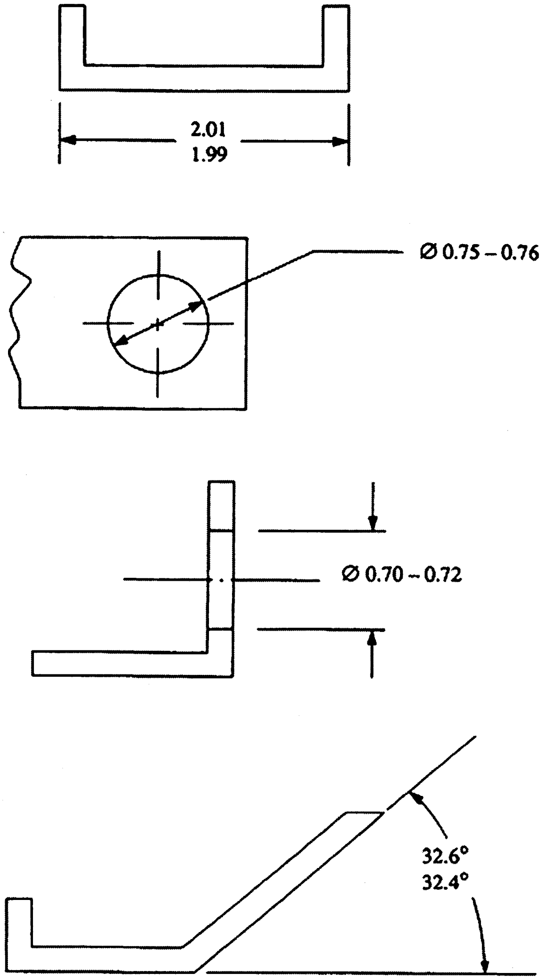


FIGURE 2.3 *Examples of limit tolerances.*

ever more consistent and accurate dimensions, but variations of some frequency and magnitude are inevitable. Different manufacturing processes are also inherently more capable of reducing these variations, and hence holding tighter tolerances, than others.

Tolerances can be specified by designers to limit the range of dimensions on parts that are to be considered acceptable. That is, designers can, in order to get the functionality required, limit the range of dimensional variations in those parts that reach the assembly line. However, the more strict these limitations are, and the more dimensions that are subject to special tolerance limitations, the more expensive the part will be to produce.

Fortunately, the functionality of parts seldom, if ever, requires that all or even most dimensions of parts be controlled tightly. To achieve the desired functionality (and other requirements) of a part, a few dimensions and other geometric characteristics (e.g., straightness or flatness) may require quite accurate control, while others can be allowed to vary to a greater degree. Thoughtful design can result in parts and assemblies configured so that the number of characteristics

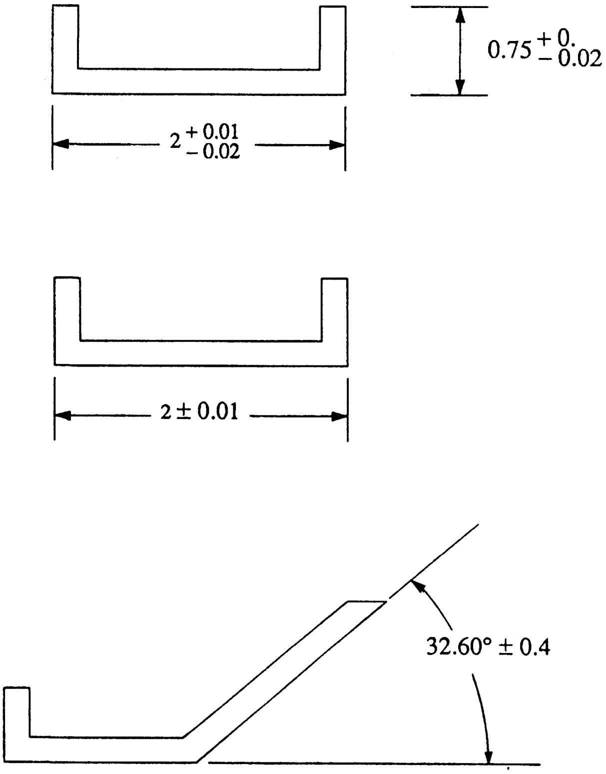


FIGURE 2.4 *More limit tolerances.*

requiring critical control is minimal. Also, those dimensions that do require critical control may be of a type or at a location where they are more easily controlled during manufacturing.

Every manufacturing process has what are most often called standard or commercial tolerances. These are the tolerance levels that can be produced with the normal attention paid to process control and inspection. Though standard tolerance values are not always completely and accurately defined—and available in print for designers—they are well known to manufacturing process engineers. There is no need to guess; designers can go visit their friendly manufacturing colleague.

Parts designed so that there are no tolerance requirements tighter than standard will be the least expensive to produce. Moreover, and this is an important point for designers, the number of tolerances that must be critically controlled, whether standard or tighter, is crucial to the ease and cost of manufacturing. Controlling one or two critical dimensions, unless they are of an especially difficult type or extremely tight, is often relatively easy to do if the other dimensions of the part do not need special control.

2.2.2 Some Definitions

Before providing a precise definition of tolerance we must first understand some preliminary definitions. The *limits of size* are the two extreme permissible sizes of a part between which the actual size must lie. For the part shown in Figure 2.3

the *maximum limit of size* is 2.01. The *minimum limit of size* for this same part is 1.99. *Tolerance* is the difference between the maximum limit of size and the minimum limit of size. For the part shown in Figure 2.3 the tolerance, T_a, is 0.02.

The size by reference to which the limits of size are fixed is called the *basic size*. For the parts shown in Figure 2.4 the basic size is 2.

Tolerances can be applied bilaterally, as shown in Figure 2.4, or unilaterally as indicated below.

$$2^{+0.02}_{-0.00}$$

When parts must fit together (a shaft inside a hole, for example), the tolerances on both parts must be considered simultaneously. The relationship resulting from the difference, before assembly, between the sizes of the two parts to be assembled is called the *fit*.

A *clearance* exists if the diameter of the hole is greater than the diameter of the shaft. This allows for relative movement (translation or rotation) between the two parts. An *interference* exists if the diameter of the hole is less than the diameter of the shaft. This is used when an alignment of parts is required or stiffness is needed.

As stated above, regardless of the process used, there will always be variations in dimensions from the nominal, and not all parts produced will have the same dimensions. Hence, in the case of a shaft and hole, a *clearance fit* exists if the minimum hole diameter is greater than the maximum shaft diameter. An *interference fit* is said to exist if the maximum hole diameter is less than the minimum shaft diameter. A *transitional fit* is said to exist if we sometimes get clearance and sometimes get interference.

At times there is a tendency to confuse tolerance with allowance. Allowance is the intentional desired difference between the dimensions of two mating parts. It is the difference between the dimensions of the largest interior-fitting part and the smallest exterior-fitting part. In the case of a clearance fit, allowance is the minimum clearance between the two parts. In the case of an interference fit, allowance is the maximum interference between two mating parts.

Example

If D_H represents the diameter of a hole and D_S represents the diameter of a shaft, then can you explain why the following hole-shaft combination results in a transitional fit?

$$D_H = 50.00^{+0.10}_{-0.00}$$

$$D_S = 50.00^{+0.10}_{-0.00}$$

2.3 MECHANICAL AND PHYSICAL PROPERTIES

2.3.1 Introduction

The design of special purpose parts involves the determination of a material class (steel, aluminum, thermoplastic, etc.) and the basic manufacturing process to be used (injection molding, forging, die casting, etc.). A part's size, shape, and geometry, and the material's mechanical and physical properties, affect the choice of material-process combination. Chapters 3 to 11 are devoted to a discussion of how a part's size, shape, and geometry affect the ease or difficulty of producing a part by various processes. Chapter 13, "Selecting Materials and Processes for Special Purpose Parts," presents a general methodology for selecting one or more material-process combinations for special purpose parts at the conceptual design stage. In the remainder of this chapter we will briefly review what is meant by the mechanical and physical properties of materials.

2.3.2 Mechanical Properties

Mechanical properties of materials are generally expressed in terms of the elastic behavior of the material, the *yield stress*, σ_y, and the *ultimate stress*, σ_u. The elastic behavior is characterized by *Young's modulus*, E, and the *engineering stress*, σ_e.

The most common method for determining these properties is via a uniaxial tension test. In this test a test specimen is placed in a tensile testing machine (Figure 2.5) and subjected to increasing loads in order to elongate it until it fractures.

Engineering stress, we know, is defined as

$$\sigma_e = \frac{P}{A_o}$$

and engineering strain is defined as

$$\varepsilon_e = \frac{l - l_o}{l_o}$$

In this case P is the tensile load applied to the specimen, A_o is the initial cross-sectional area of the specimen, l_o is the original gage length of the specimen, and l is the final length.

Also in common use are the *true stress*, defined as

$$\sigma = \frac{P}{A}$$

and the *natural strain*, defined as

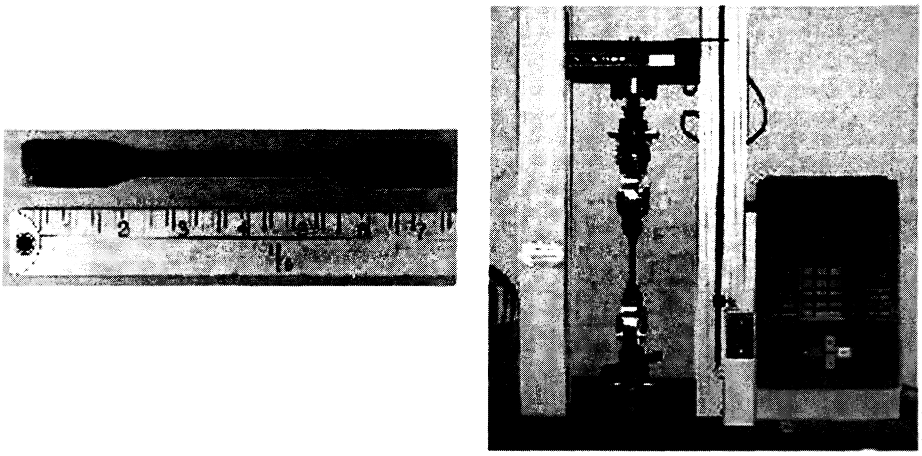


FIGURE 2.5 *A test specimen being subjected to uniaxial loads.*

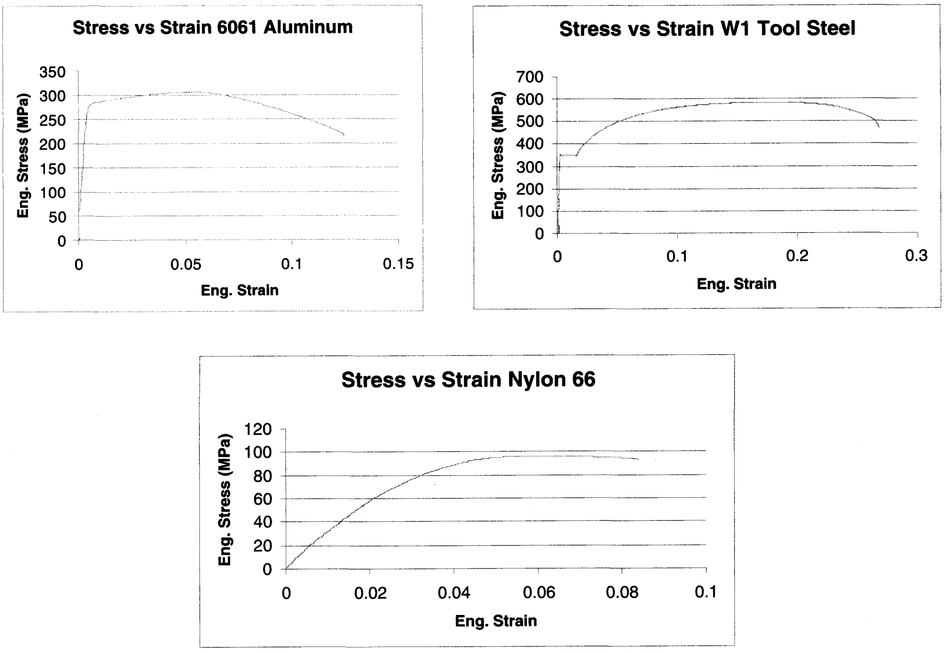


FIGURE 2.6 *Plots of engineering stress versus engineering strain for some specimens tested using the apparatus shown in Figure 2.5.*

$$\varepsilon = \ln\left(\frac{l}{l_o}\right)$$

In this case the true cross-sectional area is represented by A.

It is easy to show that the natural strain and engineering strain are related by the following expression, namely,

$$\varepsilon = \ln(1+\varepsilon_e)$$

Figure 2.6 shows some test results obtained using the setup shown in Figure 2.5. The actual shape of the curve depends upon the specific material or alloy used. Figure 2.7 shows a plot of true stress versus natural strain superimposed upon a plot of the engineering stress versus engineering strain curve for the 6061 aluminum specimen shown in Figure 2.6.

Figure 2.7 shows that while the engineering stress reaches a maximum, referred to as the ultimate tensile stress (UTS), and then decreases until the specimen fractures, the true stress always increases. This is due to the fact that the actual cross-sectional area continually decreases.

A study of the curves shown in Figure 2.7 shows that both curves have linear and nonlinear regions and that initially the two curves coincide. In the linear region where E is the slope of the curve and is referred to as Young's modulus

$$\sigma_e = E\varepsilon_e$$

Young's modulus is a measure of the stiffness of the beam and is used in the calculation of the deflection of beams. In this region, if the load is released the specimen returns to its original length.

Beyond the elastic limit, the test specimen will not return to its original length upon removing the load. In this nonlinear region the specimen is said to deform

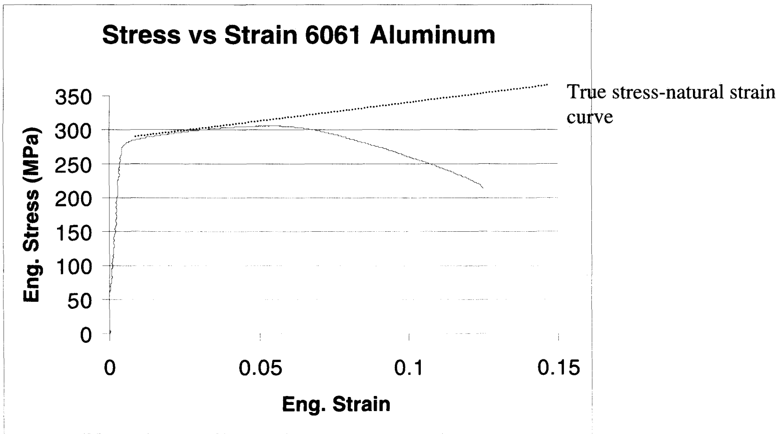


FIGURE 2.7 *A true stress–natural strain curve for 6061 aluminum superimposed on an engineering stress–engineering strain curve.*

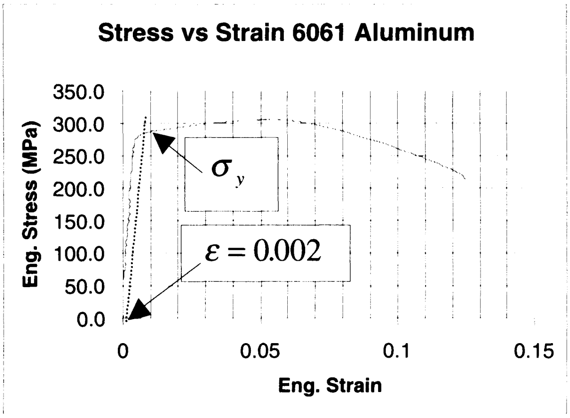


FIGURE 2.8 *Determination of the offset yield stress.*

plastically. In general it is difficult to determine the exact value of the stress when elastic deformation no longer takes place. The offset yield stress, σ_y, is used to indicate where plastic deformation begins. It is determined as indicated in Figure 2.8.

Knowing the value of the yield stress is important in design where in general we prefer not to obtain stresses that will result in permanent deformation of our product. Knowing the value of the yield stress is also important in metal forming where in general we do wish to obtain permanent deformation.

The true stress–natural strain curve is often represented by the following expression, namely,

$$\sigma = K\varepsilon^n$$

where K is a constant (= E in the elastic region) and n is referred to as the strain-hardening coefficient (= 1 in the linear region; varies between 0.1 and 0.5 in the nonlinear or plastic region). At necking, which begins when the engineering stress becomes equal to the ultimate tensile stress, it can be shown that the natural

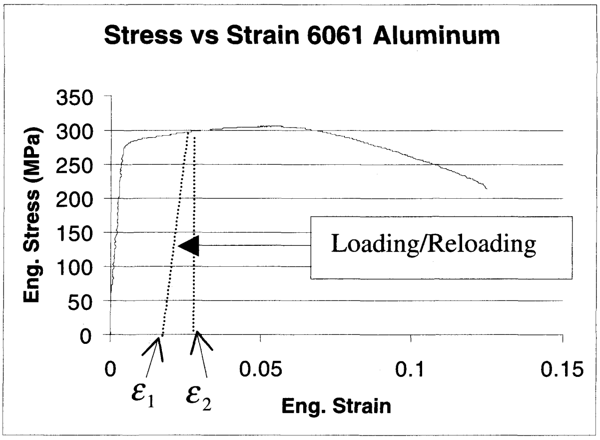


FIGURE 2.9 *Stress-strain curve showing the effects of loading and reloading in the non-linear regions of the curve.*

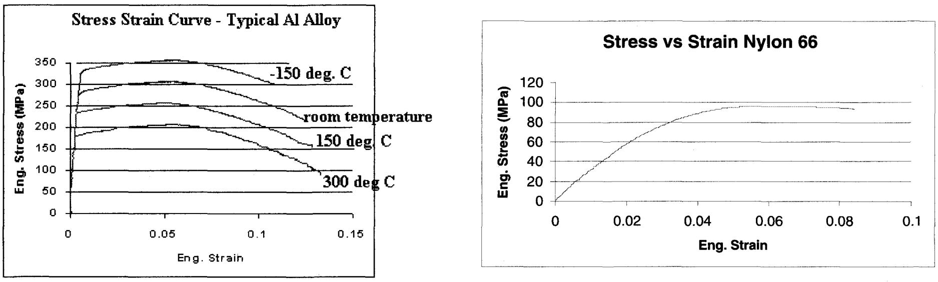


FIGURE 2.10 *Stress-strain curves for a typical aluminum alloy (plots on the left) at various temperatures and the stress-strain curve for nylon 66.*

strain, ε, is equal to n. Thus, the higher the value of n the greater the amount of elongation that can take place before the onset of necking—that is, the more ductile the material.

When the specimen is stretched beyond the yield point and then unloaded, it follows a path parallel to the linear region (Figure 2.9). Reloading the specimen will result in retracing our steps along the same curve we followed when unloading the specimen. As seen in Figure 2.9 the new yield stress is increased in value. This phenomena is referred to as strain hardening. *Springback*, which is the difference in the value of the strain when the specimen is loaded and the value of the strain when the specimen is unloaded, places an important role in the creation of stamped sheet-metal parts. For example, because of springback, a part that is to be bent, say 30°, must be over bent in order to accommodate springback.

2.3.3 Metals versus Plastics

In this section we briefly review some of the basic differences between metals and plastics. Figure 2.10 helps explain some of these differences.

Figure 2.10 shows that as the temperature changes the shape of the curve and the modulus of elasticity, E remains essentially the same. Figure 2.10 also shows that the yield stress, σ_y, the ultimate tensile stress, UTS, and strain hardening all decrease. In addition, it turns out that over a reasonably wide temperature range around room temperature, the value of E varies only slightly.

On the other hand, the modulus for plastics can change dramatically with both time and temperature, even for temperature changes of as little as 20°C. In addition, the shape of the curve changes with temperature and the material "creeps." Hard plastic generally refers to a plastic with a high modulus, a strong plastic is one with a high tensile yield stress.

2.4 PHYSICAL PROPERTIES OF MATERIALS

The physical properties of materials also play a significant role in the selection of a material-process combination for the production of special purpose parts. By physical properties we mean such characteristics as the *melting point, thermal conductivity, density, specific heat, thermal expansion, electrical conductivity, electrical resistivity*, and *corrosion resistance.*

The melting point of a material can affect energy costs for shaping parts via injection molding and casting. Thermal conductivity, which is a measure of the ease with which heat flows through a material, affects cycle time, hence, processing costs. Metals have high values of thermal conductivity, and ceramics and plastic have low thermal conductivity.

Density, of course, is important when considering strength-to-weight ratios as well as stiffness-to-weight ratios and weight savings. Low values of specific heat, which is a measure of the energy required to raise the temperature of a unit mass of material by one degree, cause temperatures to rise while processing the material. This can have a detrimental effect while machining because the workpiece can become too hot to handle and can result in a poor surface finish.

The amount of thermal expansion that takes place depends on the value of the coefficient of thermal expansion. The amount of thermal expansion that takes place is important when clearances and running fits are needed in an assembly.

Corrosion resistance or degradation is a measure of the ability of a metal or plastic to resist deterioration. This plays an extremely important role in the selection of a material for a given part and in turn affects which processes can or cannot be used to produce the part. For example, steel has poor resistance to corrosion and stainless steel has high resistance to corrosion.

In summary, selecting a material based on physical properties affects the choice of the process and the ease or difficulty of forming the material. For example, stainless steel resists corrosion but, as we will find out in Chapter 6, "Metal Casting Processses," it cannot be die cast. Also, stainless steel has a higher melting temperature than plastics, which implies that more energy is required to melt stainless steel. Although in some applications titanium may be a good choice based on its physical and mechanical properties, titanium is also more difficult to forge than aluminum due to its higher yield strength.

2.5 SUMMARY

This chapter has described the importance of the interchangeability of parts to modern manufacturing. In addition, this chapter has also discussed how the physical and mechanical properties of materials can effect the choice of process to be used to manufacture a part, and how these properties can affect the ease or difficulty of creating the part via a particular process.

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QUESTIONS AND PROBLEMS

2.1 Why is the interchangeability of parts important in the production of consumer products?

2.2 Explain the difference between tolerance and allowance.

2.3 What type of fit would best describe the following:
- a) Cork in a wine bottle.
- b) Floppy disk at the entrance to a floppy drive.
- c) Cover of a ballpoint pen.
- d) Laser printer cartridge and the printer.

2.4 Discuss the difference between true stress and engineering stress, and natural strain and engineering strain. Which stress-versus-strain curve makes more sense?

2.5 Imagine you are faced with the situation of choosing a metal that has high ductility. Can you define what is meant by ductility? How would you recognize which material has the higher ductility?

2.6 Name a product or component of a product for which physical properties are more important than mechanical properties. Explain!

2.7 Describe situations where it would be desirable to have a part that has:
- a) high density,
- b) low density,
- c) high melting point,
- d) low melting point,
- e) high thermal conductivity,
- f) low thermal conductivity.

2.8 Imagine you are faced with the decision of choosing between a plastic or a metal for a part you are designing. What are some of the reasons you would use for selecting plastic? What are some of the reasons you would use to select a metal?

Chapter 3

Polymer Processing

3.1 THE PROCESSES

A large number of polymer processing techniques exist; among the most common are injection molding, compression molding, transfer molding, extrusion, and extrusion blow molding.

Injection molding, compression molding, and transfer molding are capable of the economical production of complex parts (with significant levels of geometric detail) and simple parts (with little detail). Extrusion is limited to the production of long parts with a uniform cross-section. Extrusion blow molding is confined primarily to relatively simple hollow objects such as bottle containers. Each of these processes is described in more detail later in this section.

3.2 MATERIALS USED IN POLYMER PROCESSING

There are literally hundreds—maybe thousands—of polymeric materials available for processing, and more will continue to be developed. In general, these materials fall into two broad classes: thermoplastics and thermosets. Some polymers are available in both thermoplastic and thermoset formulations.

Thermoplastic materials, like water and wax, can be repeatedly softened by heating and hardened by cooling, and are formed into parts primarily by injection molding, extrusion, and extrusion blow molding.

For common product applications, most parts made by injection molding use thermoplastic materials. Examples are gears, cams, pistons, rollers, valves, fan blades, rotors, washing machine agitators, knobs, handles, camera cases, battery cases, telephone and flashlight cases, sports helmets, luggage shells, housings and components for business machines, power tools, and small appliances.

Thermoplastics are divided into two classes: crystalline and amorphous. Crystalline thermoplastics have a relatively narrow melting range. They are opaque, have good fatigue and wear resistance, high but predicable shrinkage, and relatively high melt temperatures and melt viscosities. Reinforcement of crystalline polymers with glass fibers or other materials improves their strength significantly. (Such reinforced plastics are often called composites.) Examples of crystalline plastics include acetal, nylon, polyethylene, and polypropylene (PP).

Amorphous thermoplastics melt over a broader temperature range, are transparent, and have less shrinkage, but they have relatively poor wear and fatigue resistance. The use of reinforcing fibers does not significantly improve the strength of amorphous thermoplastics at high temperatures. Examples of amorphous materials are ABS, polystyrene, and polycarbonate.

It should be noted that although amorphous polymers have no crystallinity, no polymer is more than about 90% crystalline. Thus, many thermoplastic polymers exhibit a mixture of amorphous as well as crystalline properties.

The small number of thermoplastics noted above include some that are called commodity or general purpose plastics (polystyrene, polyethylene, and polypropylene) as well as engineering thermoplastics (ABS, polycarbonate, acetal, and nylon-6). The largest proportion of thermoplastics used are commodity plastics used to produce film, sheet, tubes, toys, and such throwaway articles as bottles and food packaging. Compared to the commodity plastics, engineering thermoplastics are capable of supporting higher loads, for longer periods of time, and at higher temperatures.

Thermoset materials are polymeric materials that, similar to an egg, transform permanently on heating and cannot be remelted. Thermosets are formed primarily by compression molding and transfer molding. Parts made of thermoset materials can be subjected to higher temperatures without creeping, tend to have a harder surface, and are more rigid than thermoplastic parts made by injection molding. For this reason, parts used at higher temperatures (molded fryer pan housings, electrical connections, etc.), or parts that may be subjected to harsher environments (automotive carburetor spacers, automatic transmission thrust washers, etc.) are made of thermoset materials. Thus, such parts are formed by compression or transfer molding.

Typical thermosets include phenolics, ureaformaldehyde, epoxies, polyesters, and polyurethanes. Thermoplastics and thermosets can both be combined with one or more additives (colorants, flame retardants, lubricants, heat or light stabilizers), fillers or reinforcements (glass fibers, hollow glass spheres), or with other polymers to form a blend or alloy in order to increase dimensional stability and improve their mechanical properties. Some of the commodity plastics, such as polypropylene, are reclassified as engineering plastics when they are reinforced with glass fibers.

With all the basic polymer materials available, together with all the possible combinations of fillers and additives, there is a dizzying array of possibilities for designers to choose from. There are also pitfalls, as not all the properties of all these combinations are well known. Consultation with a polymer materials expert is well advised!

3.3 INJECTION MOLDING

In injection molding, thermoplastic pellets are melted, and the melt is injected under high pressure (approximately 10,000 psi or about 70 MPa) into a mold. There the molten plastic takes on the shape of the mold, cools, solidifies, shrinks, and is ejected. Figure 3.1 shows a stripped down version of an injection-molding machine along with a mold used to form a simple box-shaped part.

Molds are generally made in two parts: (1) the cavity half gives a concave part its external shape, and (2) the core half gives such a part its internal shape. As the geometry of a part becomes complex, molds of course increase in complexity—and hence in cost.

As a part cools, it shrinks onto the core. Therefore, an ejector system is needed to push the part off. Because the fixed (cavity) half of the mold contains the "plumbing system"—elements called runners, sprues, and gates—used to transfer the melt to the mold, the ejector system is usually in the core (moving) half of the mold. The ejector system generally consists of pins that are used to push the part off the core. Careful examination of most injection-molded parts will reveal the marks of the ejection pins—slight circular depressions about 3/16 of an inch in diameter. If a satisfactory flat part surface area does not exist to accommodate a pin, then a blade may be used to press against a narrow rib or part edge to eject the part.

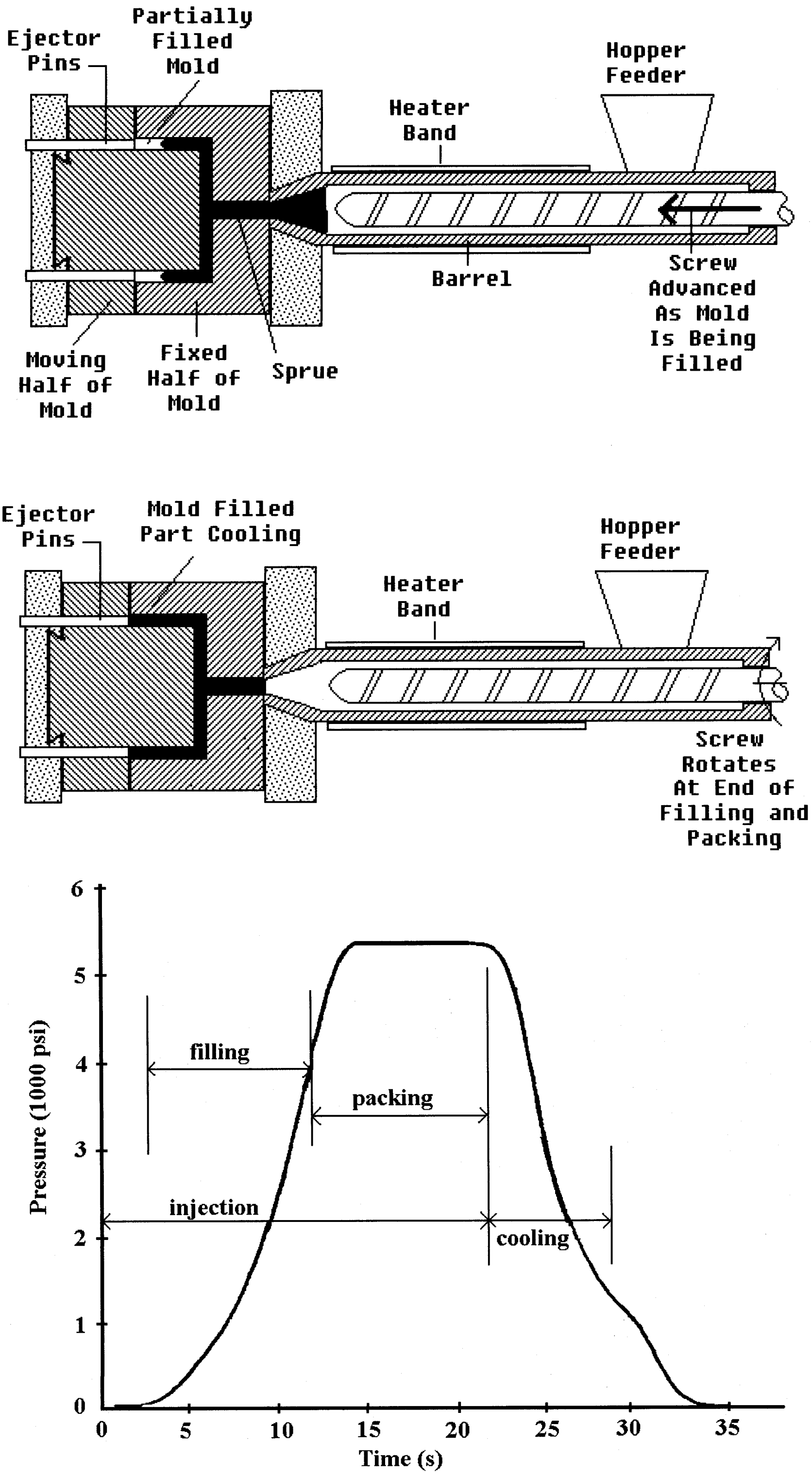

FIGURE 3.1 *Screw-type injection-molding machine.*

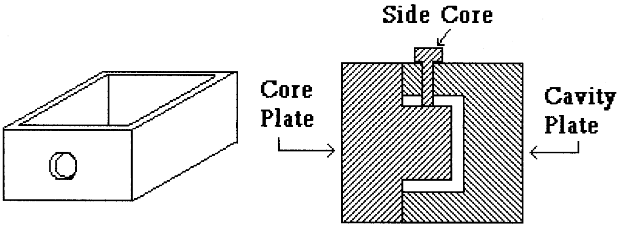

FIGURE 3.2 *Example of a part with an external undercut.*

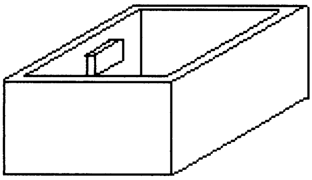

FIGURE 3.3 *Example of a part with an internal undercut.*

A through-hole feature in the vertical wall, such as the one shown in Figure 3.2, is referred to as an external undercut. To produce it requires a relatively costly side core to form the hole; the core is made to slide out of the way to permit ejection of the part. In general, external undercuts are features that will, without special provisions, prevent the part from being extracted from the cavity half of the die.

An internal undercut, such as the one caused by the projection that exists on the inner wall of the boxed-shaped part shown in Figure 3.3, is one that prevents the core mold half of the part from being extracted. In general, internal undercuts require even more costly molds than external undercuts.

Undercuts and their effect on tooling and processing costs for injection-molded parts are discussed in more detail in Chapter 4, "Injection Molding: Relative Tooling Cost," and Chapter 5, "Injection Molding: Total Relative Part Cost."

Per-part processing time (or cycle time) for an injection-molded part is primarily dependent on the time required for solidification, which can account for about 70% of the total cycle time. Solidification time in turn depends primarily on the thickness of the thickest wall. Typical solidification times for thermoplastic parts range from 15 seconds to about 60 seconds. Other part features that also influence cycle time are discussed in Chapter 5, "Injection Molding: Total Relative Part Cost."

3.4 COMPRESSION MOLDING

Compression molding for forming thermoset materials uses molds similar to those for injection molding. The mold (Figure 3.4), mounted on a hydraulic press, is heated (by steam, electricity, or hot oil) to the required temperature. A slug of material, called a charge, is placed in the heated cavity where it softens and becomes plastic. The mold is then closed so that the slug is subjected to pressures between 350 kPa (50 psi) to 80,000 kPa (12,000 psi) forcing the slug to take the shape of the mold.

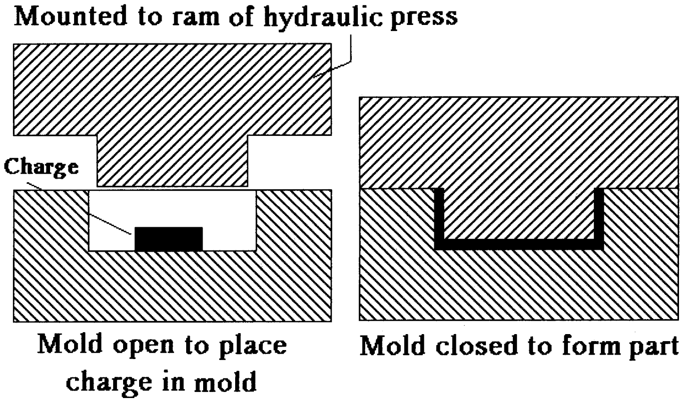

FIGURE 3.4 *Tooling for compression molding.*

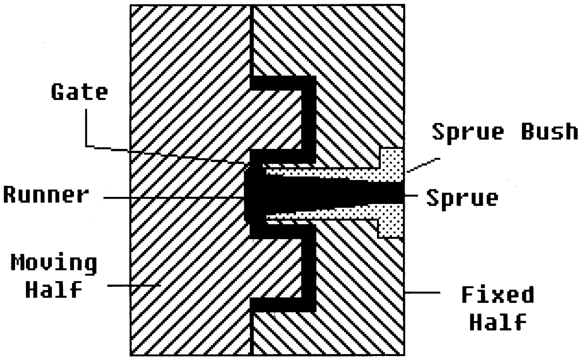

FIGURE 3.5 *Two-plate mold showing sprue, gate, and runner system.*

The mold remains closed under pressure until the part hardens (cures). The mold is then opened, the part removed, and the cycle repeated. The cure time for parts can be as low as 20 seconds for small, thin-walled parts, from 1 to 3 minutes for larger parts, and as long as 24 hours for massive, thick-walled parts such as an aerospace rocket nozzle.

Compression molded parts may have external undercuts, but as in injection molding, undercuts increase tooling cost and should be avoided if possible. Compression molds, however, are somewhat simpler than injection molds since the compression molds do not need a "plumbing system" (sprue, runner, and gates) to feed and distribute the melt. Figure 3.5 shows a two-plate injection molding-type mold with sprue, gate, and runner system.

3.5 TRANSFER MOLDING

The main difference between compression molding and transfer molding is in the mold. In a transfer mold (Figure 3.6), the upper portion of the mold contains a pot where a slug (or charge) is placed, heated, and melted. After the charge is melted the mold is closed, forcing the liquid resin through a sprue into the lower

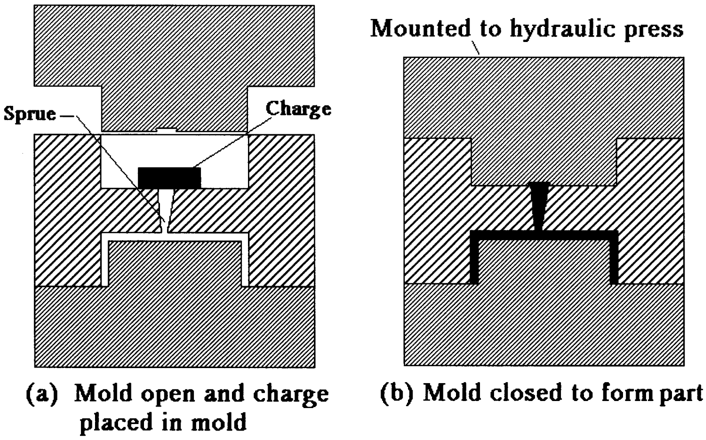

FIGURE 3.6 *Tooling for transfer molding.*

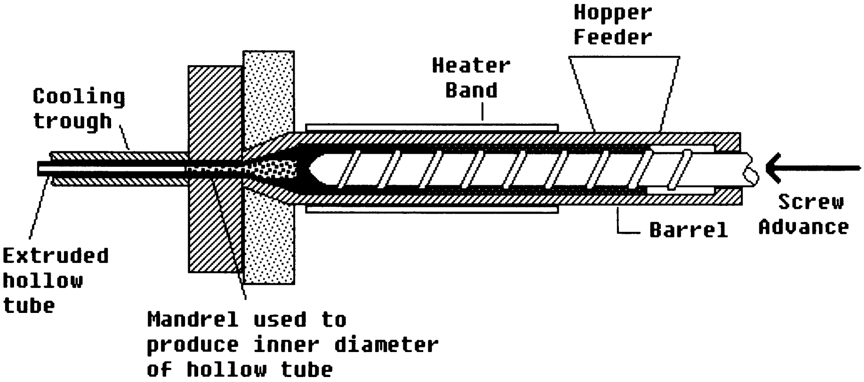

FIGURE 3.7 *A screw-type extruder.*

portion of the mold. The melt then takes the shape of the mold, hardens, and is removed.

3.6 EXTRUSION

Plastic extrusion is a process in which thermoplastic pellets are placed into a hopper that feeds into a long cylinder (called a barrel) that contains a rotating screw (Figure 3.7). The screw transports the pellets into a heated portion of the barrel where the pellets are melted and mixed to form a uniform melt. The resulting melt is then forced through a die hole of the desired shape to form long parts of uniform cross-section such as tubes, rods, molding, sheets, and other regular or irregular profiles. Figure 3.8 shows some common structural shapes produced by extrusion.

Extruded parts are generally long in comparison with their cross-section. Short parts with uniform cross-sectional shapes can also be produced by injection molding as well as extrusion, but the longer the part, the more advantageous the use of extrusion.

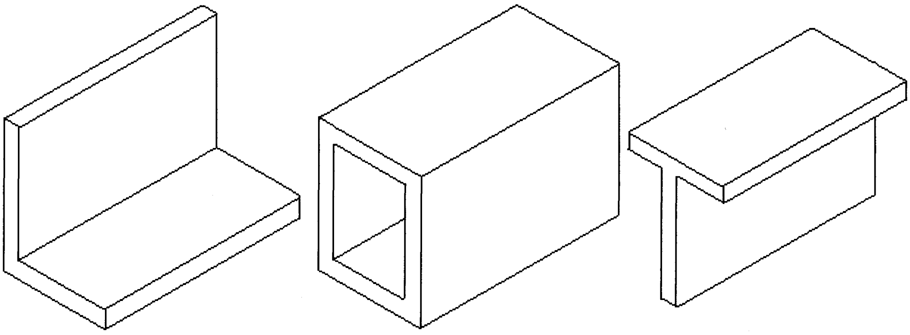

FIGURE 3.8 *Some common structural shapes produced by extrusion.*

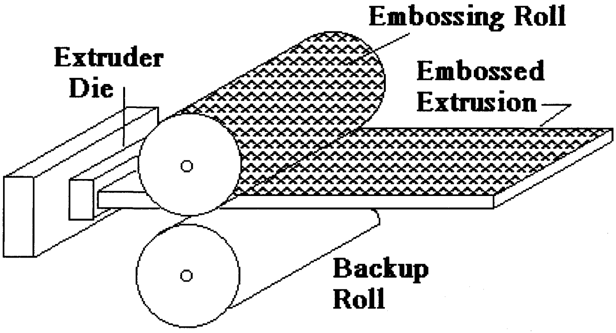

FIGURE 3.9 *Post-processing of extruded sheets.*

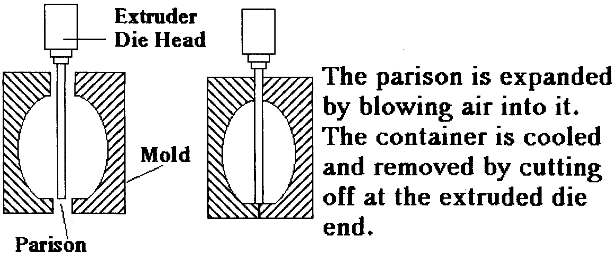

FIGURE 3.10 *Extrusion blow molding.*

Shapes formed by extrusion can be subjected to post-processing techniques by passing them through rollers (Figure 3.9) or stationary blades or formers that modify the shape of the (still hot and soft) extrusion. Sheets, for example, can be embossed to form patterns on them.

3.7 EXTRUSION BLOW MOLDING

Extrusion blow molding is a process used to form hollow thermoplastic objects (especially bottles and containers). The process (Figure 3.10) takes a thin-walled tube called a *parison* that has been formed by extrusion, entraps it between two halves of a larger diameter mold, and then expands it by blowing air (at about

100psi) into the tube, forcing the parison out against the mold. The outside of the thin-walled part takes the shape of the inside of the mold. By controlling variations in the parison thickness along its length, the wall thickness of the final part can be approximately controlled.

In addition to bottles and containers, blow molding is used to form such shapes as simple balls, lightweight baseball bats, dolls, and animal toys. Although items like carrying cases for instruments and tools, large drums, ducts, and automobile glove compartments can also be made by blow molding, this process is not usually used to produce such "engineering" type parts.

No further consideration is given to blow molding in this book. For more on this subject, the reader should consult the *Modern Plastic Encyclopedia* and the book by S. S. Schwarz and S. H. Goodman, *Plastic Materials and Processes.*

3.8 OTHER POLYMER PROCESSES

We have so far described only the most commonly used polymer processing techniques. Others exist—examples are calendering, foam processing, and rotational molding—but these processes tend to be used for rather specialized or low production runs. For example, calendering is used to produce film and sheeting, foam processing for disposable cups and food containers, and rotational molding for battery cases and for very large parts.

For the production of shallow-shaped components, such as bus panels, boats, camper tops, lighting panels, trays, door and furniture panels, and other products, a process called *thermoforming* is often used. Thermoforming involves heating to soften a previously made thermoplastic sheet, clamping it over a mold, and then drawing and forcing it (via air pressure or vacuum) so that it takes the shape of the mold.

The books *Modern Plastic Encyclopedia* and *Plastic Materials and Processes* contain detailed description of these, as well as some other, polymer processing techniques.

3.9 QUALITATIVE DFM GUIDELINES FOR INJECTION MOLDING, COMPRESSION MOLDING, AND TRANSFER MOLDING

Injection molding, compression molding, and transfer molding are all internal flow processes that are followed by cooling and solidification, which are followed by ejection from the mold. That is, in each of these processes, a liquid (plastic resin) flows into and fills a die cavity. Then the liquid is cooled to form a solid, and finally the part is ejected. The physical nature of these processes—flow, cooling to solidify, and ejection—provides the basis for a number of the qualitative DFM guidelines or rules of thumb that have been established. Parts should ideally be designed so that: (1) the flow can be smooth and fill the cavity evenly; (2) cooling, and hence solidification, can be rapid to shorten cycle time and uniform to reduce warpage; and (3) ejection can be accomplished with as little tooling complexity as possible.

To design parts properly for these manufacturing processes, designers must at least understand the meaning of (1) mold closure direction and (2) parting surface. Dies are made in two parts forming a cavity that is very close to the shape of the part. (The cavity may be slightly different from the part to allow for inevitable shrinkage and warping.) Thus there is a closure direction for the die halves, and a parting "surface" (not necessarily planar) created where

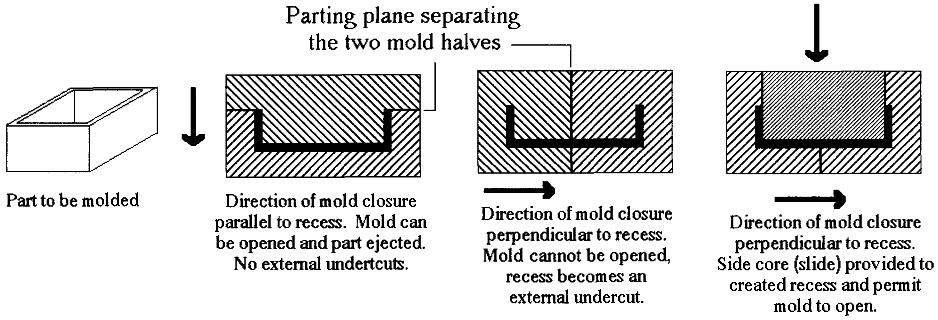

FIGURE 3.11 *External undercut created by choice in the direction of mold closure.*

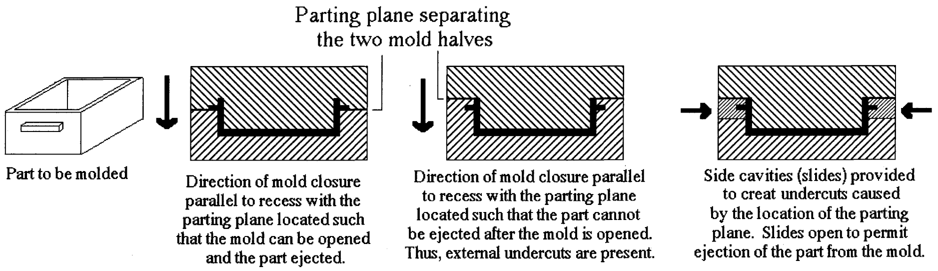

FIGURE 3.12 *External undercuts created by location of the parting plane between the die halves.*

the die sections meet when they are closed. The location of the parting surface, the direction of closure, and the design of the part must be considered simultaneously in order to provide for ejection of the part from the mold after solidification.

Knowing the mold closure direction enables designers to recognize and thus possibly avoid designing unnecessary undercuts. A fairly easy way to identify a potential undercut is to consider the shadows that would be created on the part from a light shining in the mold closure direction. If a part casts shadows onto itself, then the feature causing the shadow is an undercut. This is discussed again in the next chapter.

Figures 3.11 and 3.12 illustrate how the choice of mold closure direction and the location of the parting surface influence design and, in particular, tool design and tool cost.

With knowledge of mold closure direction and the location of the parting surface—and keeping in mind that the material should flow smoothly into and through the mold, solidify rapidly and uniformly, and then be easily ejected—designers can well understand and make good use of the following DFM guidelines:

1. In designing parts to be made by injection molding, compression molding, and transfer molding, designers must decide—as a part of their design—the direction of mold closure and the location of the parting surface. Though these decisions are tentative, and advice should be sought from a manufacturing expert, it is really impossible to do much design for manufacturing in these processes without considering the mold closure direction and parting surface location.

2. An easy to manufacture part must be easily ejected from the die, and dies will be less expensive if they do not require special moving parts (such as side cores) that must be activated in order to allow parts to be ejected. Since undercuts require side cores, parts without undercuts are less costly to mold and cast. Some examples of undercuts are shown in Figures 3.2 and 3.3. With knowledge of the mold closure direction and parting surface, designers can make tentative decisions about the location(s) of features (holes, projections, etc.) in order to avoid undercuts wherever possible.
3. Because of the need for resin or metal to flow through the die cavity, parts that provide relatively smooth and easy internal flow paths with low flow resistance are desirable. For example, sharp corners and sudden changes or large differences in wall thickness should be avoided because they both create flow problems. Such features also make uniform cooling difficult.
4. Thick walls or heavy sections will slow the cooling process. This is especially true with plastic molding processes since plastic is a poor thermal conductor. Thus, parts with no thick walls or other thick sections are less costly to produce.
5. In addition, every effort should be made to design parts of uniform, or nearly uniform, wall thickness. If there are both thick and thin sections in a part, solidification may proceed unevenly causing difficult to control internal stresses and warping. Remember, too, that the thickest section largely determines solidification time, and hence total cycle time.
6. We will not discuss gate location in this book except in this paragraph. However, in large or complex parts, two or more gates may be required through which resin will flow in two or more streams into the mold. There will, therefore, be fusion lines in the part where the streams meet inside the mold. The line of fusion may be a weak region, and it may also be visible. Therefore, designers who suspect that multiple gates may be needed for a part should discuss these issues with manufacturing experts as early as possible in the design process. With proper design and planning, the location of the fusion lines can usually be controlled as needed for appearance and functionality.

These DFM "rules" are not absolute, rigorous laws. Note, for example, how the molded-in, very thin hinge, referred to as a "living hinge" by custom molders, in a computer disk carrying case (Figure 3.13) violates the general thrust of the fifth rule above. If there are designs that have great advantages for function or marketing, then those designs can be given special consideration. Manufacturing engineers can sometimes solve the problems that may be associated with highly desirable functional but difficult to manufacture designs at a cost low enough to justify the benefit.

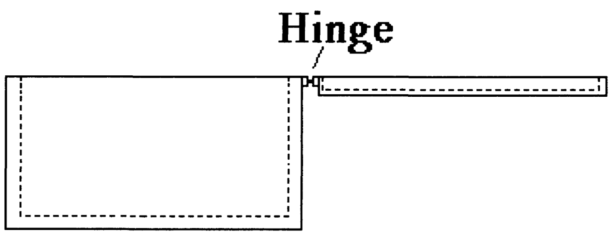

FIGURE 3.13 *Living hinge on computer disk carrying case.*

However, relatively easy to manufacture designs should always be sought. More often than not, a design can be found that will be both efficient from a functional viewpoint and relatively easy to manufacture.

3.10 SUMMARY

This chapter has described some of the most common polymer processing methods and materials used for the economical production of both complex parts (with significant levels of geometric detail) and simple parts (with little geometric detail). Included in this chapter was a discussion of design for manufacturing issues as they apply to the production of plastic parts. The chapter concluded with a set of qualitative DFM guidelines for injection molding, compression molding, and transfer molding.

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QUESTIONS AND PROBLEMS

3.1 Figure P3.1 shows the sectional view of two proposed alternative designs for an injection-molded box-shaped part that is enclosed on four sides. From the point of view of tooling cost, which design is more costly to produce? Why? Assume that the wall thickness is the same in both designs.

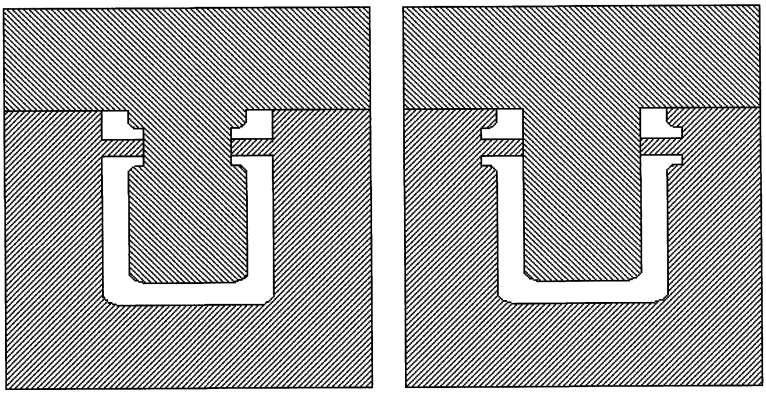


FIGURE P3.1

3.2 Figure P3.2 shows the sectional view of two proposed alternative designs for an injection-molded box-shaped part that is enclosed on four sides. From the point of view of tooling costs, which of the two designs is the most costly? Assume that the wall thickness is the same in all designs.

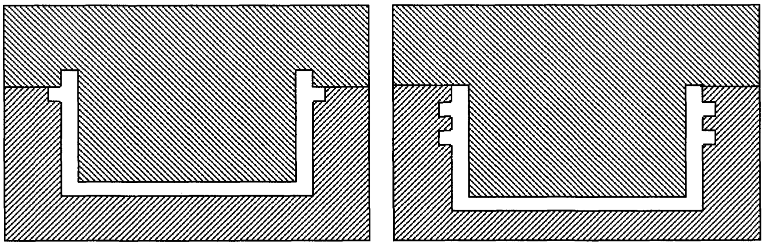


FIGURE P3.2

3.3 Figure P3.3 shows the preliminary sketch of two proposed designs. Assuming the part is to be injection molded, which of the two designs is less costly to produce? Why? Assume that the wall thickness is the same in both designs.

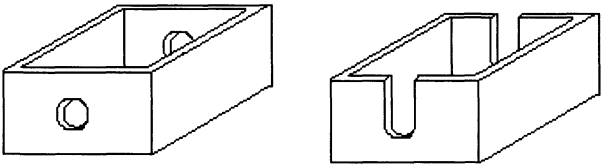


FIGURE P3.3

3.4 Figure P3.4 shows the preliminary sketch of two proposed injection-molded designs. From the point of view of tooling, which of the two designs is least costly to produce? Why? Assume both parts have the same wall thickness.

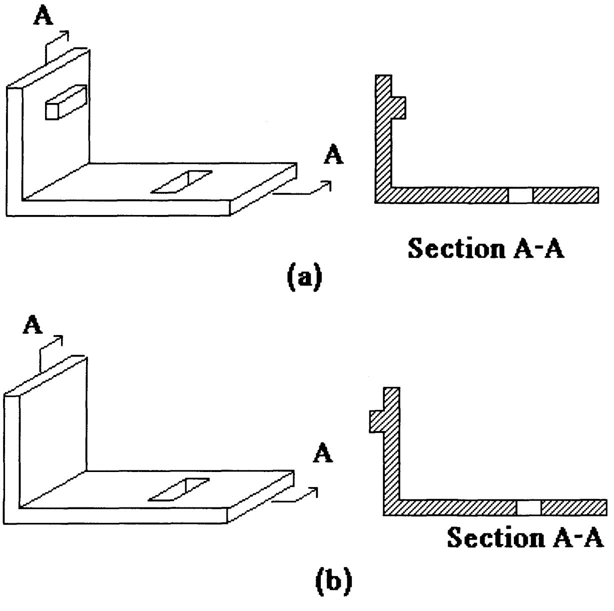


FIGURE P3.4

3.5 In an effort to become more competitive, a large automotive company has decided to expand its design for manufacturing group. Assume that you have applied for a position with that group. As part of the interview process you have been shown the proposed design of a compression-molded part similar to the part shown in Figure P3.5. What suggestions would you make in order to reduce the cost to mold the part? What suggestions would you make if the part were to be injection molded?

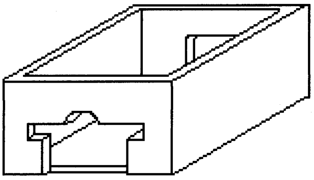


FIGURE P3.5

3.6 Repeat Problem 3.5 for the part shown in Figure P3.6.

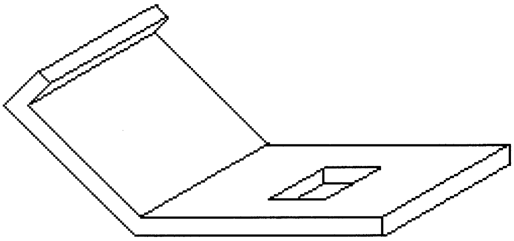


FIGURE P3.6

3.7 Name two or three "engineering" parts that are better suited for plastics than for metals.

3.8 How do thermoplastics differ from thermosets?

3.9 How do engineering plastics differ from commodity plastics?

Chapter 4

Injection Molding: Relative Tooling Cost

4.1 INTRODUCTION

Generally during the early stages of part design the procedures followed by a designer will result in several possible part configurations whose generation has been guided by qualitative reasoning related to both function and, it is hoped, manufacturability. In this chapter, we will discuss methods by which designers can perform more formal quantitative manufacturability evaluations of injection-molded parts at the configuration stage. In Chapter 5, "Injection Molding: Total Relative Part Cost," we will make use of the near final dimensions, locations, and orientation of features to evaluate the relative cost to process a part by injection molding.

The ability to evaluate part manufacturability at the configuration stage—before exact dimensions have been determined—is important because, in practice, design decisions made at this stage often become essentially irrevocable. Thus, before moving on to the sometimes computationally difficult and time-consuming task of assigning values to attributes (i.e., to parametric design), it is important for designers to be as certain as possible that the configuration selected is the best possible one considering both function and manufacturability.

In this book, we present detailed, quantitative manufacturability methods for three manufacturing domains: injection molding, die casting, and stamping. Design for manufacturability issues in other processes—such as assembly, forging, extrusion, and others—are also covered, but not in as much detail as these three. The essential reason for concentrating on these particular manufacturability domains is that they account for more than 70% of the special purpose parts found in consumer products.

It should always be remembered that the best method for reducing assembly costs is to reduce the number of parts in an assembly. This is often accomplished by combining several individual parts into one (sometimes more complex) part using either injection molding, die casting, or stamping. To do this by taking full advantage of the capabilities of the process, but without exceeding those capabilities, requires that designers be able to perform detailed DFM analyses.

This chapter is devoted to DFM methods for the ease of tool design for injection molding. Chapter 7, "Die Casting: Total Relative Part Cost," and Chapter 9, "Stamping: Relative Tooling Cost," deal with DFM for ease of tool designs for die casting and stamping.

4.2 ESTIMATING RELATIVE TOOLING COSTS FOR INJECTION-MOLDED PARTS

The cost of an injection-molded part consists of three subcosts: (1) tooling (or mold) cost, K_d/N; (2) processing cost (or equipment operating cost), K_e; and (3) part material cost, K_m.

$$\text{Total Cost of a Part} = K_d/N + K_e + K_m \qquad \text{(Equation 4.1)}$$

where K_d is the total tooling cost for a part and N is the number of parts to be produced with the mold—that is, the production volume.

At low production volumes (N less than, 20,000, e.g.), the proportion of the part cost due to tooling is often relatively high compared with processing costs, since the total cost of tooling, K_d, is divided by a small value of N. As the production volume increases, however, the total tooling cost (K_d) does not change; consequently, the tooling cost per part decreases, while the material and processing cost per part remains essentially the same. Thus, at high production volumes the proportion of total part cost due to tooling is relatively low, and the major costs are due to processing and materials.

With only configuration information available, we can do little to estimate processing costs (K_e) or part material costs (K_m). However, we can make a reasonably accurate estimate of tooling costs (K_d). In fact, if we restrict ourselves to relative tooling cost, then the analysis is accurate enough to permit a comparison between competing designs. As pointed out above, tooling costs are often important, and the fact that we can perform a DFM analysis of them at the configuration stage (before parametric design) is useful. The analysis helps designers identify the features of proposed configurations that contribute most significantly to tooling costs so that the features can be eliminated, or at least so that their negative impact on manufacturing cost can be reduced.

4.2.1 Relative Tooling Cost (C_d)

The DFM methodology to be presented here determines the tooling cost of injection-molded parts as a ratio of expected tooling costs to the tooling costs for a reference part. This ratio is called *relative cost.* Actual costs depend upon local practices and methods and can vary considerably from one location to another. To eliminate these effects costs relative to a reference part are used. Thus, relative to a reference part, total die costs are

$$C_d = \text{Cost of Tooling for Designed Part/Cost of Tooling for Reference Part}$$

$$C_d = (K_{dm} + K_{dc})/(K_{dmo} + K_{dco}) \qquad \text{(Equation 4.2)}$$

where K_{dmo} and K_{dco} refer to die material cost and die construction cost for the reference part. (In this case, the reference part is a flat 1 mm thick washer with OD = 72 mm and ID = 60 mm. The approximate tooling cost for this reference part—in the 1991–1992 time frame—is about \$7,000, including about \$1,000 in die material costs.)

Equation (4.2) can be written as

$$\begin{aligned} C_d &= K_{dm}/(K_{dmo} + K_{dco}) = K_{dc}/(K_{dmo} + K_{dco}) \\ &= A(K_{dm}/K_{dmo}) + B(K_{dc}/K_{dco}) \qquad \text{(Equation 4.3)} \end{aligned}$$

where

$$A = K_{dmo}/(K_{dmo} + K_{dco})$$

$$B = K_{dco}/(K_{dmo} + K_{dco})$$

Based on data collected from mold-makers, a reasonable value for A is between 0.15 and 0.20 and a reasonable value for B is between 0.80 and 0.85. For our purposes we will take A and B to be 0.2 and 0.8, respectively. Hence, Equation 4.3 becomes

$$C_d = 0.8C_{dc} + 0.2C_{dm} \qquad \text{(Equation 4.4)}$$

where C_d is the total die cost of a part relative to the die cost of the reference part, C_{dc} is the die construction cost for the part relative to the die construction cost of the reference part, and C_{dm} is the die material cost for the part relative to the die material cost of the reference part.

In this section, we show how to determine the relative tooling construction costs (C_{dc}). The following section deals with the relative tool material costs (C_{dm}).

4.2.2 Relative Tooling Construction Costs (C_{dc})

To estimate relative tool construction costs for a part, designers must understand in some detail the complex relationships between the part and its mold. Certain features and combinations of features result in more complex molds and, hence, higher tooling costs. It may be that, in order to meet a part's function, such features or their combinations cannot be changed or eliminated, but in many cases they can be—saving time and money. In any case, designers should know the tooling costs their designs are causing, and they should make every attempt to reduce them.

The time required for tooling to be designed, manufactured, and tested is also a factor. In general, however, the higher the cost of tooling, the longer the time required for making the tool.

Relative tooling construction cost, C_{dc}, is computed here as the product of three factors:

$$C_{dc} = C_b C_s C_t \qquad \text{(Equation 4.5)}$$

where C_b = The approximate relative tooling cost due to size and basic complexity;

C_s = A multiplier accounting for other complexity factors called subsidiary factors;

C_t = A multiplier accounting for tolerance and surface finish issues.

We will now discuss how to compute each of these factors, and look at examples of their use with actual parts. Readers of this chapter will be rewarded with an easy-to-use understanding of design for manufacturing principles and practices for injection-molded parts. Much of what is learned will be useful in understanding other manufacturing domains as well. In order to use the methodology, however, a reader must be familiar with a number of concepts related specifically to the manufacture of injection-molded parts. Though there appears to be a large number of them (they are explained in the next subsections), the concepts are individually relatively easy to understand. All are explained as they are introduced.

4.3 DETERMINING RELATIVE TOOLING CONSTRUCTION COSTS DUE TO BASIC PART COMPLEXITY (C_b)

4.3.1 Overview

Values for C_b—the relative tooling cost factor due to basic part complexity—are found in the interior boxes of the matrix in Figure 4.1.

The numbers above the slanted lines in the boxes in Figure 4.1 apply to flat parts; those below the slanted line apply to box-shaped parts. Note that the value for C_b in the upper left corner of the matrix for a flat part is 1.00—thus this box corresponds to the cost of the reference part.

Readers should note that, in general, values for C_b decrease significantly as one moves up and to the left in the matrix. This fact will help guide designers to redesigns that can reduce tooling costs.

4.3.2 The Basic Envelope

Figure 4.1 requires that the part to be evaluated be classified as either flat or box-shaped. (This is done because, in general, box-shaped parts require more mold machining time and, hence, result in higher tool construction costs, than flat parts.) In order to determine whether a part is flat or box-shaped, we determine the ratio of the sides of the basic envelope for the part. The basic envelope is the smallest rectangular prism that completely encloses the part.

The lengths of the sides of the basic envelope are denoted by L, B, and H, where $L \geq B \geq C$. (See Figure 4.2.) A part is considered flat if L/H is greater than about 4; otherwise it is considered box-shaped.

In order not to overestimate the amount of mold machining time required, in determining the basic envelope, small, isolated projections are ignored. Isolated projections are considered small if their greatest dimension parallel to the surface from which they project is less than about one-third times the envelope dimension in the same direction (as shown in Figure 4.3). This is done so that a part that is basically flat when the projection is ignored is not classified as a box-shaped part. If more than one projection exists, each should be examined separately.

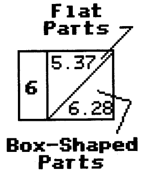
4.3.3 The Mold Closure Direction

As noted briefly in Chapter 3, "Polymer Processing," designers of injection-molded parts must consider the direction of mold closure in order to be able to design for ease of manufacturability. The reason is that the orientation of certain part features and configurations in relation to the mold closure direction can have an important influence on tooling construction costs. This is also reflected in the fact that knowledge of the mold closure direction is essential in order for designers to use Figure 4.1, and hence to estimate tooling construction costs.

Knowledge of the mold closure direction is also essential in order to identify and possibly redesign the features that may be causing high tooling costs.

Recessed Features

In order to determine the best or most likely direction of mold closure, it is necessary to understand the meaning of a recessed feature. A recessed feature is



1 in = 25.4 mm; 100 mm/25.4 mm = 3.94 in

		BASIC COMPLEXITY			SECOND DIGIT										
					L ≤ 250 mm (4)				250mm < L ≤ 480mm				L > 480 mm		
					Number of External Undercuts (5)				Number of External Undercuts (5)				Number of External Undercuts (5)		
					zero	one	two	More than two	zero	one	two	More than two	zero	one	More than one
FIRST DIGIT					0	1	2	3	4	5	6	7	8	9	10
Parts Without Internal Undercuts (1)		Parts whose peripheral height from a planar dividing surface is constant (2)	Part in one half(3)	0	1.00 1.64	1.23 1.87	1.38 2.02	1.52 2.16	1.42 2.89	1.65 3.12	1.79 3.27	1.94 3.41	1.83 4.28	2.07 4.51	2.33 4.77
			Part not in one half(3)	1	1.14 1.86	1.37 2.09	1.52 2.24	1.66 2.38	1.61 2.99	1.84 3.22	1.99 3.37	2.13 3.51	2.09 4.42	2.32 4.66	2.58 4.92
		Parts whose peripheral height from a planar Dividing Surface is not constant – or – parts with a non-planar Dividing Surface(2)		2	1.28 1.92	1.51 2.15	1.66 2.29	1.80 2.44	1.81 3.38	2.04 3.61	2.19 3.76	2.33 3.90	2.34 5.01	2.58 5.24	2.84 5.50
Parts With Undercuts (1) Internal	On Only One Face of the Part	Parts whose ONLY Dividing Surface (2) is planar, or parts whose peripheral height from a planar dividing surface is constant		3	2.33 3.19	2.57 3.43	2.71 3.57	2.86 3.72	2.75 4.44	2.98 4.68	3.13 4.82	3.27 4.97	3.17 5.83	3.40 6.07	3.66 6.33
		Parts whose peripheral height from a planar Dividing Surface is not constant – or – parts with a non-planar Dividing Surface(2)		4	2.98 3.73	3.21 3.97	3.36 4.11	3.50 4.26	3.52 5.20	3.75 5.43	3.89 5.58	4.04 5.72	4.04 6.82	4.28 7.06	4.54 7.32
	On More Than One Face of the Part	Parts whose ONLY Dividing Surface (2) is planar, or parts whose peripheral height from a planar dividing surface is constant		5	4.20 5.37	4.43 5.61	4.58 5.75	4.72 5.89	4.62 6.62	4.85 6.86	4.99 7.00	5.14 7.14	5.03 8.01	5.27 8.24	5.53 8.51
		Parts whose peripheral height from a planar Dividing Surface is not constant – or – parts with a non-planar Dividing Surface(2)		6	5.37 6.28	5.60 6.52	5.74 6.66	5.89 6.81	5.90 7.74	6.13 7.98	6.28 8.12	6.42 8.27	6.43 9.37	6.67 9.60	6.93 9.86

FIGURE 4.1 *Classification system for basic tool complexity, C_b. (The numbers in parentheses refer to notes found in Appendix 4.A.)*

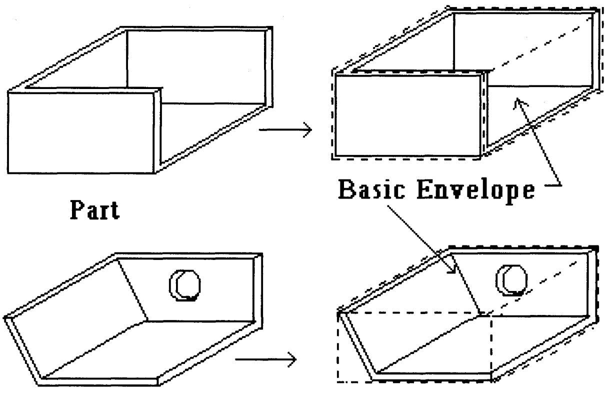


FIGURE 4.2 *Basic envelope for a part.*

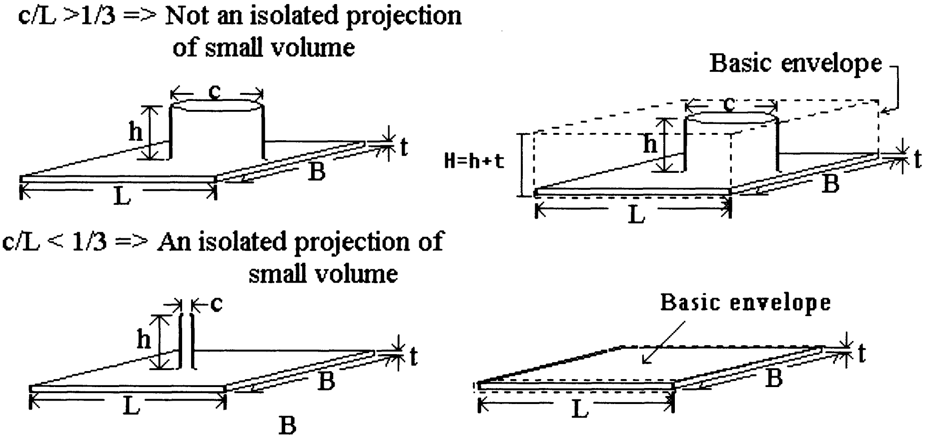


FIGURE 4.3 *Isolated projections of small volume.*

any depression or hole in a part, including also depressed features that come about due to closely spaced projecting walls. Figure 4.4 shows some examples of recessed features. Also shown in Figure 4.4 are sectional views of the molds that can be used to produce these features. The part shown in Figure 4.4d is not considered to have a recess because the direction of mold closure does not affect basic tool construction difficulty.

Holes and Depressions

Depressions are pockets, recesses, or indentations of regular or irregular contour that are molded into a portion of an injection-molded part. Holes are the prolongation of depressions that completely penetrate some portion of the molding.

Circular holes and depressions can be formed either by an integer mold in which the projections required to create the two holes are machined directly into the core half of the mold as shown in Figure 4.4f, or by an insert mold. In the case of an insert mold, as in Figure 4.4g, the projections shown in the first version of the mold are replaced by a core pin that is inserted into the core.

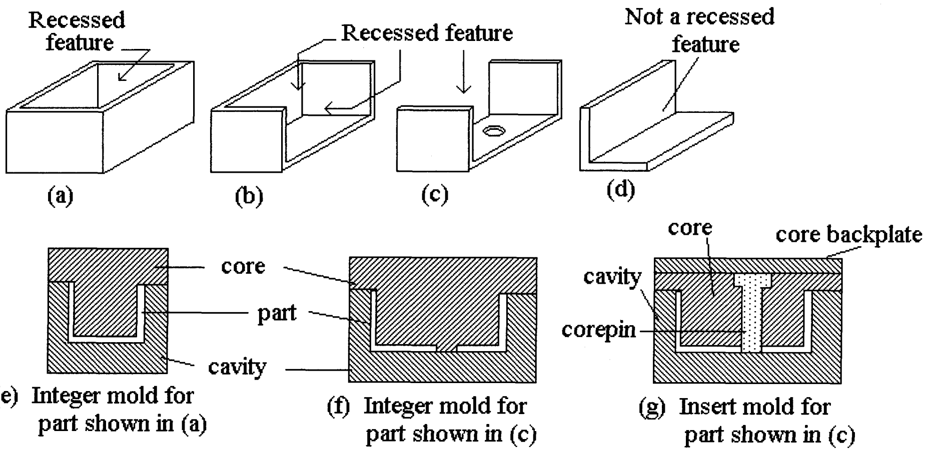


FIGURE 4.4 *Examples of parts with recessed features and section views of the molds used to produce them.*

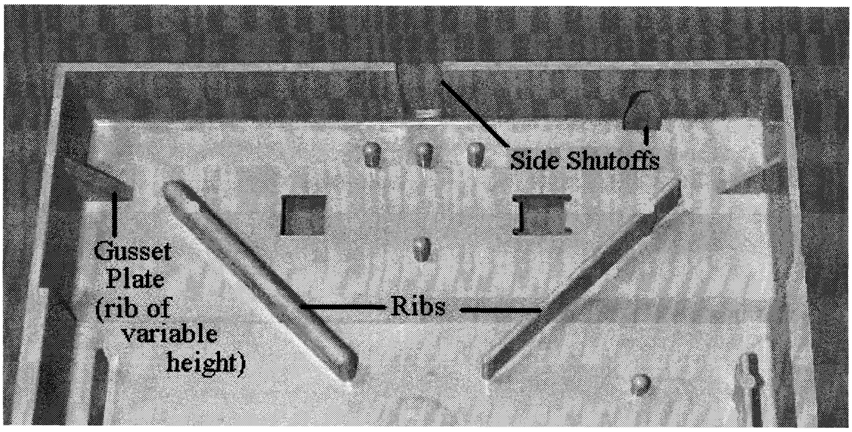


FIGURE 4.5 *Photograph of an injection-molded part showing ribs and shutoffs.*

Rectangular holes and irregularly shaped holes can also be formed by either the use of integer molds or insert molds, but the cost to create the tooling to form these holes is more costly (See "Questions and Problems" in Chapter 11, "Other Metal Shaping Processes.")

Projections

A feature that protrudes from the surface of a part is considered a projection. The most common examples are ribs and bosses.

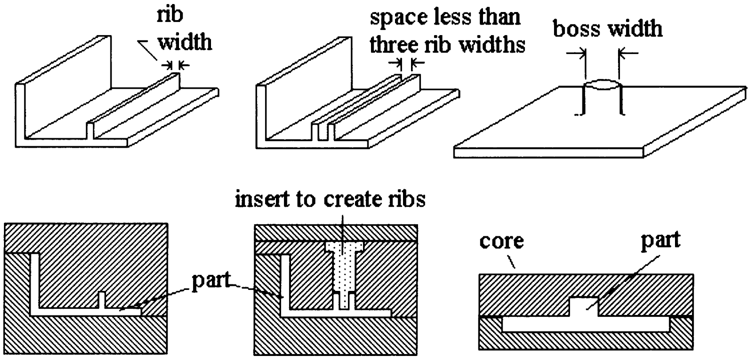
A *rib* is a narrow elongated projection with a length generally greater than about three times its width (thickness), both measured parallel to the surface from which the feature projects (see Figure 4.5) and a height less than six times its width. Ribs may be located at the periphery or on the interior of a part or plate. A rib may run parallel to the longest dimension of the part (a longitudinal rib), or it may run perpendicular to this dimension (a lateral rib). Radial ribs and concentric ribs are also common. A rib may be continuous or discontinuous, or it may be part of a network of other ribs and projecting elements. If the height of a narrow elongated projection is greater than six times its width, then the projection is considered a wall.

Nonperipheral ribs and nonperipheral walls are generally created by milling or by electrical discharge machining (EDM) a cavity in either the core half or cavity half of the mold (see Figure 4.6a). If the minimum rib thickness is greater than or equal to about 3 mm (0.125 inches), then the cavity is machined by milling; otherwise it is machined by the EDM process.

Two closely spaced longitudinal or lateral ribs, that is two ribs whose spacing is less than three times the rib width, are usually formed by first milling a cavity in the core half of the plate and then using an insert to form the two closely spaced ribs (see Figure 4.6b). The cost to create this cluster of two closely spaced ribs is about equal to the cost to create a single rib.

A *boss* is an isolated projection with a length of projection that is generally less than about three times its overall width, the latter measured parallel to the surface from which it projects (Figure 4.7). A boss is usually circular in shape but it can take a variety of other forms called knobs, hubs, lugs, buttons, pads, or "prolongs."

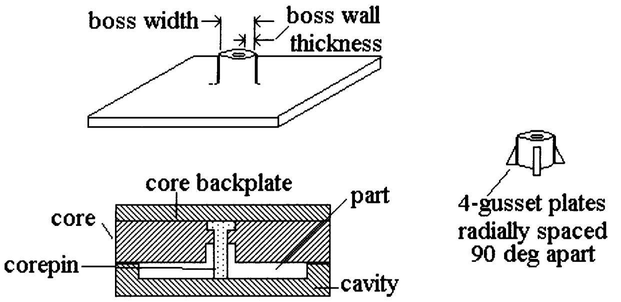
Bosses can be solid or hollow. In the case of a solid circular boss, the length of the boss and its width are both equal to the boss diameter. A boss is created by simply milling a hole in the core half of the mold (Figure 4.6c). In the case of



(a) Part with longitudinal rib

(b) Part with two closely spaced ribs

(c) Part with solid boss



(d) Part with hollow boss

(e) Boss with cluster of gusset plates

FIGURE 4.6 *Example of parts with ribs and bosses and sectional views of the molds used to produce them.*

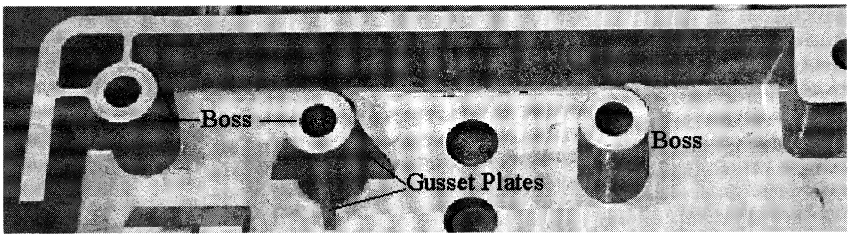


FIGURE 4.7 *Photograph of a part with bosses.*

a circular hollow boss, a pin is used to create the hole (Figure 4.6d). Although the width of the boss is still equal to the outside diameter, the boss thickness is equal to the difference between the outside and inside radii.

Bosses, and sometimes ribs, are supported by ribs of variable height called *gusset plates*. In the case of bosses, these supports are radially located, as shown in Figure 4.6e. These ribs are machined in simultaneously using the EDM process. For this reason this cluster of ribs costs about the same to create as a single rib.

Dividing and Parting Surfaces

One reason the determination of the direction of mold closure is so crucial to tooling cost evaluation is that it affects the location of the parting surface between the mold halves. The mold closure direction and the parting surface location together establish which recessed features can be molded in the direction of mold closure, and which (because they are not parallel to the mold closure direction) will require special tooling in the form of side action units or lifters in order to permit ejection of the part. (These subsidiary features, i.e., holes, projections, etc., are often referred to as add-ons.)

In order to determine where a parting surface should be located, we will introduce the concept of dividing surface. Given a direction of mold closure, the dividing surface (Figure 4.8) is defined as an imaginary surface, in one or more planes, through the part for which the portion of the part on either side of the surface can be extracted from a cavity conforming to the form of the outer shape of the portion in a direction parallel to the direction of mold closure.

If the dividing surface is in one plane only, it is called a *planar dividing surface*. In general, the dividing surface that results in the least costly tooling is the one that should be used as the parting surface in the actual construction of the tooling. Figure 4.9 shows the parting surface that was used in the tooling for the box-shaped part shown in Figure 4.8. Figure 4.10 shows the tooling used to produce an L-bracket similar to the one shown in Figure 4.8.

A dividing surface is a potential parting surface. A part may have several dividing surfaces, but of course a mold when constructed has only one parting surface.

Designers who understand the process of injection molding can usually plan for a convenient mold closure direction quite readily with just a little thought and study of the part.

4.3.4 Undercuts

In general, undercuts are combinations of part features created by recesses or by projections whose directions are not parallel to the mold closure direction. Undercuts are classified as either internal or external.

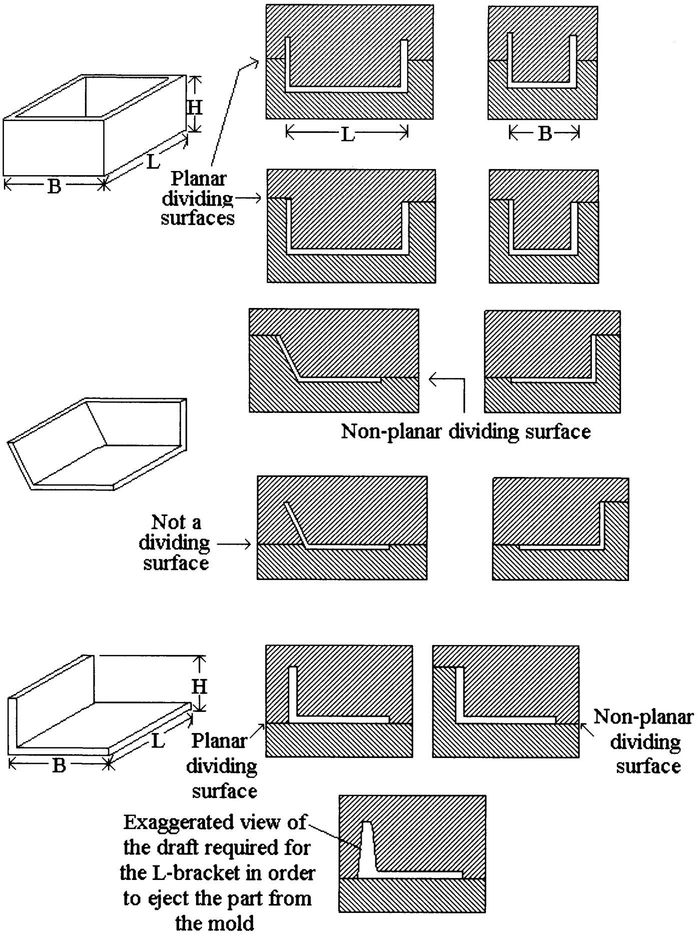


FIGURE 4.8 *Dividing surface of a part.*

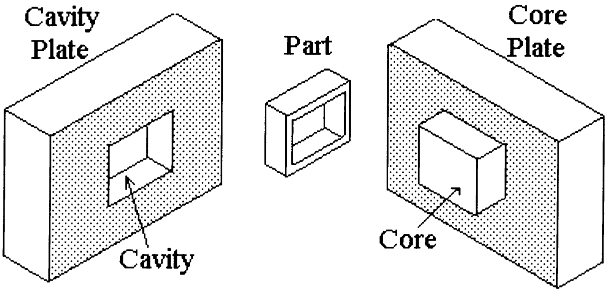


FIGURE 4.9 *Tooling for box-shaped part—shows parting surface between the core and cavity halves of the mold.*

By reference to Figure 4.1, readers should note how the number of external undercuts increases the part's tooling cost by moving the part's location to the right in the Figure. Similarly, note how the number of internal undercuts moves a part's place in the matrix downward, thus also increasing tooling cost.

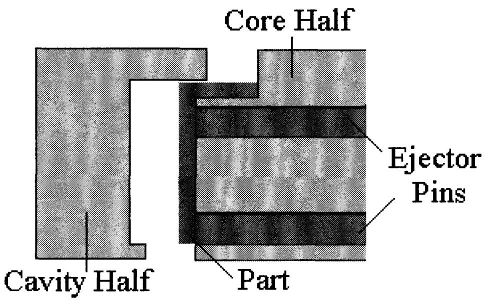


FIGURE 4.10 *Tooling for L-bracket.*

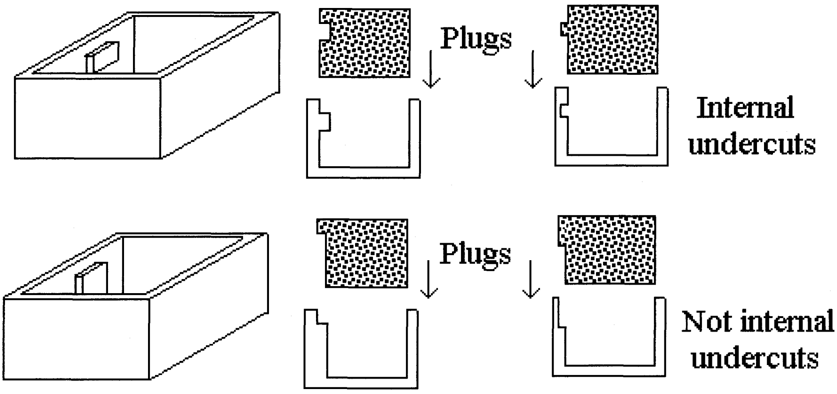


FIGURE 4.11 *Examples of internal undercuts.*

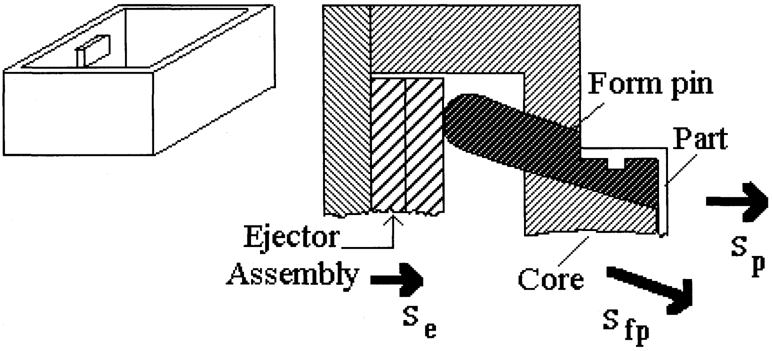


FIGURE 4.12 *Form pin used to form internal undercut.*

Internal Undercuts

Internal undercuts are recesses or projections on the inner surface of a part which, without special provisions, would prevent the mold cores from being withdrawn in the line of closure (often called the *line of the draw*). (See Figure 4.11.)

To permit withdrawal of the core when there is an internal undercut, hardened steel pins (called *form pins*) must be built into the cores. Figure 4.12 shows an illustration of a form pin. When the part solidifies, it shrinks onto the core.

The mold then opens and the core and part are withdrawn from the cavity. As the ejector assembly plate moves to the right, relative to the core (see vector S_e), the form pin slides in the direction shown by vector S_{fp}. The part then moves in a direction parallel to the motion of the ejector plate (see vector S_p) and the internal projection is lifted from the core pin cavity and the part removed or blown off. Alternatively, cores called *split cores* must be constructed in two or more parts. Both split cores and form pins add to the complexity and hence the cost of the tooling. Figure 4.13 shows a screen capture from an animation used to illustrate how internal undercuts are formed.

External Undercuts

In general, external undercuts are holes or depressions on the external surface of a part that are not parallel to the direction of mold closure (Figure 4.14). Some exceptions to this generalization are discussed below.

The number of external undercuts in a part is equal to the number of surfaces that contain external undercuts. For example, Figure 4.14a shows a part with only one surface that contains an external undercut; thus, the number of undercuts is 1. In Figure 4.14b, however, the part has two surfaces with external undercuts; thus, the number of external undercuts is 2.

In addition, projections located on the external surface of a part such that a single mold-dividing surface (planar or nonplanar) cannot pass through them all, are also considered external undercuts.

As with internal undercuts, the presence of external undercuts requires special provisions to allow for ejection of parts from the mold cavity. To permit ejection, a steel member called a *side cavity* or *side core* must be mounted and operated at right angles to the direction of mold closure. However, this solution also adds to tooling complexity and cost. See Figure 4.15.

Side Shutoffs

In some situations, a hole or a groove in the side wall of a part can be molded without the need for side action cores. Figure 4.16 shows two examples. In these cases, a portion of the core abutting the face of the cavity forms the hole. Such holes are called *simple side shutoffs* because contact between mold halves occurs on one surface only. *Complex side shutoffs* occur when contact between mold surfaces occurs on more than one plane. A tab (Figure 4.16) is an example of a complex side shutoff. Figure 4.17 shows a part with other features that are also considered to be complex side shutoffs.

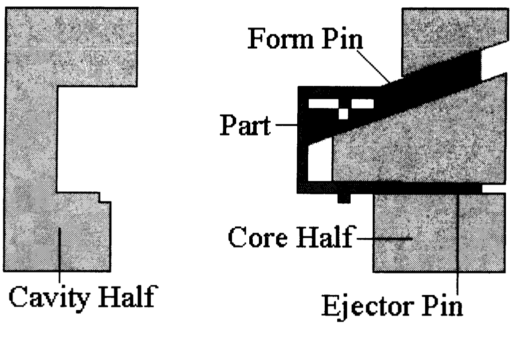


FIGURE 4.13 *A screen capture from an animation showing the formation of a part with an internal undercut.*

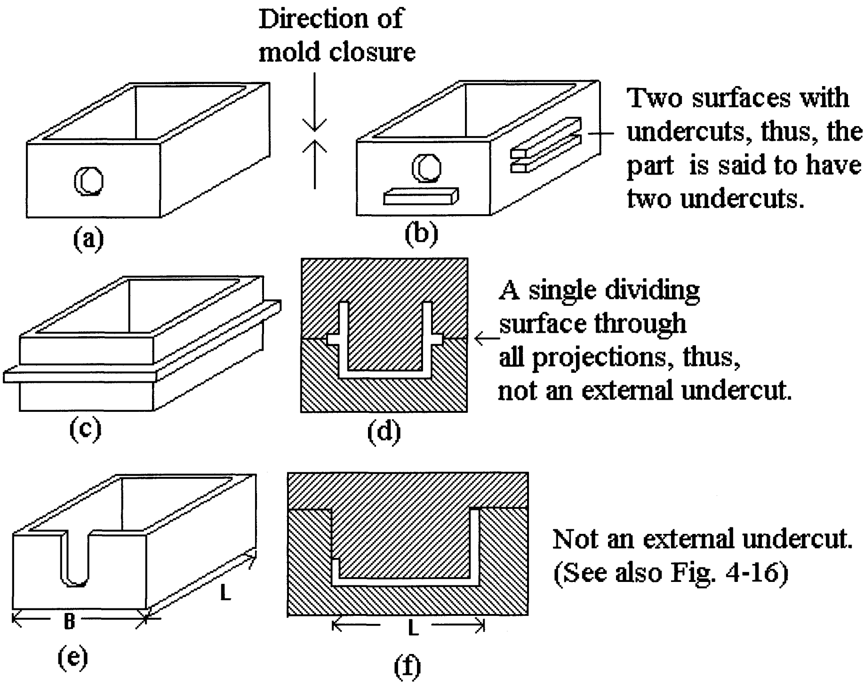


FIGURE 4.14 *External undercuts.*

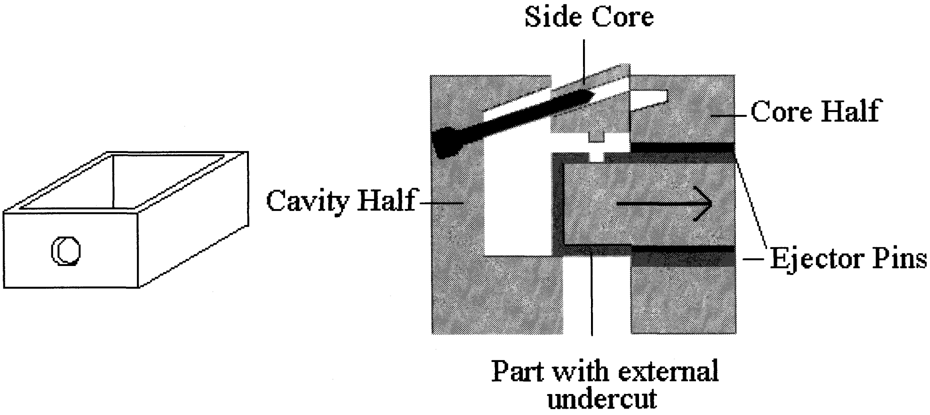
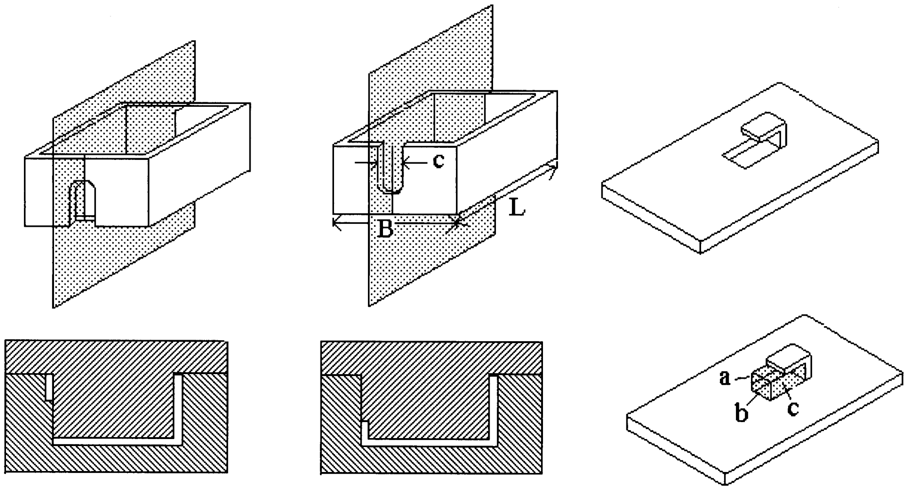


FIGURE 4.15 *Side core used to create an external undercut created by a circular hole.*

To determine whether a hole or depression is a side shutoff or an undercut, the following test can be applied: With a solid plug conforming to the exact shape of the inner surface of the part already inserted, imagine the part inserted into a plug conforming to the exact shape of the outer surface of the part. If the outer plug can now be removed, by the use of straight-line motion parallel to the direction of mold closure, the hole is considered a side shutoff. If the outer plug cannot be removed, the hole is considered an undercut.

A part with isolated grooves and cutouts on the external surface of a part can also sometimes be considered a part with side shutoffs and constant periph-



(a) Simple side shutoff. Contact between molds on one surface only and $c<0.33B$. Note: If $c \geq 0.33B$, peripheral height is not treated as constant and side shutoff is ignored in determining cavity detail.

(b) Complex side shutoff. Contact between molds along three side surfaces, a, b, and c.

FIGURE 4.16 *Simple and complex side shutoffs.*

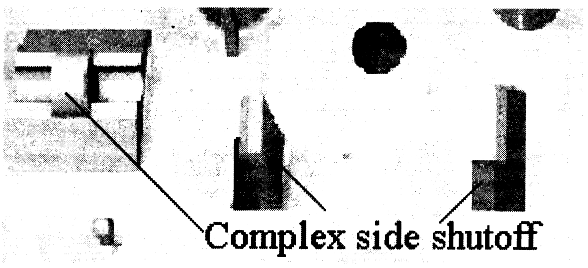


FIGURE 4.17 *Photograph of part with complex side shutoffs.*

eral height, rather than a part whose peripheral height is not constant. A groove or cutout is considered isolated if its dimension normal to the direction of mold closure is less than 0.33 times the envelope dimension in the same direction (see Figure 4.16).

4.3.5 Other Factors Influencing C_b

Parts Molded in One-Half the Mold

Mold costs are influenced to some extent by the amount of machining that must be done to create the core and cavity hollow sections. If the part cavity can be molded entirely in one-half of the mold, then the other part of the mold needs no special machining. A part is said to be in one-half the mold (Figure 4.18) when the entire part is on one side of a planar dividing surface.

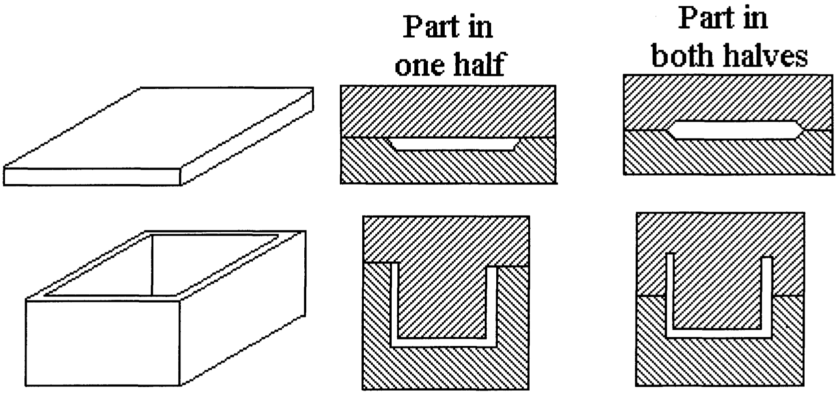


FIGURE 4.18 *Part with cavity in one-half of die.*

Peripheral Height

Although the L-shaped part shown in Figure 4.8 does have a planar dividing surface and could be molded using a planar parting surface, in general this would not be done. To use a planar parting surface would require a taper (draft) on the vertical wall, the wall parallel to the direction of mold closure, so that the part can be easily removed from the mold (see Figure 4.8).

To avoid the need for a taper, a nonplanar parting surface is generally used. To indicate situations where a nonplanar parting surface would probably be used, even if a planar dividing surface exists, the concept of a constant peripheral height is introduced. For the box-shaped part shown in Figure 4.8, a planar dividing surface exists and the peripheral height as measured from a planar dividing surface is constant (i.e. the wall height is constant); thus, a planar parting surface is used to produce the part (Figure 4.9). However, for the L-shaped part, the peripheral height from the planar dividing surface is not constant (i.e. the wall height is zero on three of the four peripheral surfaces) and, thus, a nonplanar parting surface would be used to construct the tooling.

4.3.6 Entering and Using Figure 4.1

The value of C_b can readily be determined from Figure 4.1 given the following information, all of which can be found easily by methods explained above in Sections 4.3.2 to 4.3.6:

1. the longest dimension of the basic envelope, L;
2. the number of external undercuts;
3. the number and location (on one or more faces of the part) of internal undercuts;
4. whether or not the part will be made in one-half of the mold;
5. whether the dividing surface will be planar or not;
6. whether or not the part's peripheral height from a planar dividing surface is constant or not; and
7. whether the part is flat or box-shaped.

For example, refer to Figure 4.1 and consider two parts with the following characteristics:

	PART A	PART B
1. Longest dimension (mm)	400	200
2. External undercuts	0	3
3. Internal undercuts (faces)	0	1
4. Dividing surface	Planar	Planar
5. Peripheral height	Constant	Constant
6. Part in one-half?	Yes	—
7. Flat or box-shaped	Flat	Box

Readers should verify that the relative cost is 1.42 for Part A and 3.72 for Part B.

4.4 DETERMINING C_S

As noted previously, the relative tooling construction cost for a part is found from

$$C_{dc} = C_b\ C_s\ C_t \qquad \text{(Equation 4.5)}$$

where C_b = The approximate relative tooling cost due to size and basic complexity;
C_s = A multiplier accounting for other complexity factors called subsidiary factors;
C_t = A multiplier accounting for tolerance and surface finish issues.

In the preceding section, we showed how C_b is determined. In this section, we show how to obtain an appropriate value for C_s.

Features like ribs, bosses, holes, lettering, and other elements that are aligned with the mold closure direction contribute to mold complexity. We refer to the

Feature		Number of Features (n)	Penalty per Features	Penalty
Holes or Depressions	Circular		2n	
	Rectangular		4n	
	Irregular		7n	
Bosses	Solid (8)		n	
	Hollow (8)		3n	
Non-peripheral ribs and/or walls and/or rib clusters (8)			3n	
Side Shutoffs	Simple (9)		2.5n	
	Complex (9)		4.5n	
Lettering (10)			n	
			Total Penalty	

SMALL PARTS ($L \leq 250$ mm)

Total Penalty ≤ 10 => Low cavity detail
$10 <$ Total Penalty ≤ 20 => Moderate cavity detail
$20 <$ Total Penalty ≤ 40 => High cavity detail
Total Penalty > 40 => Very high cavity detail

MEDIUM PARTS ($250 < L \leq 480$ mm)

Total Penalty ≤ 15 => Low cavity detail
$15 <$ Total Penalty ≤ 30 => Moderate cavity detail
$30 <$ Total Penalty ≤ 60 => High cavity detail
Total Penalty > 60 => Very high cavity detail

LARGE PARTS ($L > 480$ mm)

Total Penalty ≤ 20 => Low cavity detail
$20 <$ Total Penalty ≤ 40 => Moderate cavity detail
$40 <$ Total Penalty ≤ 80 => High cavity detail
Total Penalty > 80 => Very high cavity detail

1 in = 25.4 mm; 100 mm/25.4mm = 3.94 in

FIGURE 4.19 *Determination of cavity detail. (The numbers in parentheses refer to notes found in Appendix 4.A.)*

number and complexity of such features as cavity detail. Figure 4.19 shows the method for rating the cavity detail as low, moderate, high, or very high. Figure 4.20 shows photographs of two parts, one with low cavity detail (on the left) and one with high cavity detail (on the right).

In addition to the level of cavity detail, C_s is influenced by the complexity and number of external undercuts. Table 4.1 requires only that a judgment be made about whether extensive undercut complexity exists or does not exist. External undercuts other than unidirectional holes or depressions are considered extensive since the creation of such tooling is more costly. Figure 4.21 provides an example of a part that clearly has extensive external undercut complexity.

4.5 DETERMINING C_t

The effects of surface finish requirements, sometimes referred to as surface quality, and the strictness of required tolerances on relative tool construction

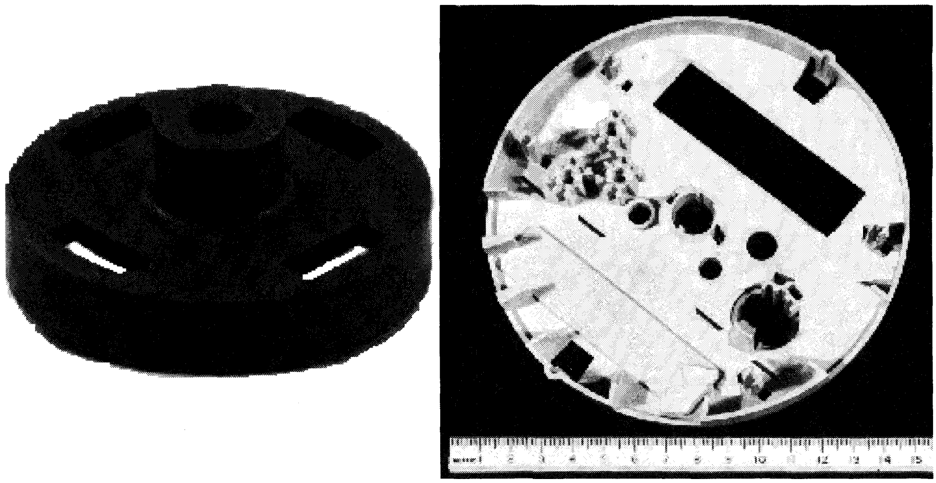


FIGURE 4.20 *Photographs of parts with low (on left) and high (on right) cavity detail.*

Table 4.1 Subsidiary complexity rating, C_s. (The numbers in parentheses refer to notes found in Appendix 4.A.)

				Fourth Digit	
				Without Extensive (7) External Undercuts (5)	With Extensive (7) External Undercuts (5)
				0	1
Third Digit	Cavity Detail (6)	Low	0	1.00	1.25
		Moderate	1	1.25	1.45
		High	2	1.60	1.75
		Very High	3	2.05	2.15

costs are accounted for by the factor C_t, which is obtained from Table 4.2. Guidelines relating the surface quality of the part and the various SPI (Society of the Plastics Industry) finishes of the mold are given below:

SPI-SPE 1: Used on transparent moldings requiring minimum distortions and surface blemishes. Good for most optical lenses.

SPI-SPE 2: Near optical. Used when require good transparent clarity and high gloss. Also good for bearing surface due to minimum of surface scratches.

SPI-SPE 3: Finely abraded surface. Resembles very lightly brushed stainless steel. Used when high gloss not required.

SPI-SPE 4: Medium, abraded surface resembling brushed steel. Used in nonaesthetic areas not usually seen. Inexpensive surface, yet provides easy ejection from the mold.

SPI-SPE 5: 40 micro-inch textured surface that has the appearance of frosted glass. Good for areas needing adhesive bonding or products requiring smooth, nonglass surface that absorbs light.

SPI-SPE 6: Medium-textured surface similar to 400-to-600-grit emery paper. Good for bonding and absorbing light. Inexpensive, appealing finish for industrial products and some consumer products.

4.6 USING THE PART CODING SYSTEM TO DETERMINE C_b, C_s, AND C_t

When analyzing a part for entry into Figure 4.1 and Tables 4.1 and 4.2, it is convenient to make use of the part coding system that has been developed for this purpose. The coding system involves six digits that, in effect, describe the part in the fashion of group technology.

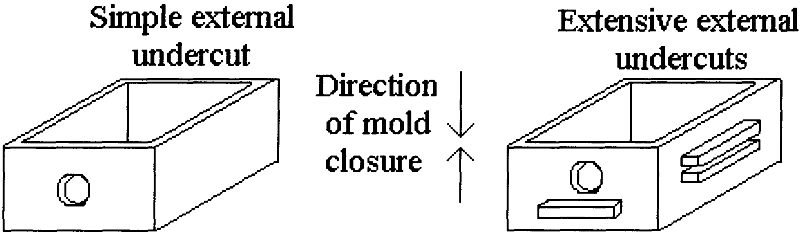


FIGURE 4.21 *External undercuts caused by features other than circular, unidirectional holes are considered extensive external undercuts because the tooling is more costly to create.*

Table 4.2 Tolerance and surface finish rating, C_t. (The numbers in parentheses refer to notes found in Appendix 4.A.)

				Sixth Digit	
				Commercial Tolerance, T_a	Tight Tolerance, T_a
				0	1
Fifth Digit	Surface Finish, R_a	SPI 5–6	0	—	—
		SPI 3–4	1	1.00	1.05
		Texture	2	1.05	1.10
		SPI 1–2	3	1.10	1.15

In group technology, as can be seen in Figure 4.1, data is organized in the form of a matrix that gives one a qualitative feel for the impact of the part attributes on the ease or difficulty of producing, in this case, the tooling for the part. In addition, it provides a comprehensive checklist of cost factors and presents the user with a consistent and systematic method for analyzing part designs for manufacturability. It also facilitates implementation on a computer.

Here are the descriptions of the meaning of the digits in the coding system and their interpretation.

For Figure 4.1

First Digit (0–6): The first digit in the coding system identifies the row in Figure 4.1 (for C_b) that describes the part. It is fixed by (1) the number of faces with internal undercuts, (2) whether the part is in one-half the mold or not, (3) whether the dividing surface is planar or nonplanar, and (4) whether the peripheral height is constant from the dividing surface.

Second Digit (0–9): The second digit identifies the column in Figure 4.1 that describes the part. It is thus fixed by (1) the part size (L), and (2) the number of external undercuts.

Together, the first and second digits locate the place in Figure 4.1 where the value of C_b is found. (Remember: the values above the slanted line in that Figure refer to flat parts; values below the line refer to box shaped parts.)

Readers should verify that the first two digits of the code for parts A and B just described are, respectively, 0–4 and 3–3.

For Table 4.1

C_s is determined from Table 4.1 by the third and fourth digits of the coding system as follows:

Third Digit (0–3): The third digit in the coding system identifies the row in Table 4.1 (for C_s) that describes the part. It is determined by the level of cavity detail as determined from Figure 4.19.

Fourth Digit (0–1): The fourth digit identifies the column in Table 4.1 that describes the part. It is determined by the extent of external undercut complexity.

As an example, readers should verify from Figure 4.19 that the penalty factor for a part with five radial ribs, three hollow bosses, three simple side shutoffs, and localized lettering is 32.5—resulting in a level of cavity detail for a large part (L >480 mm) of Moderate. Also verify from Table 4.1 that C_s for such a part with extensive external undercuts and moderate cavity detail is 1.45. (The third and fourth digits in the coding system for this part are 1 and 1, respectively.)

For Table 4.2

The coding system for entry into Table 4.2 is as follows:

Fifth Digit (0–3): The fifth digit identifies the row in Table 11.2 (for C_t) that describes the part. It is fixed by the nature of the required surface finish.

Sixth Digit (0–1): The sixth digit identifies the column in Table 4.2 that describes the part. It is fixed by whether the tolerances required are commercial or tight.

4.7 TOTAL RELATIVE TOOLING CONSTRUCTION COST

As defined earlier, the total relative mold construction cost is:

$$C_{dc} = C_b C_s C_t \qquad \text{(Equation 4.5)}$$

and it is determined, as shown above in section 4.6, at the configuration stage of part design, that is, prior to any detailed knowledge concerning part dimensions, rib sizes, wall thickness, and so on. The results show very clearly and simply the aspects of a part's design that contribute most heavily to tooling construction costs. In Figure 4.1, for example, designers can see clearly that parts should be redesigned if possible to move the rating up and to the left in the matrix, and they can compute approximately how much can be saved. Removing undercuts accomplishes this goal, as do other simplifying changes that reduce detail or eliminate the need for special finishes or tight tolerances.

4.8 RELATIVE MOLD MATERIAL COST

In order to compute total relative tooling costs, we must be able to estimate the mold material cost as well as its construction costs. This is relatively easy to do from a knowledge of the approximate size of a part—which in turn dictates the required size of the mold. Referring to Figure 4.22, we define the following mold dimensions:

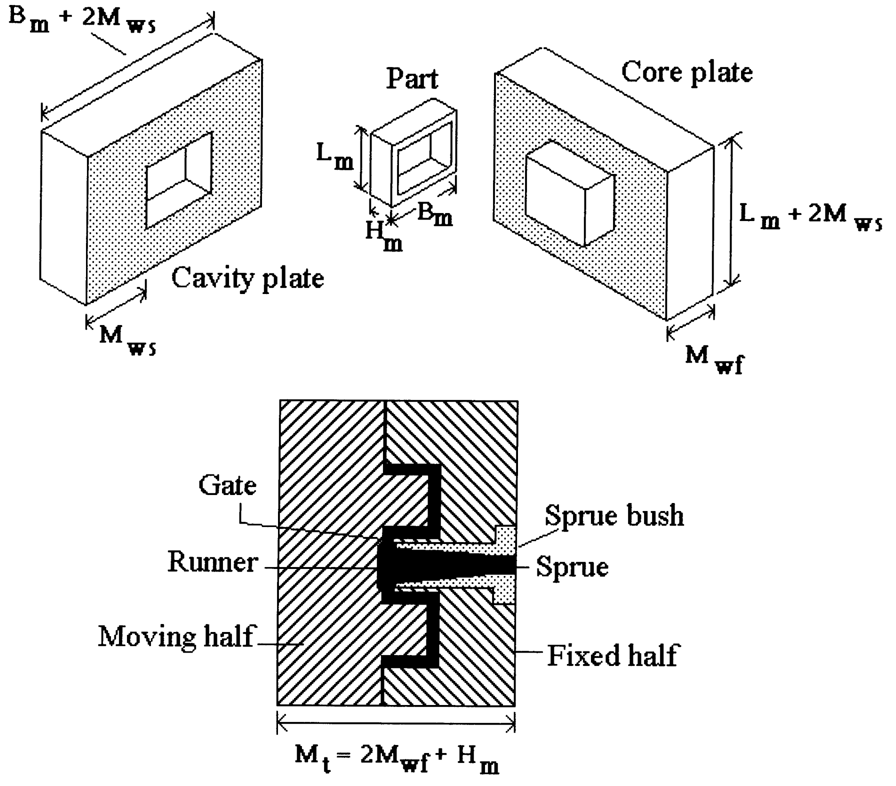


FIGURE 4.22 *Mold dimensions for two-plate mold.*

M_{ws} = Thickness of the mold's side walls (mm)

M_{wf} = Thickness of core plate (mm)

L_m and B_m = The length and width of the part in a direction normal to the mold closure direction (mm)

H_m = The height of the part in the direction of mold closure (mm) (H_m not necessarily equal to H)

M_t = The required thickness of the mold base (mm)

With these definitions, the following equations can be used sequentially to determine the projected area of the mold base, M_a, and the required thickness of the mold base, M_t, which in turn are used to obtain the relative mold material cost (C_{dm}) from Figure 4.24.

C = value obtained from Figure 4.23

$$M_{ws} = [0.006CH_m^4]^{1/3} \qquad \text{(Equation 4.6)}$$

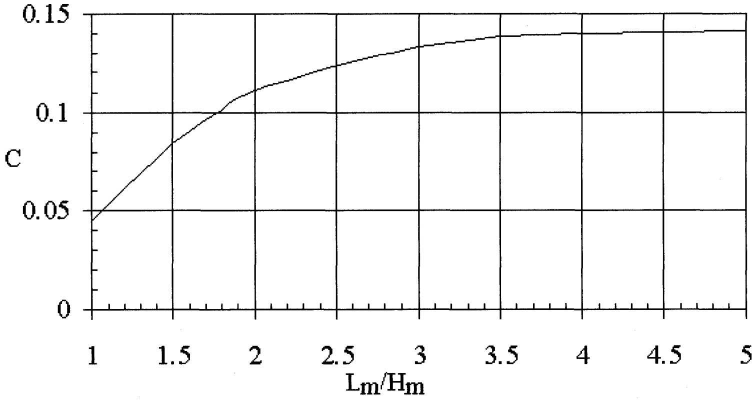


FIGURE 4.23 *Value of C for use in Equation 4.6. (If L_m/H_m <1, then use the value of H_m/L_m to determine C.)*

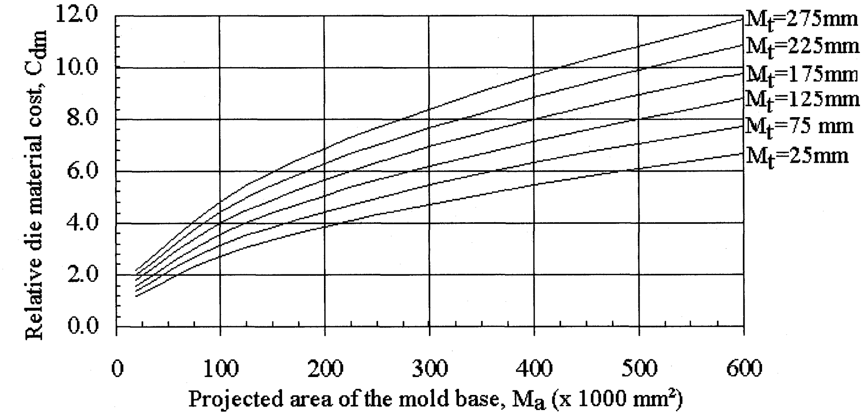


FIGURE 4.24 *Relative die material cost.*

$M_{wf} = 0.04L_m^{4/3}$ (Equation 4.7)

$M_a = (2M_{ws} + L_m)(2M_{ws} + B_m)$ (Equation 4.8)

$M_t = (H_m + 2M_{wf})$ (Equation 4.9)

C_{dm} = value obtained from Figure 4.24

The data for the plot shown in Figure 4.24 is based on the assumption that a standard two-plate die block unit is being used. This corresponds to DME's A-series. It is also assumed that the highest quality steel, namely, P-20 and S-7, is used as the mold material. Using DME cost data, a parabolic curve was fit to the data and the plot shown in Figure 4.24 was obtained (see Juan R. Escudero, 1991).

4.8.1 Total Relative Mold Cost

The total relative mold cost is determined from Equation 4.4, namely,

$$C_d = 0.8C_{dc} + 0.2C_{dm} \qquad \text{(Equation 4.4)}$$

where C_d is the total mold cost of a part relative to the mold cost of the standard part, C_{dc} is the mold construction cost relative to the standard, and C_{dm} is the mold material cost relative to the mold material cost of the standard part.

4.9 MULTIPLE CAVITY MOLDS

The above discussion and equations apply to single cavity molds only. For the case of multiple cavity molds, the mold construction costs for a mold consisting of n_c cavities, $C_{dc}(n_c)$, is approximately given by the following expression:

$$C_{dc}(n_c) = C_{dc}(0.73n_c + 0.27) \qquad \text{(Equation 4.10)}$$

Although the projected area of the mold base depends on the actual layout of a multiple cavity mold, it is assumed here that the projected area is roughly given by the product of the projected area for a single cavity mold, M_a, times the number of cavities n_c, that is,

$$M_a(n_c) = M_a n_c \qquad \text{(Equation 4.11)}$$

4.10 EXAMPLE 1—RELATIVE TOOLING COST FOR A SIMPLE PART

4.10.1 The Part

As our first example we will consider the part shown in Figure 4.25. The only dimensions shown are those that indicate the general overall size of the part. Also shown are the rough location of the ribs that appear on the side walls of the part.

Commercial tolerances will be satisfactory, and the required surface finish is (Society of the Plastics Industry) SPI-3, which coincides with the low-gloss finish found on most industrial products.

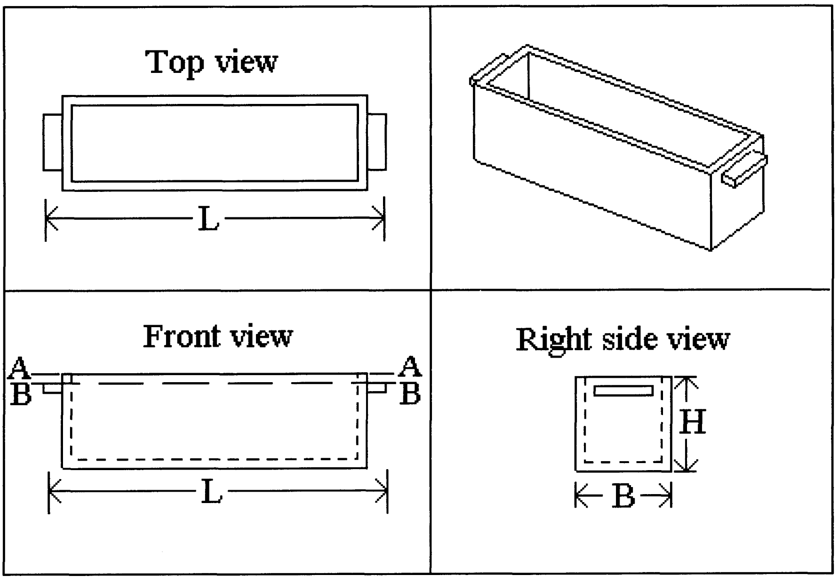


FIGURE 4.25 *Original Design—Example 4.1. (L = 180 mm, B = H = 50 mm.)*

4.10.2 Relative Tooling (Mold) Construction Cost

Basic Complexity

The dimensions of the basic envelope of this part are:

$$L = 180\,\text{mm}, \quad B = 50\,\text{mm}, \quad H = 50\,\text{mm}$$

Since L/H is less than 4, the part is box-shaped.

If the direction of mold closure is assumed to be in the direction of the recess, then a planar dividing surface exists for the part. Planes AA and BB are just two of the many planar dividing surfaces that exist for this part (i.e., just two of the many surfaces that could be used to separate or part the two halves of the mold). Initially, dividing surface AA is taken as the parting surface. In this case there are no internal undercuts, the peripheral height from the planar dividing surface (AA) is constant, and the part is in one-half of the mold. Thus, the first digit of the coding system is 0.

With dividing surface AA, there are two surfaces that contain external undercuts, hence there are two undercuts. Since L is less than 250 mm, the second digit is 2.

With the first two digits being 0 and 2, Figure 4.1 indicates a value for C_b of 2.02.

Since one of the major methods available for reducing mold manufacturability costs is to reduce the number of external and internal undercuts, the tooling cost for the part is reexamined using BB as the planar dividing surface.

In this case, the peripheral height from BB is still constant; however, the part is no longer in one-half the mold. Thus, the first digit is 1.

Since BB passes through both external projections, they are no longer considered undercuts. Thus, the second digit is 0.

Therefore, with BB as the dividing plane, from Figure 4.1 we get a value for C_b of 1.86. This lower value of C_b indicates that the use of BB as the parting plane will result in a lower basic tool construction cost.

Subsidiary Complexity

Since there are no ribs, bosses, holes, depressions, or other elements in the direction of mold closure, cavity detail is low and the third digit of the coding system is 0.

The fourth digit is also 0 since with BB as the parting plane there are no external undercuts.

Thus from Table 4.1 we find the multiplying factor, C_s, due to subsidiary complexity is 1.00.

Surface Finish/Tolerance

The part has a surface finish of SPI-3 and commercial tolerances are used. Thus, the fifth and sixth digits are 1 and 0, respectively giving a value for C_t from Table 4.2 of 1.00.

Total Relative Mold Construction Cost C_{dc}

$$C_{dc} = C_bC_sC_t = 1.86(1)(1) = 1.86$$

4.10.3 Relative Mold Material Cost

From Figure 4.23, for L_m/H_m of 3.6, C is 0.138. Thus, the thickness of the mold wall is given by:

$$M_{ws} = [0.006CH_m^4]^{1/3} = [0.006(0.138)(50)^4]^{1/3} = 17.3\,\text{mm}$$

and the thickness of the base is:

$$M_{wf} = 0.04\,L_m^{4/3} = 0.04(180)^{4/3} = 40.7\,\text{mm}.$$

Consequently, the projected area of the mold base is

$$M_a = [2(17.3) + 180][2(17.3) + 50] = 18155\,\text{mm}^2$$

and the required plate height is

$$M_t = [50 + 2(40.7)] = 131.4\,\text{mm}.$$

From Figure 4.24, the relative mold material cost, C_{dm}, for this part is approximately 1.6, and the total relative mold cost is

$$C_d = 0.8C_{dc} + 0.2C_{dm} = 0.8(1.86) + 0.2(1.6) = 1.81$$

4.10.4 Redesign Suggestions

The mold manufacturability costs for this part can be reduced slightly if the part is in one-half the mold. This can be done by moving the two side projections to

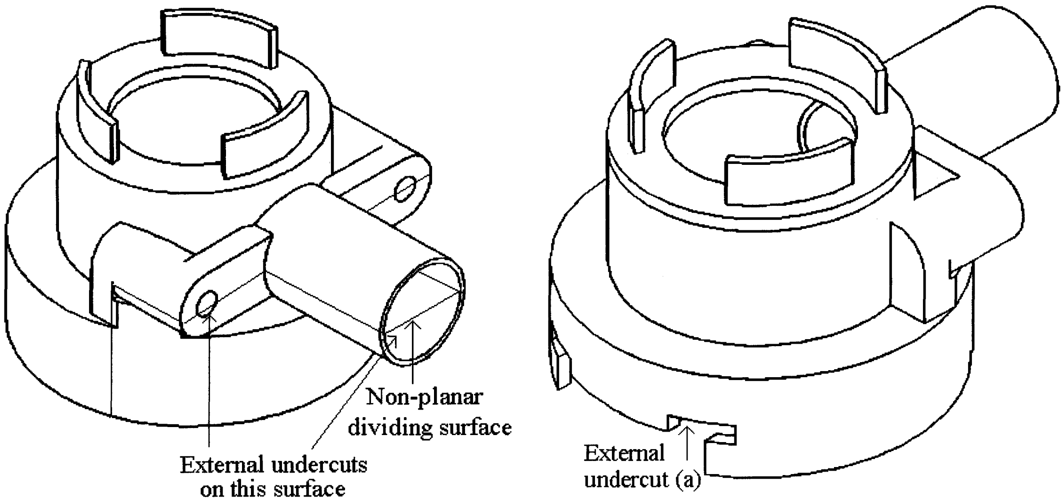


FIGURE 4.26 *Original Design—Example 4.2. (L = 55mm, B = 40mm, H = 20mm.)*

the top; that is, so that the tops of the projections are tangent to plane AA. In addition, relocating the side projections in this manner avoids the need for “reverse” taper or draft.

4.11 EXAMPLE 2—RELATIVE TOOLING COST FOR A COMPLEX PART

4.11.1 The Part

As a second example we will consider the part shown in Figure 4.26. We will assume that we are at the configuration stage of the design and that detailed dimensions concerning wall thickness, holes sizes, and other elements are not available. Thus, the only dimensions given are those that indicate the overall size and shape of the part.

4.11.2 Relative Mold Construction Cost

Basic Complexity

The dimensions of the basic envelope of this part are:

$$L = 55\,\text{mm}, \quad B = 40\,\text{mm}, \quad H = 20\,\text{mm}$$

It is possible that the projections indicated in Figure 4.26 are such that the largest dimensions parallel to the surface from which they project are less than 0.33 times the envelope dimension in the same direction. If so, they are isolated projections of small volume, and would consequently be ignored in determining the basic envelope. Since we are at the configuration stage of the design and the detailed dimensions are not yet known, it will be assumed that these are not isolated projections of small volume. Hence, the dimensions of the basic envelope of the part are those given above. Therefore, L/H is less than 4, and the part is box-shaped. (Even if the features were isolated projections of small volume, the part would still have been box-shaped.)

If the direction of mold closure is assumed to be in the direction of the major recess (i.e., normal to the LB plane of the part), then a nonplanar dividing surface is required for the part.

Since there are no internal undercuts, the first digit of the coding system is 2.

There are two surfaces with external undercuts, hence, two external undercuts are present, and L is less than 250 mm. Thus, the second digit is 2.

With the first digits of 2 and 2, the value of C_b from Figure 4.1 is 2.29.

Subsidiary Complexity

There is one set of concentric ribs, and one circular hole in the direction of mold closure. Thus the total penalty for this small part is 5, cavity detail is low, and the third digit is 0.

The fourth digit is 1 because the external undercuts are extensive. Therefore, from Table 4.1, the factor C_s, due to subsidiary complexity, is 1.25.

Surface Finish/Tolerance

The part has a surface finish of SPI-3 and commercial tolerances are used. Thus the fifth and sixth digits are 1 and 0, respectively. Thus, from Table 4.2, C_t is 1.00.

Total Relative Mold Construction Cost C_{dc}

$$C_{dc} = C_bC_sC_t = 2.29(1.25)(1) = 2.86$$

4.11.3 Relative Mold Material Cost

Since L_m = 55 mm and H_m = 20 mm, then L_m/H_m = 2.75; and from Figure 4.23, C is 0.13. Thus, the thickness of the mold wall is

$$M_{ws} = [0.006CH_m{}^4]^{1/3} = [0.006(0.13)(20)^4]^{1/3} = 5.0\,\text{mm}$$

and the thickness of the base is

$$M_{wf} = 0.04\,L_m{}^{4/3} = 0.04(55)^{4/3} = 8.4\,\text{mm}$$

Consequently, the projected area of the mold base is

$$M_a = [2(5.0) + 55][2(5.0) + 40] = 3250\,\text{mm}^2$$

and the required plate height is

$$M_t = [20 + 2(8.4)] = 36.8\,\text{mm}$$

Hence, from Figure 4.24, the relative mold material cost, C_{dm}, for this part is approximately 1.2.

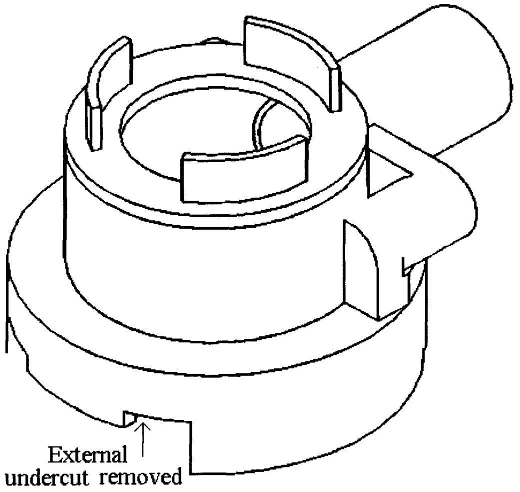


FIGURE 4.27 *Redesigned part.*

4.11.4 Total Relative Mold Cost

$$C_d = 0.8C_{dc} + 0.2C_{dm} = 2.53$$

4.11.5 Redesign Suggestions

The two features causing tooling complexity cost in this case are the two surfaces containing external undercuts. If external undercut (a) can be eliminated, as shown in Figure 4.27, then the new basic complexity code becomes B21, and C_b becomes 2.15.

With this redesign, the cavity detail remains low, and the third digit is still 0. The remaining external undercut does not constitute an extensive undercut. Hence, the fourth digit is 0, and C_s is 1.00.

With these values, the new total mold construction cost C_{dc} becomes

$$C_{dc} = (2.15)(1)(1) = 2.15$$

which is a 25% reduction in mold construction costs, and about a 23% reduction in total mold cost.

4.12 WORKSHEET FOR RELATIVE TOOLING COST

The determination of the relative die construction costs, the relative die material costs, and the overall relative die costs is a straightforward, though sometimes cumbersome, procedure. The following worksheet can be used to simplify the calculations. To illustrate the use of the worksheet, it has been filled out for the part shown in Figure 4.26 (Example 4.2).

A blank version of the worksheet is shown in Appendix 4.B at the end of this chapter. The worksheet shown in Appendix 4.B may be copied for use with this book.

Worksheet for Relative Tooling Costs—Injection Molding

Original Design

Relative Die Construction Cost

Basic Shape	$L = 55$	$B = 40$	$H = 16$	Box/Flat Box
Basic Complexity	1st Digit = 2	2nd Digit = 2	$C_b = 2.29$	
Sub. Complexity	3rd Digit = 0	4th Digit = 1	$C_s = 1.25$	
T_a/R_a	5th Digit = 1	6th Digit = 0	$C_t = 1.00$	

Total relative die construction cost C_{dc}	$= C_bC_sC_t = 2.86$

Relative Die Material Cost

$L_m = 55$	$B_m = 40$	$H_m = 20$
Die closure parallel to H	$L_m/H_m = 2.75$	Thus, $C = 0.13$

$M_{ws} = [0.006CH_m{}^4]^{1/3} = 5\,\text{mm}$
$M_{wf} = 0.04L_m{}^{4/3} = 8.4\,\text{mm}$
$M_a = (2M_{ws} + L)(2M_{ws} + B) = 3250\,\text{mm}$
$M_t = (H_m + 2M_{wf}) = 36.8\,\text{mm}$

Thus,

$C_{dm} = 1.2$	$C_d = 0.8C_{dc} + 0.2C_{dm} = 2.53$

Redesign Suggestions

Eliminate external undercut (a) as shown in Figure 4.27.

Basic Shape	$L = 55$	$B = 40$	$H = 16$	Box/Flat Box
Basic Complexity	1st Digit = 2	2nd Digit = 1	$C_b = 2.15$	
Sub. Complexity	3rd Digit = 0	4th Digit = 1	$C_s = 1.0$	
T_a/R_a	5th Digit = 1	6th Digit = 0	$C_t = 1$	

Total relative die construction cost C_{dc}	$= C_bC_sC_t = 2.15$
$C_d = 0.8C_{dc} + 0.2C_{dm} = 1.96$	
% Savings = (2.49 – 1.96)/2.49 = 0.21 => 21%	

4.13 SUMMARY

This chapter has described a systematic approach for calling designers' attention to those features of injection molding that tend to increase the tooling cost to manufacture parts—and for estimating the relative costs of tooling. The system employs a six-digit coding system for determining total relative tooling cost, which groups parts according to their similarity in tool construction difficulty. The system highlights those features that significantly increase cost so that designers can minimize difficult-to-produce features.

Using the methodology presented, designers can perform a tooling cost evaluation of a proposed part using only the information available at the configuration stage of part design. That is, the evaluation can be performed from only the knowledge of whether certain features are present or absent and, if present, their approximate location and orientation. Detailed dimensions are not needed. The methodology points out what features or arrangements of features contribute to the cost so that the direction of improved redesign is made apparent.

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QUESTIONS AND PROBLEMS

4.1 As part of a training program that you are participating in at Plastics.com you are explaining to some new hires that the tooling cost of transfer molded parts is a function of both *basic complexity* as well as *subsidiary complexity*. Explain in greater detail exactly which features of a part affect basic complexity and which features of a part influence subsidiary complexity.

4.2 As part of the same training program described in Problem 4.1 you have decided to use the parts shown in Figures P3.1 to P3.4 of Chapter 3 as examples to illustrate both basic complexity and subsidiary complexity. Explain which features of these parts, if any, affect basic complexity, and which features, if any, affect subsidiary complexity.

4.3 Assume that you work for DFM.com, a large cap manufacturing company whose product line consists of a family of widgets of various sizes and shapes. In an effort to become more competitive, the company has decided to completely redesign Widget A. In addition, it has decided to organize the team responsible for redesigning Widget A along the lines described in Figure 1.3 in Chapter 1. As one of the lead designers on the team, you are responsible for commenting on the proposed designs of all Widget A components. What comments would you make concerning the tooling costs for the component part shown in Figure P4.3? In other words, what suggestions would you make to reduce mold costs?

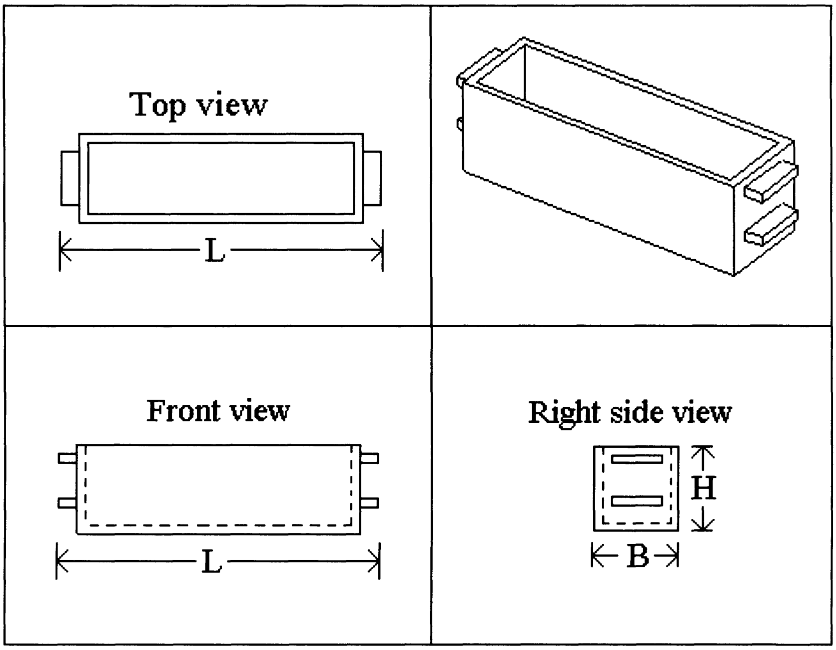


FIGURE P4.3

4.4 Some members of the integrated product and process design (IPPD) team formed in Problem 4.3 are unconvinced that your suggested redesign of the part shown in Figure P4.3 will yield significant savings in tooling cost. In an effort to convince them, calculate the savings in tool costs that you can achieve by redesigning the part. Assume that L = 180 mm, B = H = 50 mm, the part has a surface finish of SPI-3, and that commercial tolerances are to be used.

4.5 As another alternative to your redesign suggestion for the part shown in Figure P4.3 (see Problem 4.3), another member of the team has suggested redesigning the part as shown in Figure P4.5. What are the savings in tool costs between the design shown in Figure P4.5 and your proposed redesign of the part shown in Figure P4.3? Again, assume that the part has a surface finish of SPI-3, that commercial tolerances are to be used, and that L = 180 mm, B = H = 50 mm.

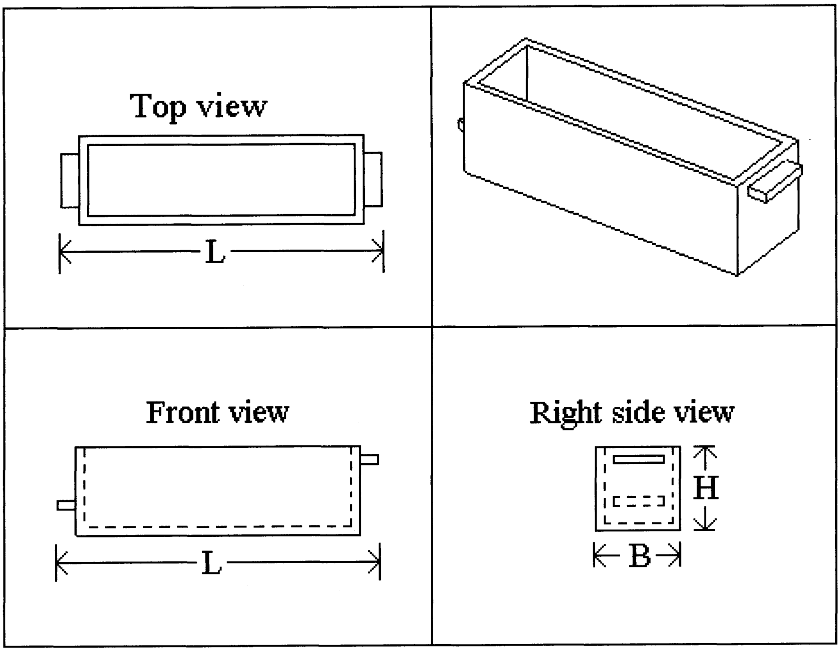


FIGURE P4.5

4.6 Although the total tooling costs for a part can be distributed over the entire production volume of the product, tooling costs are up-front costs and must be paid for before the mold is delivered to the vendor and any injection-molded parts can be produced. Therefore, as a lead member of the design team described in Problem 4.3, you are responsible for suggesting changes to the proposed design shown in Figure P4.6 so as to reduce tooling costs. What suggestions would you make?

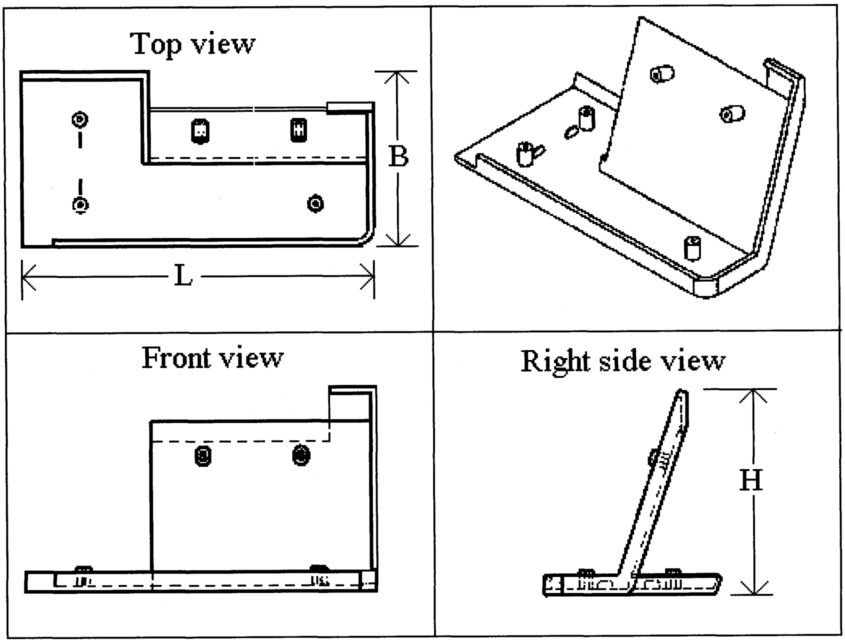


FIGURE P4.6

4.7 Estimate the savings in tooling costs achievable by the redesign suggestions you made in Problem 4.6. Assume that the part has a surface finish of SPI-3, that commercial tolerances are to be used, and that L = 250 mm, B = 130 mm, and H = 120 mm.

4.8 As a continuation of the redesign efforts of Widget A, as outlined in Problem 4.3, what suggestions can you make in order to reduce tooling costs for the proposed design of the part shown in Figure P4.8?

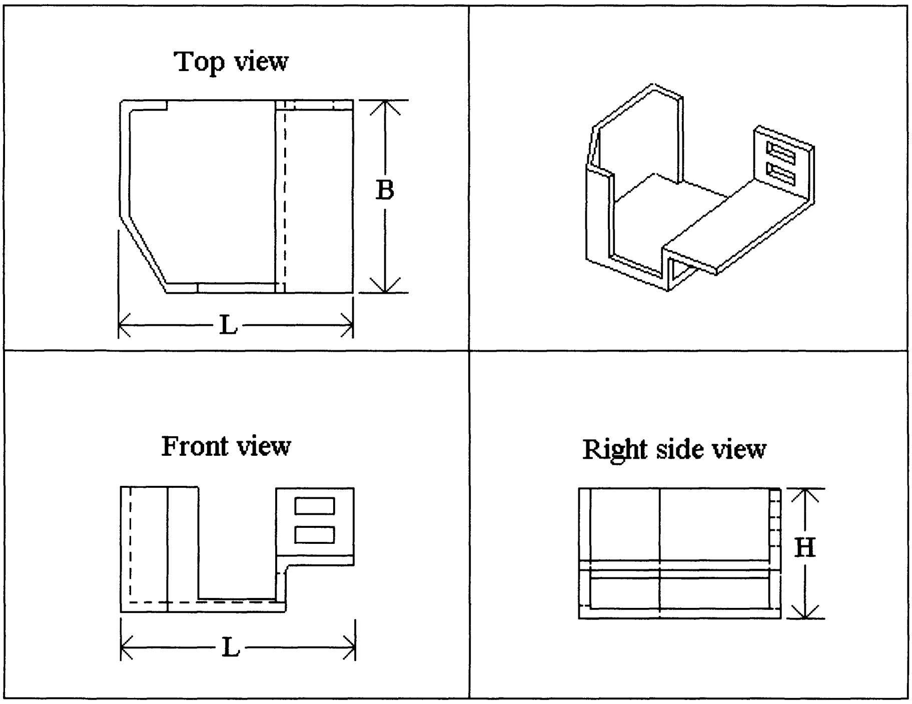


FIGURE P4.8

4.9 What are the savings in tool costs that can be achieved by redesigning the part shown in Figure P4.8 as you suggested in Problem 4.8? Assume that the part has a textured surface finish, that tight tolerances are to be used, and that L = 70 mm, B = H = 50 mm.

4.10 Determine the relative die cost for the part shown in Figure P4.10. Assume that the part has a surface finish of SPI-3, that commercial tolerances are to be used, and that L = 160 mm, B = 130 mm, and H = 13 mm.

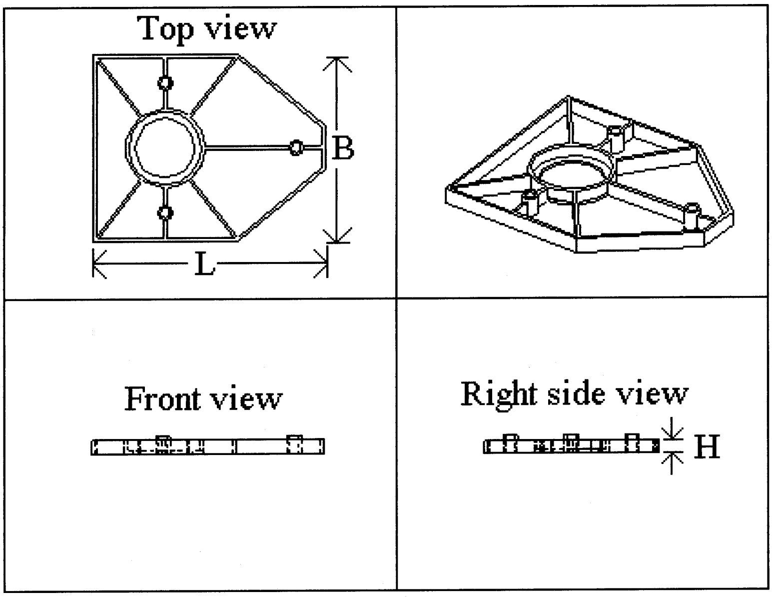


FIGURE P4.10

APPENDIX 4.A

Notes for Figures 4.1 and 4.19, and Tables 4.1 and 4.2

(1) Internal undercuts are recesses or projections on the inner surface of a part that prevents solid plugs, conforming to the exact shape of the inner surface of the part, from being inserted. See Figure 4.11.

(2) Dividing Surface. Given a direction of mold closure, a dividing surface is defined as an imaginary surface, in one or more planes, through the part, for which the portion on either side of the surface can be extracted from a cavity, conforming to the complementary form of the outer shape of the portion, in a direction parallel to the direction of mold closure. If the dividing surface is in one plane only, it is regarded as a planar dividing surface.

The peripheral height from a planar dividing surface is considered constant if the height does not vary by more than three times the wall thickness. See Figure 4.8.

(3) A part is said to be in one-half of the mold when the entire part is on one side of a planar dividing surface. See Figure 4.18.

(4) L is the longest dimension of the basic envelope of the part. If H is the smallest dimension of the basic envelope, then when L/H is greater than 4 the part is considered flat; otherwise it is considered box-shaped.

(5) External undercuts are holes or depressions on the external surface of a part that are not parallel to the direction of mold closure. Projections that are on the external surface of a part and are such that a single dividing surface, planar or nonplanar, cannot pass through all of them are also considered external undercuts.

The number of external undercuts is equal to the number of surfaces bearing unidirectional holes or depressions not in the direction of mold closure, and projections that prevent a single dividing surface from passing through all of the projections. See Figure 4.14.

(6) Cavity detail is a measure of the concentration of features parallel to the direction of mold closure. Typical features that increase cavity detail are ribs, bosses, and holes. See Figure 4.19.

(7) External undercuts other than unidirectional circular holes or depressions are considered extensive external undercuts. See Figure 4.21.

(8) A rib is a narrow elongated projection with a length generally greater than about three times its width (thickness), both measured parallel to the surface from which the feature projects, and a height less than six times its width. Ribs may be located at the periphery or on the interior of a part or plate. Peripheral ribs are not included in the rib count.

A narrow elongated projection with a height greater than six times its width is considered a wall.

A cluster of two closely spaced longitudinal ribs or lateral ribs, that is two ribs whose spacing is less than three times the rib width, are counted as one rib.

A boss is an isolated projection with a length of projection that is generally less than about three times its overall width, the latter measured parallel to the surface from which it projects. A boss is usually circular in shape, but it can take a variety of other forms called knobs, hubs, lugs, buttons, pads, or "prolongs."

Bosses can be solid or hollow. In the case of a solid circular boss, the length of the boss and its width are both equal to the boss diameter.

Bosses, and sometimes ribs, are supported by a cluster of ribs of variable height called gusset plates. This cluster of ribs is treated as one rib or one cluster of ribs. See Figures 4.5, 4.6, and 4.7.

(9) Holes in a component that do not need to be classified as undercuts are considered side shutoffs. Side shutoffs can be simple or complex. Isolated grooves or cutouts on the external surface of a part are also considered side shutoffs. A groove or cutout is considered isolated if the dimension of the cutout normal to the direction of mold closure is less than 0.33 times the envelope dimension in the same direction. Penalties due to simple side shutoffs are not considered for parts whose first digit is 2, 4, or 6. See Figures 4.16 and 4.17.

(10) All words and symbols at one location on the part are classified as a single lettering entity since the entire lettering pattern on the tooling will be made using one electrode.

APPENDIX 4.B

Worksheet for Relative Tooling Costs—Injection Molding

Original Design

Relative Die Construction Cost

Basic Shape	L =	B =	H =	Box/Flat
Basic Complexity	1st Digit =	2nd Digit =	C_b =	
Sub. Complexity	3rd Digit =	4th Digit =	C_s =	
T_a/R_a	5th Digit =	6th Digit =	C_t =	

Total relative die construction cost C_{dc}	$= C_bC_sC_t =$

Relative Die Material Cost

L_m =	B_m =	H_m =
Die closure parallel to	L_m/H_m =	Thus, C =

$M_{ws} = [0.006CH_m^4]^{1/3} =$

$M_{wf} = 0.04L_m^{4/3} =$

$M_a = (2M_{ws} + L_m)(2M_{ws} + B_m) =$

$M_t = (H_m + 2M_{wf}) =$

Thus,

C_{dm}=	$C_d = 0.8C_{dc} + 0.2C_{dm} =$

Redesign Suggestions

Basic Shape	L =	B =	H =	Box/Flat
Basic Complexity	1st Digit =	2nd Digit =	C_b =	
Sub. Complexity	3rd Digit =	4th Digit =	C_s =	
T_a/R_a	5th Digit =	6th Digit =	C_t =	

Total relative die construction cost C_{dc}	$= C_bC_sC_t =$
$C_d = 0.8C_{dc} + 0.2C_{dm} =$	
% Savings =	

Chapter 5

Injection Molding: Total Relative Part Cost

5.1 INJECTION-MOLDED PART COSTS

5.1.1 Introduction

As we learned in the previous chapter, the first stage of a manufacturability evaluation for injection-molded parts is an evaluation of tooling costs. It can be done at the configuration design stage where only approximate dimensions, locations, and orientations of features are known. At the parametric stage, making use of the near final dimensions, locations, and orientation of features, a manufacturing evaluation of the relative cost to process a part can be made. Then the total cost of a part can be computed as the sum of the per part tooling costs, processing costs, and material costs.

As in the previous chapter, throughout this chapter we will be dealing with the concept of relative part cost. Relative cost, you will recall, was defined as the cost of your current part compared with the cost of some standard part. The standard or reference part used in the previous chapter was a 1 mm thick flat washer whose outer and inner diameters are 72 mm and 60 mm, respectively.

As was pointed out before, actual part costs depend upon local practices and methods and can vary considerably from one plant or location to another. Since the main objective here is to develop a methodology for making design decisions among various competing alternative designs, actual costs aren't necessarily required. In general, it suffices to have an appreciation for the cost drivers associated with the particular process under consideration so that the relative costs of competing designs can be compared. In this way informed design decisions can be made, better original designs will be proposed, and ultimately unnecessary redesigns will be avoided.

5.1.2 Processing Costs

Processing costs (sometimes called operating costs) are the charges for use of the injection molding machine used to produce the part. They depend on the machine hourly rate, C_h (\$/hr), and the effective cycle time of the process, t_{eff}. The effective cycle time is the machine cycle time, t, divided by the production yield, Y. Production yield, or just yield, is the fraction of the total parts produced that are satisfactory and, hence, usable. Thus,

$$\text{Processing cost per part, } K_e = C_h t_{eff} = C_h(t/Y) \quad \text{(Equation 5.1)}$$

where

Table 5.1 Data for the reference part.

Material	*Polystyrene*
Material Cost (K_{po})	1.46×10^{-4} cents/mm$^{3(1)}$
Vol (V_o)	1244 mm^3
Die Material Cost (K_{dmo})	\$980$^{(2)}$
Die Construction Time (Includes design and build hours)	200 hours$^{(2)}$
Labor Rate (Die Construction)	\$30/hr$^{(2)}$
Cycle time (t_o)	16 s$^{(2)}$
Mold Machine Hourly Rate (C_{ho})	\$27.53$^{(3)}$

(1) *Plastic Technology*, June 1989; (2) Data from collaborating companies; (3) *Plastic Technology*, July 1989.

Y = Production Yield (usable parts/total parts produced)

Part surface "quality" requirements and tolerances are the main causes for variations in production yield. A low yield reduces the number of acceptable parts that are produced in a given time, and thus increases the "effective cycle time" to a value higher than the actual machine cycle time, t. Increases of 10% to 30% in the effective cycle time for a given part are typical. The reasons for this increase are discussed in greater detail in Section 5.9.

The relative processing cost is the cost of producing a part relative to the cost of producing a reference part. Relative processing cost, C_e, can be expressed as:

$$C_e = \frac{tC_h}{t_oC_{ho}} = t_rC_{hr} \qquad \text{(Equation 5.2)}$$

where t_o and C_{ho} represent the cycle time and the machine hourly rate for the reference part, C_{hr} represents the ratio C_h/C_{ho}, and t_r is the total relative cycle time for the part compared with the reference part; that is:

$$t_r = \frac{t}{t_o} \qquad \text{(Equation 5.3)}$$

The reference part in this case is the same flat washer used as a reference part in Chapter 4: a 1-mm-thick flat washer whose outer and inner diameters are 72 mm and 60 mm, respectively. Some additional data (part material, material cost, tooling cost, etc.) for the reference part are given in Table 5.1.

5.1.3 Material Costs

The material cost for a part, K_m, is given by

$$K_m = VK_p \qquad \text{(Equation 5.4)}$$

where V is the part volume and K_p is the material cost per unit volume. Thus, if the subscript "o" is used to indicate the reference part, then the relative material cost can be expressed as

$$C_m = \frac{K_m}{K_{mo}} = \left(\frac{V}{V_o}\right)\left(\frac{K_p}{K_{po}}\right) = \left(\frac{V}{V_o}\right)C_{mr} \qquad \text{(Equation 5.5)}$$

Table 5.2 Relative material prices, C_{mr}, for engineering thermoplastics. (Based on material prices in *Plastics Technology*, June 1990.)

Material	C_{mr}
ABS	1.71
Acetal	2.92
Acrylic	1.54
Nylon 6	2.79
Polycarbonate	2.96
Polyethylene	0.71
Polypropylene	0.62
Polystyrene	1.00
PPO	2.33
PVC	0.62

Table 5.2 contains the relative material prices for the most often used engineering thermoplastics. The prices are all relative to polystyrene.

5.1.4 Total Cost

The total production cost of a part, K_t, can be expressed as the sum of the material cost of the part, K_m, the tooling cost, K_d/N, and processing cost, K_e, where K_d represents the total cost of the tool and N represents the production volume or total number of parts produced with the tool or mold. Thus,

$$K_t = K_m + \frac{K_d}{N} + K_e \qquad \text{(Equation 5.6)}$$

If the manufacturing cost of a reference part is denoted by K_o, then the relative total cost of the part, C_r, can be expressed as:

$$C_r = \frac{K_m + K_d/N + K_e}{K_o} \qquad \text{(Equation 5.7)}$$

In the remainder of this chapter, we present methods for computing the relative costs for injection-molded parts. We have already described, in Chapter 4, "Injection Molding: Relative Tooling Cost," how to estimate relative tooling costs for injection-molded parts.

A prerequisite step to determining total relative processing cost is the determination of the total relative cycle time. Thus we will begin in the next section with relative cycle time.

5.2 DETERMINING TOTAL RELATIVE CYCLE TIME (t_r) FOR INJECTION-MOLDED PARTS—OVERVIEW

As noted in the previous chapter, statistical studies of tooling cost as a function of part geometries have shown that tooling cost is more a function of

1. Overall part size (small, medium, or large) and shape (flat or box);
2. Presence and location of holes and projections that, depending upon their location, can lead to undercuts;

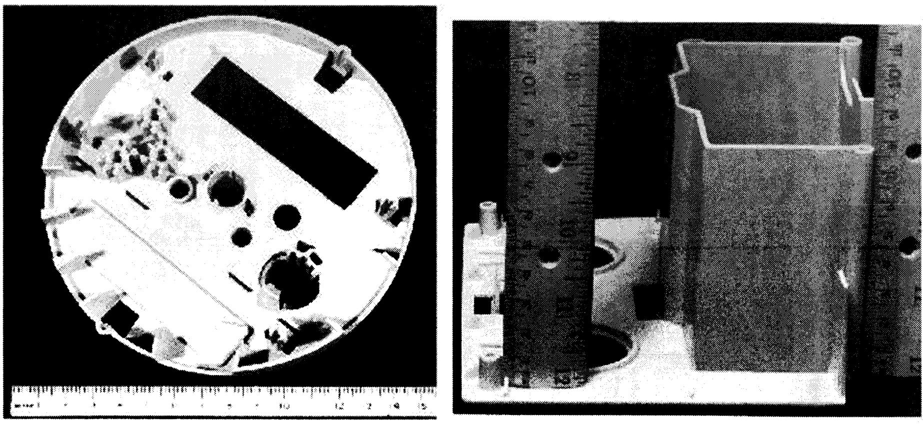


FIGURE 5.1 *Photographs of two injection-molded parts.*

3. Mold closure direction and parting surface location that can also, if poorly selected, lead to undercuts;

and less a function of localized features and details. On the other hand, similar statistical studies of processing costs as a function of part geometries have shown that cycle times are more a function of the localized features and details of parts. For example, in the case of parts such as those shown in Figure 5.1, the question becomes, is there a particular part feature (rib, boss, wall, etc.) whose wall thickness, height, layout, and other features result in a solidification time for that feature to be greater than all other part features? For it is the feature that takes longest to solidify that determines the cycle time of the part.

Efforts to emulate the conditioned knowledge possessed by molders, based upon years of experience, has led to a part-coding system for determining injection-molding processing costs similar to the coding system used for tooling costs. The mechanics of using the system are explained in the next several subsections. The overall result, however, is that the total cycle time relative to the standard or reference part, t_r, is obtained as a function of three parameters:

1. The *basic relative cycle time*, t_b
2. An *additional relative cycle time*, t_e, due to the presence of inserts and internal threads, and
3. A *multiplying penalty factor*, t_p, to account for the effects of part surface quality and tolerances.

In terms of these parameters, the *total relative cycle time*, that is the cycle time relative to the reference part, t_r, is given by

$$t_r = (t_b + t_e)t_p \qquad \text{(Equation 5.8)}$$

The basic relative cycle time, t_b, is given by values found in one of the three matrices shown in Figure 5.2, which define the first and second digits of the coding system. Note that to use this figure, the meaning of a number of basic terms must be understood, including: partitionable and non-partitionable parts; slender (S), non-slender (N), and frame-like parts; elemental plates; part thickness (w); grilles and slots; ribs and types of ribs; gussets; significant ribs and bosses; and easy- versus difficult-to-cool parts. We also must recall the definition of the basic enve-

SECOND DIGIT

Wall Thickness

FIRST DIGIT

(a) Slender Partitionable Parts, S

				$w < 1$ mm	$1\text{mm} \leq w \leq 2\text{mm}$	$2\text{mm} < w \leq 3\text{mm}$	$3\text{mm} < w \leq 4\text{mm}$	$4\text{mm} < w \leq 5\text{mm}$	$w > 5\text{mm}$
				0	1	2	3	4	5
Parts with $L_u/B_u \geq 10$ (1) or Frames (2)	Plates with $L_u/2w < 100$ (3) without lateral projections (4)	Without ribs	0	Difficult to fill or eject	1.00	1.35	1.70	2.55	Use foamed materials (9)
		With ribs	1		1.10	1.45	1.85	2.70	
	Plates with $L_u/2w \geq 100$ and/or plates with lateral projections (4)	Without ribs	2		1.15	1.55	2.00	2.85	
		With ribs	3		1.25	1.82	2.20	3.85	

(b) Non-Slender Partitonable Parts, N

					$w < 1$ mm	$1\text{mm} \leq w \leq 2\text{mm}$	$2\text{mm} < w \leq 3\text{mm}$	$3\text{mm} < w \leq 4\text{mm}$	$4\text{mm} < w \leq 5\text{mm}$	$w > 5\text{mm}$
					0	1	2	3	4	5
Parts with $\frac{L_u}{B_u} \leq 10$ (1)	Plates without significant rib (5) or significant bosses (6) with or without non-peripheral ribs or bosses	Plates which are grilled or slotted (7)	Without non-peripheral ribs	0	Difficult to fill or eject	1.68	2.39	3.11	3.82	Use foamed materials (9)
			With non-peripheral ribs	1		1.82	2.53	3.25	3.96	
		Plates which are not grilled or slotted (7)	Without non-peripheral ribs	2		1.96	2.67	3.39	4.10	
			With concentric or cross ribbing	3		2.10	2.81	3.53	4.24	
			With radial or unidirectional ribbing	4		2.24	2.96	3.67	4.39	
	Plates with significant ribs (5) and/or significant bosses (6)	Plates with rib and/or boss thickness less than the wall thickness (8)	Ribs/bosses supported by gusset plates	5		2.38	3.10	3.81	4.53	
			Ribs/bosses not supported by gusset plates	6		2.52	3.24	3.95	4.67	
		Plates with rib and/or boss thicknes (8) greater than or equal to the wall thickness		7		2.66	3.38	4.09	4.81	

(c) Non-Partitionable Parts

			$w < 1$ mm	$1\text{mm} \leq w \leq 2\text{mm}$	$2\text{mm} < w \leq 3\text{mm}$	$3\text{mm} < w \leq 4\text{mm}$	$4\text{mm} < w \leq 5\text{mm}$	$w > 5\text{mm}$
			0	1	2	3	4	5
Parts which are not partitionable	Easy to cool (10)	0	Difficult to fill or eject	2.66	3.38	4.09	4.81	Use Foamed Materials
	Difficult to cool (10)	1		3.56	4.50	5.47	6.40	

1 in = 25.4 mm; 1 mm/25.4 mm = 0.04 in

FIGURE 5.2 *Classification system for basic relative cycle time, t_b. (The numbers in parentheses refer to notes found in Appendix 5.A.)*

Table 5.3 Additional relative time, t_e, due to inserts and internal threads. (The numbers in parentheses refer to notes found in Appendix 5.A.)

Third Digit	Parts without internal threads (11)	Without molded-in inserts (12)	0	0.0
		With molded-in inserts (12)	1	0.5*
	Parts with internal threads (11)	Without molded-in inserts (12)	2	0.1*
		With molded-in inserts (12)	3	0.1*/0.5*

Table 5.4 Time penalty, t_p, due to surface requirements and tolerances. (The numbers in parentheses refer to notes found in Appendix 5.A.)

					Fifth Digit	
					Tolerances not difficult to hold (14)	Tolerances difficult to hold (14)
					0	1
Fourth Digit	Plate surface requirements (13)	Low		0	1.00	1.20
		H	$1\,\text{mm} \le w \le 2\,\text{mm}$	1	1.30	1.43
		i	$2\,\text{mm} < w \le 3\,\text{mm}$	2	1.22	1.41
		g	$3\,\text{mm} < w \le 4\,\text{mm}$	3	1.16	1.37
		h	$4\,\text{mm} < w \le 5\,\text{mm}$	5	1.10	1.32

lope of a part that was introduced in Chapter 4, "Injection Molding: Relative Tooling Cost."

The additional relative time due to inserts and internal threads, t_e, is found from Table 5.3. Table 5.3 defines the third digit of the coding system.

The time penalty factor, t_p, to account for surface requirements and tolerances, is found in Table 5.4, which defines the fourth and fifth digits in the coding system. To use Table 5.4, we must be able to distinguish between tolerances that are "easy" to hold and those that are more "difficult" to hold. We must also be able to distinguish surface finish requirements that are "low" from those that are "high." These issues are discussed and explained in Section 5.9.

As in the tooling evaluation system, the value of the basic relative cycle time, t_b, for the reference part is 1.00; it can be found in the upper-left-hand corner for slender or frame-like parts. (The washer chosen as the reference part is a frame-like part.) Note that the values for t_b increase significantly as one moves down and to the right of the matrix. This information, again, helps guide designers to redesigns that can reduce relative cycle time, hence, processing costs.

In the next few subsections, we will discuss the meaning of these terms, and then illustrate the use of the coding system in the evaluation of several example parts.

5.3 DETERMINING THE BASIC PART TYPE: THE FIRST DIGIT

In order to focus our attention on that particular feature or detail of a part that controls cycle time, when possible, parts are decomposed or partitioned into a series of elemental plates (Figure 5.3). The concept here is that every elemental plate has its own corresponding cooling time, hence, the plate with the longest

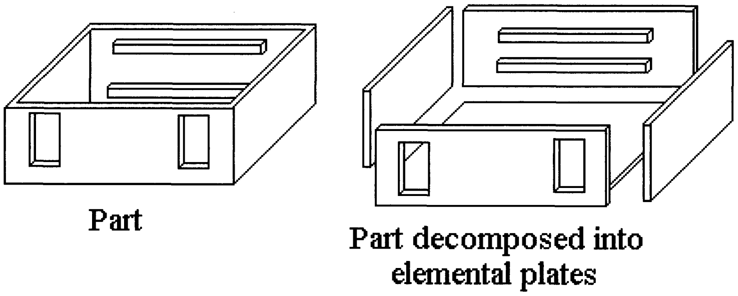


FIGURE 5.3 *Example of a part decomposed into a series of elemental plates.*

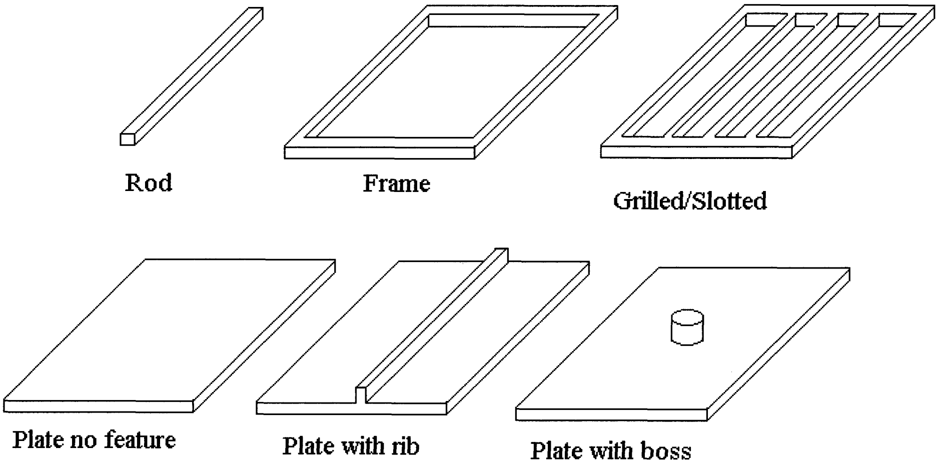


FIGURE 5.4 *Examples of elemental plates.*

cooling time controls the cycle time for the part. Thus, although cooling time for a plate is "local" its effect on the cycle time is "global."

Not all parts can be easily separated or partitioned into elemental plates, hence, partitionable parts are defined as those parts that can be easily and completely (except for add-ons like bosses, ribs, etc.) divided into a series of elemental plates. An elemental plate is a contiguous thin flat wall section whose edges are either not connected to other plates, or are connected via distinct intersections (e.g., corners). An elemental plate may have add-on features like holes, bosses, or ribs.

Examples of several types of elemental plates are shown in Figure 5.4. A method for partitioning a part into its elemental plates is described in Section 5.4.

For each elemental plate in a part, we will determine a cooling or solidification time. The plate with the longest cooling time controls the machine cycle time of the entire part. Thus, every elemental plate should be carefully designed so that its individual solidification time is minimized.

Partitionable parts are further classified as either slender or frame-like (S), or non-slender (N).

To distinguish quantitatively between slender and non-slender parts (see Figure 5.5 for a qualitative distinction), we consider the basic envelope of the part as shown in Figure 5.6. Given a basic envelope of dimensions (if you've forgotten what the definition of the basic envelope is you may want to reread

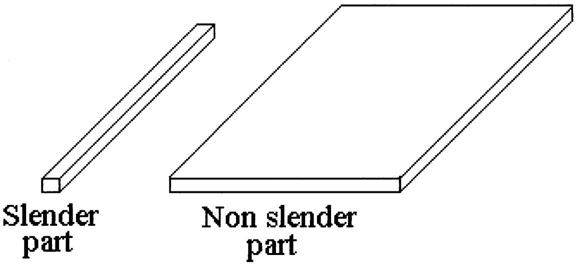
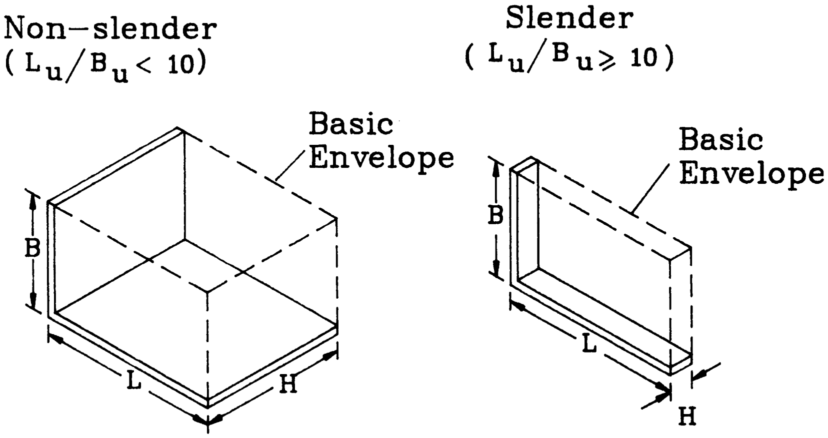


FIGURE 5.5 *A slender part.*



L, B, and H are the dimensions of the basic envelope of the part

$L_u = L + B \; ; \; B_u = H$

FIGURE 5.6 *Definition of a slender part.*

Section 4.3.2 of Chapter 4) L, H, and B, a slender partitionable part is one for which

$$L_u/B_u \geq 10$$

where

$$L_u = L + B$$

and

$$B_u = H$$

For parts with a bent or curved longitudinal axis, the unbent length, L_u, is the maximum length of the part with the axis straight (Figure 5.6). The width of this unbent part is referred to as B_u.

Frames are parts or elemental plates that have a through hole greater than 0.7 times the projected area of the part/plate envelope and whose height is equal to its wall thickness (Figures 5.7 and 5.8).

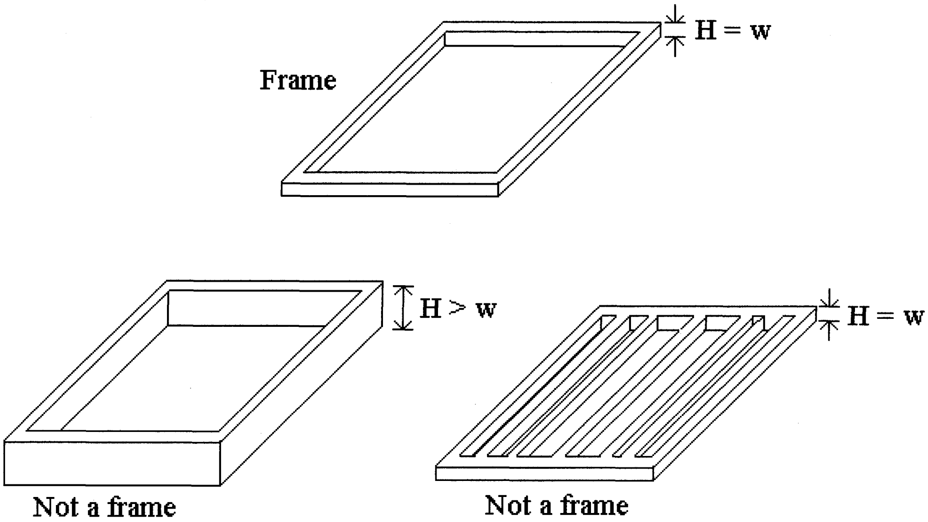


FIGURE 5.7 *Example of a frame-like part.*

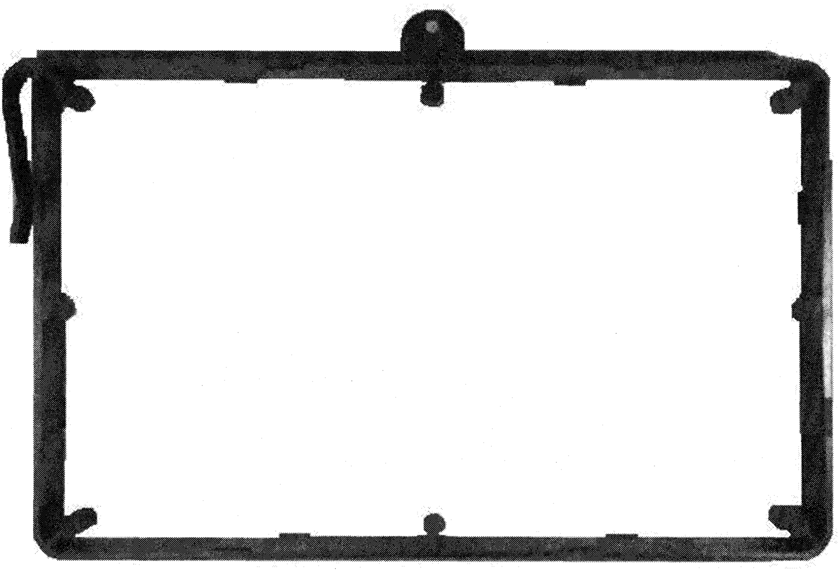


FIGURE 5.8 *Photograph of a frame-like part.*

Molds for slender parts and frames are generally more difficult to fill than molds for non-slender parts; however, slender parts are generally easier to cool.

Non-partitionable parts include parts with complex geometries, or parts with extensive subsidiary features such that they cannot be easily partitioned into elemental plates. We will also consider parts that have simple geometric shapes but contain certain difficult-to-cool features as non-partitionable. Examples of non-partitionable parts are shown in Figures 5.9, 5.10, and 5.11. A more complete discussion of non-partitionable parts is given in Section 5.5.

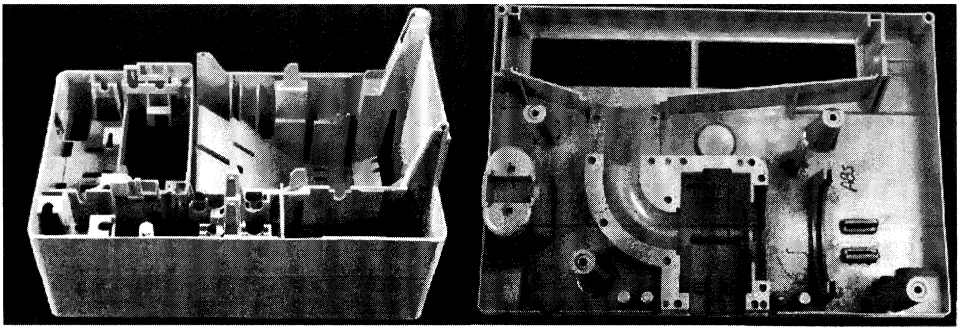


FIGURE 5.9 *Two examples of non-partitionable parts due to geometrical complexity.*

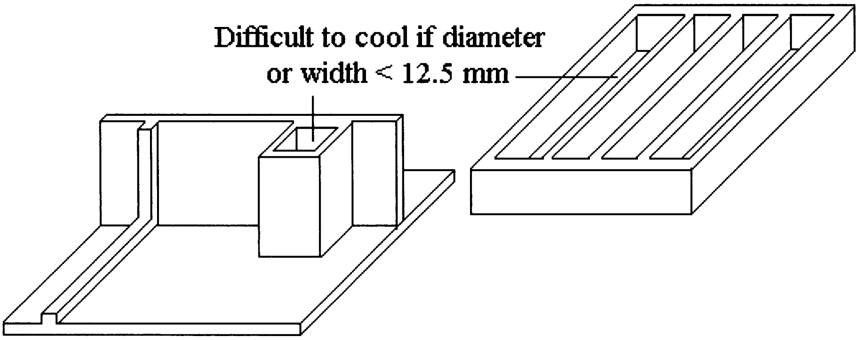


FIGURE 5.10 *Examples of non-partitionable parts due to extremely difficult to cool features.*

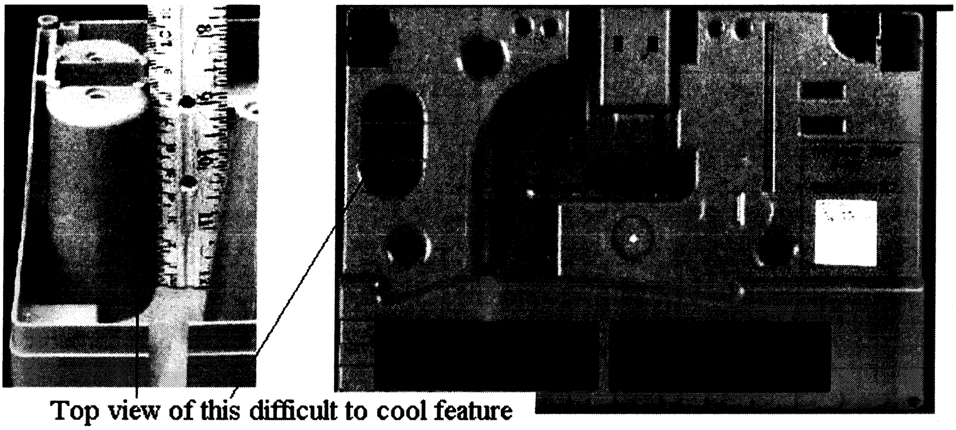


FIGURE 5.11 *Photograph of a part with a difficult to cool feature.*

5.4 PARTITIONING PARTITIONABLE PARTS

Part partitioning is a procedure for dividing or partitioning a part into a series of elemental plates similar to the ones shown in Figure 5.4. The procedure works best on parts with an uncomplicated geometrical shape, and features that can be cooled using cooling channels, bubblers, or baffles, as described below.

To partition or divide a part into a series of plates (see Figure 5.4) we proceed as follows:

1. Determine whether the part is slender or non-slender.
2. Divide the part into a series of plates with their corresponding add-on features (ribs, bosses, etc.).

Figure 5.12 shows a hollow rectangular prismatic part comprised of four side walls and a base. The four walls and base have equal and constant wall thicknesses. Also shown in Figure 5.12 are two alternative divisions of the part into elemental plates. To understand that the divisions are equivalent, it is necessary to understand how parts are cooled.

Figure 5.13 shows a schematic of a cooling system for such a part. Although the side walls (external plates) are efficiently cooled by cooling channels running parallel to the walls, the base (internal plate) needs to be cooled by more sophisticated but less efficient units such as baffles and bubblers. Thus, although plates (1), (2), (3), and (5) (Figure 5.12) are geometrically similar, plate (5) is a more difficult to cool internal plate, whereas the others are easier to cool external plates. Although plate (4) is also an external plate, it is a grilled plate.

Although the above explanation indicates that a difference in cooling time should exist between internal and external plates, in practice the increase in cycle time for injection-molded parts was not found to be statistically significant. This may be due in part to the fact that most engineering type partitionable parts have an L/H ratio small enough so that reasonable cooling occurs in any case.

Figure 5.14 shows the partitioning of some additional parts whose part envelope is rectangular. Figure 5.15 shows the partitioning of parts whose part

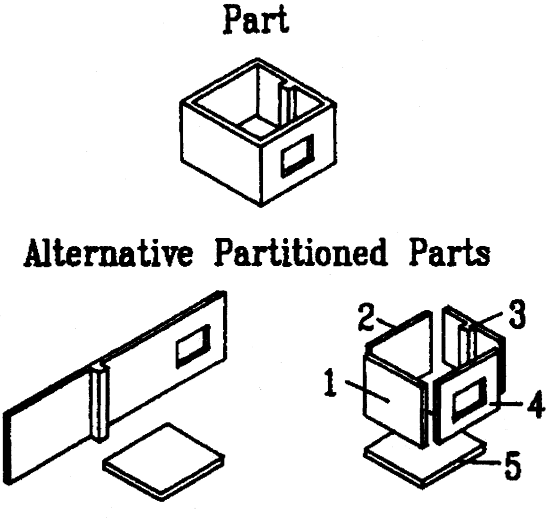


FIGURE 5.12 *Examples of part partitioning.*

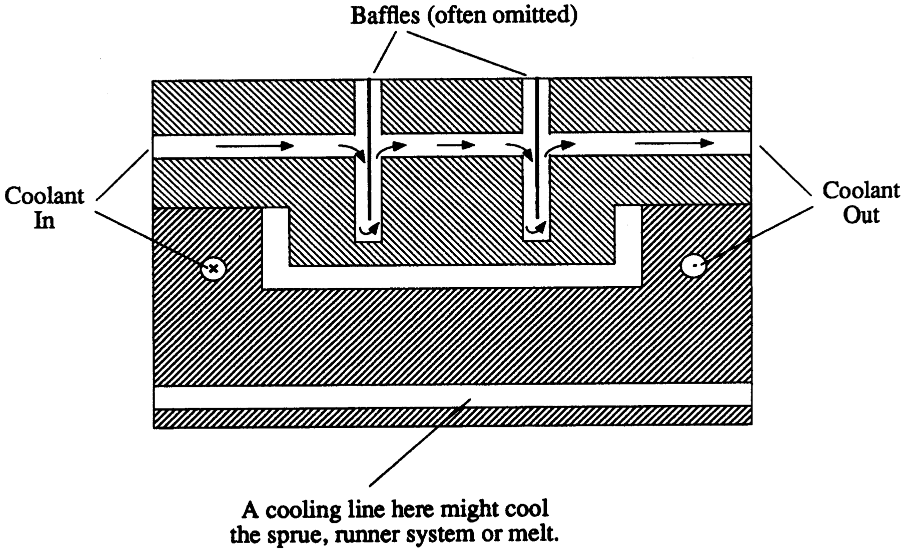


FIGURE 5.13 *Cooling system for part in Figure 5.12.*

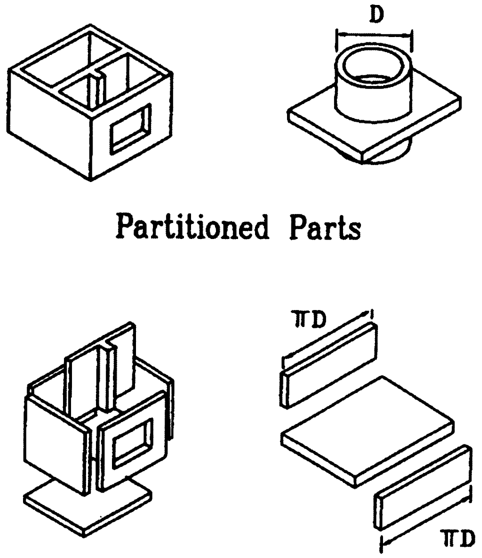


FIGURE 5.14 *Examples of part partitioning for parts whose part envelope is rectangular.*

envelope is cylindrical. The partitioning illustrated in Figure 5.15 assumes that the cylinders have a constant wall thickness and similar sets of subsidiary features (holes, projections, etc.). It is also assumed that the diameter of the cylinder is greater than 12.5mm. A smaller diameter would result in a part that would be extremely difficult to cool. If the wall thickness of the cylinder were not constant, the same partitioning could be used; however, one would use the maximum wall thickness in determining the relative cycle time of the elemental plate.

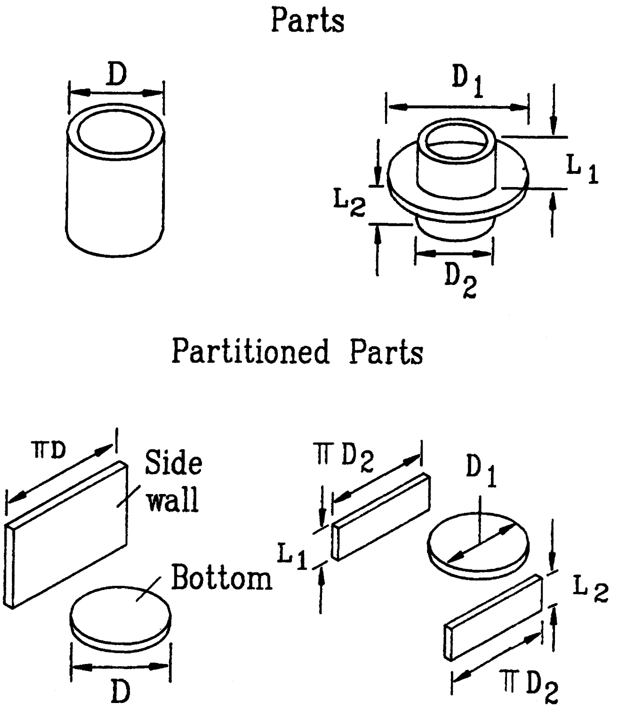


FIGURE 5.15 *Examples of part partitioning for parts whose part envelope is cylindrical.*

Before leaving this section it should be pointed out that slender parts (section (a) of Figure 5.2) tend to solidify faster than non-slender parts (section (b) of Figure 5.2). Slender parts cool faster because they are usually edge-gated, and non-slender parts are usually center-gated. Edge-gating permits cooling lines to be run along the top and bottom surfaces of the part. As indicated in Figure 5.13, center-gating precludes the use of cooling lines in the vicinity of the sprue and gate.

5.5 NON-PARTITIONABLE PARTS

Not all parts can be easily visualized as comprised of a series of elemental plates as depicted in Figure 5.4. That is to say, not all parts are partitionable. Some contain geometrically complex shapes (Figure 5.9) and others contain some extremely difficult to cool features (Figure 5.10) where even baffles and bubblers cannot be used. These parts are generally harder to cool and may produce difficulties in maintaining other requirements related to warping, surface finish, tolerances, and so on. These types of parts have relative cycle times greater than those predicted by use of the coding system applied to slender and non-slender partitionable parts. The coding system can, however, be used to determine the lower bound for the relative cycle time of non-partitionable parts. This is done by determining

1. The relative cycle time for that portion of the part that is "easy-to-cool," and
2. The relative cycle time for the most difficult to cool feature.

The lower bound will be the larger of the values determined in (a) and (b). The actual value could be 25% to 50% higher than the values obtained via the coding system.

5.6 OTHER FEATURES NEEDED TO DETERMINE THE FIRST DIGIT

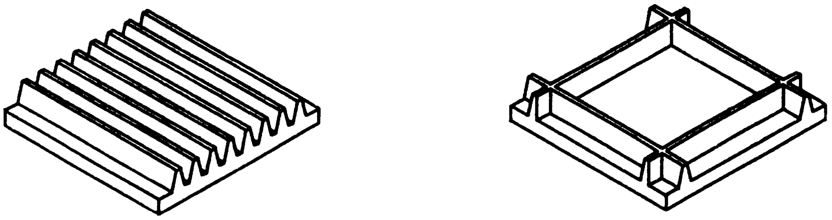
5.6.1 Introduction

The ability to identify (and partition) slender and non-slender partitionable parts enables us to determine whether the basic relative cycle time, t_b, will be found in section (a), (b), or (c) of Figure 5.2. However, to completely identify the first digit and get the actual value of t_b, we must also be able to determine the presence or absence of such features as ribs (and their types), lateral projections, grilles and slots, and gussets. Therefore, in this section, we will define the meaning of these terms as used in the coding system.

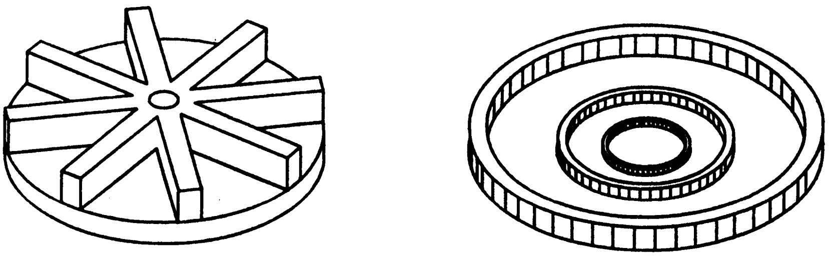
5.6.2 Ribs

Types of Ribs

When ribs are present, cycle time has been found to depend upon the types of ribs present. See Figure 5.16. Multidirectional ribs and concentric ribs provide greater rigidity than unidirectional ribs and radial ribs. For this reason multidirectional ribbing is often preferred as a means of stiffening parts with thin walls. (A properly designed thin wall with ribs can be lighter than a non-ribbed thicker



Unidirectional Ribs **Multidirectional Ribs**



Radial Ribs **Circumferential Ribs**

FIGURE 5.16 *Types of ribbing.*

wall with the same stiffness. In addition, plates with multidirectional ribbing have less of a tendency to warp than plates with unidirectional ribbing, thereby making shorter cycle times possible.) From the point of view of machine cycle time, peripheral ribs can be treated as walls because they do not increase the localized wall thickness of the part.

Significant Ribs

Significant ribs tend to increase the machine cycle time, because of increased local wall thickness at their base, and, in the case of unsupported unidirectional ribs, make tolerances difficult to hold. In addition, such ribs can be difficult to fill and result in shallow depressions (called sink marks) on the surface of the part; these are due to the collapsing of the surface following local internal shrinkage. Sink marks reduce part quality and should generally be avoided. To avoid sink marks ribs should be designed so that (1) the rib height, h, is less than or equal to three times the localized wall thickness, w, and (2) the rib width, b, is less than or equal to the localized wall thickness. Thus, we call ribs designed such that [$3w < h < 6w$] or [$b > w$] significant ribs (Figure 15.17).

5.6.3 Gussets

A rib of variable height, usually present at the junction of two elemental plates, is called a gusset plate (Figure 5.18). A gusset plate can also be present at the junction between a projection (boss, rib, etc.) and the wall to which it is attached (see Figures 4.5 and 4.7). Gusset plates facilitate mold filling, help hold tolerances, and provide stiffening that may permit a reduction in the thickness of bosses and walls.

5.6.4 Bosses

For bosses, cycle time is influenced by whether they are supported by gusset plates (see Figures 5.18 and 4.7). Plates with large (tall) projections are difficult to cool because these features significantly increase localized wall thickness, are difficult to fill, and have a tendency to warp. Significant projections should be

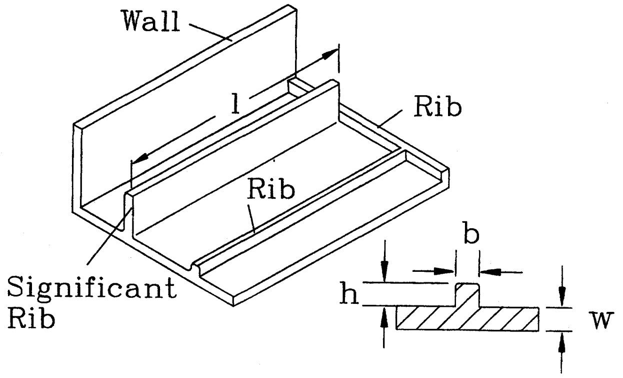


FIGURE 5.17 *Ribs. The length of the rib is denoted by l, the rib width by b, the rib height by h, and the wall thickness of the plate by w. A significant rib is one where $3w < h < 6w$ or $b > w$.*

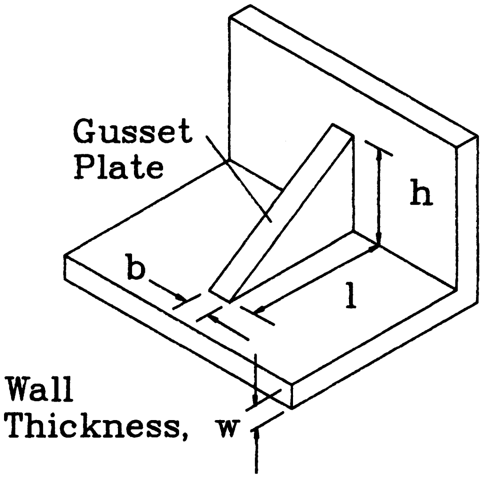


FIGURE 5.18 *Gusset Plate. The thickness of the gusset plate is denoted by b, the height by h, and the length by l. The wall thickness of the plate is w.*

supported by gusset plates to reduce their tendency to deflect due to residual stresses.

Significant Bosses

We consider bosses designed such that [3w < h] or [b > w] as significant bosses (Figure 5.19). Significant bosses tend to increase the machine cycle time, make tolerances difficult to hold, and can be difficult to fill. In addition, significant bosses often cause sink marks.

5.6.5 Grilles and Slots

Elemental plates that contain (1) multiple through holes, (2) no continuous solid section with a projected area greater than 20% of the projected area of the plate envelope, and (3) whose height is equal to its wall thickness are considered grilled/slotted (Figure 5.20). Such plates are low in strength and have low surface gloss due to the presence of multiple weld lines. The weld lines are caused when the flows from multiple gates meet (see Figure 5.21).

5.6.6 Lateral Projections

Lateral projections are add-on features that protrude from the surface of a slender plate in a direction normal to the longitudinal axis (Figure 5.22). For long slender parts, such projections are difficult to fill.

5.7 WALL THICKNESS—THE SECOND DIGIT

The definitions in Section 5.6 will enable designers to determine the basic part type, and to establish the first digit of the coding system in Figure 5.2. Determining the second digit is essentially based on the largest wall thickness (w) of the elemental plates.

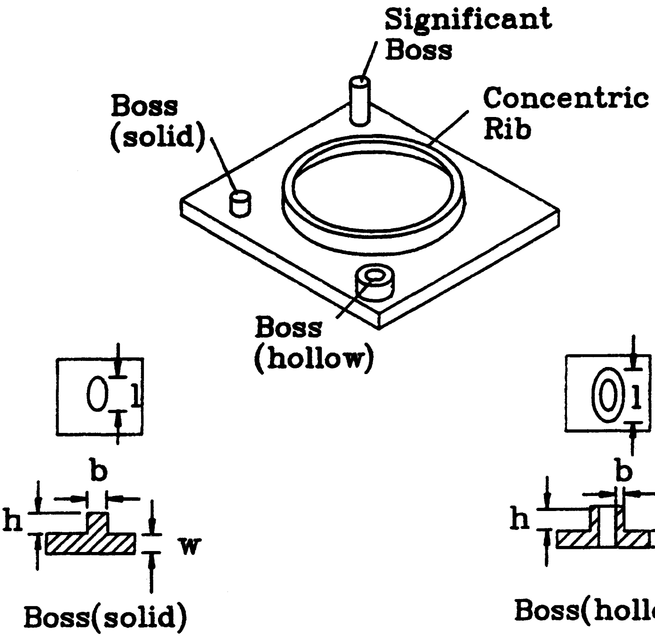


FIGURE 5.19 *Bosses. The boss length is denoted by l, the width by* b_w*, the wall thickness by b, the height by h, and the wall thickness of the plate by w.*

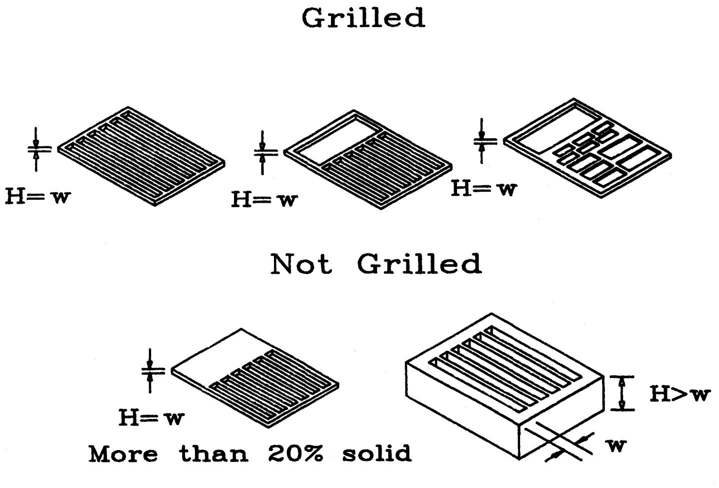


FIGURE 5.20 *Examples of grilled or slotted parts.*

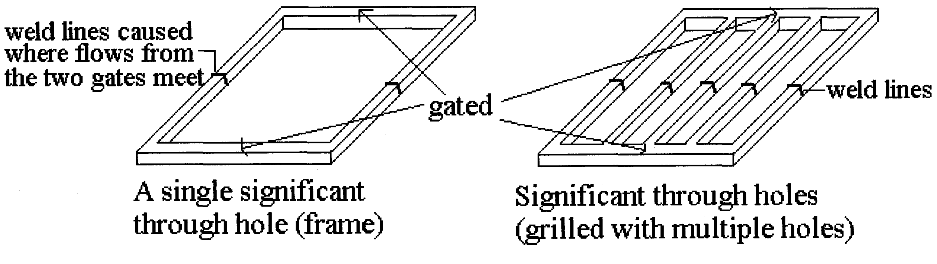


FIGURE 5.21 *Weld lines caused when the flows from two gates meet.*

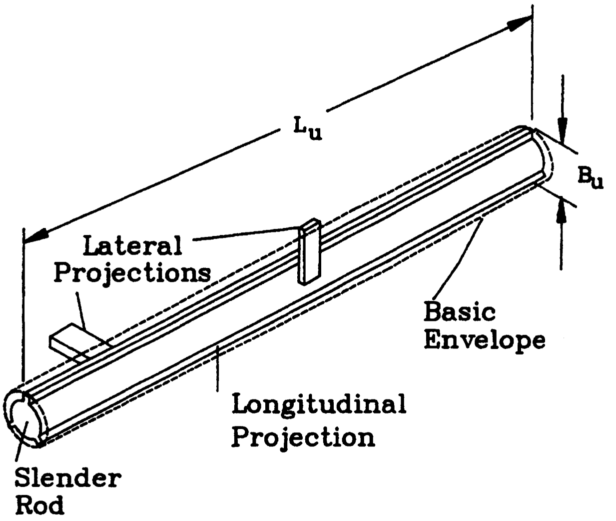


FIGURE 5.22 *Example of lateral projections.*

In the case of non-partitionable parts, two wall thicknesses need to be used. (Remember, we need to determine the cycle time based on the easy-to-cool features and the cycle time based on the difficult-to-cool features.) One wall thickness is the largest wall thickness of all the easy-to-cool portions of the part. The other wall thickness is the largest wall thickness of all the difficult-to-cool features.

5.8 INSERTS AND INTERNAL THREADS—THE THIRD DIGIT

Refer again to Table 5.3. Note that to obtain the value of t_e we need only ascertain whether or not the part has internal threads and inserts. The meaning of internal thread is obvious. Inserts are metal components added to the part prior to molding the part. Inserts are added for decorative purposes, to provide additional localized strength, to transmit electrical current, or to aid in assembly or subassembly work. The use of inserts increases the machine cycle time.

5.9 SURFACE REQUIREMENTS AND TOLERANCES—THE FOURTH AND FIFTH DIGITS

5.9.1 Surface Requirements

Hot molds produce glossier surfaces and result in longer cycle times. Cool molds yield duller finishes and result in shorter cycle times. In addition, and more importantly, high surface gloss requirements may greatly reduce production efficiency and yield because of a higher rejection rate due to visible sink marks, jet lines, and other surface flaws.

The preferred surface for a part is usually one that is produced from a mold having a Society of Plastics Industry (SPI) finish of 3 or 4. Such parts tend to be used on industrial products where high gloss is not required. Parts requiring a high gloss and good transparent clarity are produced from molds having an SPI of 1 or 2. For parts requiring a textured surface and low surface gloss, a mold having an SPI of 5 or 6 is used.

For the purposes of the coding system, the part surface requirement (see Table 5.4) is considered high when

1. Parts are produced from a mold having an SPI surface finish of 1 or 2.
2. Sink marks and weld lines are not allowed on an untextured surface.

In the coding system, parts without high surface requirements are considered to have low surface requirements.

A statistical analysis of piece parts collected from several molders shows that the adverse effect of a high-gloss requirement is more significant on thin parts than on thick parts. A possible explanation is as follows:

The colder the mold or the melt, the more viscous the flow. The more viscous the flow, the greater the tendency to leave visible "flow marks" on the surface of the part. These flow marks make it difficult to obtain a good surface gloss. Since thin parts cool faster than thick parts, poor surface gloss is more likely to occur on thin parts.

5.9.2 Tolerances

There are two types of tolerance requirements: (1) dimensional and (2) geometric. Dimensional tolerances refer to tolerances on the length, width, and height of a part as well as on the distance between features. Geometric tolerances refer to tolerances on flatness, straightness, perpendicularity, cylindricity, and other features.

For dimensional tolerances, an industry standard exists prepared by the Society of Plastic Industry, and each material supplier converts its data to suit a specific material. Thus, to determine whether the tolerances specified are tight or commercial, we must refer to either the data published by the Society of the Plastic Industry for the material in question, or to data supplied by the resin manufacturer. No industrywide standard exists as yet for geometrical tolerances.

Part yield is influenced by part tolerance requirements. Part yield decreases when part tolerances are relatively difficult to hold. Part tolerances are considered difficult to hold if:

(a) External undercuts are present.
(b) A tolerance is specified across the parting surface of the dies. The high pressures (10,000 psi) cause slides and molds to move slightly, making tolerances across the moving surfaces difficult to hold.
(c) The wall thickness is not uniform. Thick sections connected to thin sections tend to shrink more than the thin sections. This is because the thick sections continue to cool down and shrink after the thin sections have solidified. This variation in shrinkage can result in part warpage. When warping is a problem, the cycle time of a part is increased to allow the part to be more rigid when it is ejected.
(d) Unsupported projections (ribs, bosses) and walls are used. Unsupported projections can bend, making tolerances between them difficult to hold.

(e) More than three tight tolerances, or more than five commercial tolerances are required. Tolerances should be specified only where absolutely necessary. As the number of tolerances to be held increases, the proportion of defective parts produced increases.

5.10 USING THE CODING SYSTEM—OVERVIEW

To determine the relative cycle time for a part using the coding system shown in Figure 5.2 and Tables 5.3 and 5.4, we proceed as follows:

1. Determine whether or not the part is partitionable.
2. If the part is partitionable, partition it into elemental plates and assess the relative cycle time for each plate. The plate with the largest relative cycle time controls the cycle time for the part.
3. If the part is not partitionable, we first code the part using the maximum wall thickness of the part. If this is an easy to cool feature we then code the part a second time using the most difficult to cool feature. The feature with the largest relative cycle time controls the cycle time for the part.

Several Examples are presented in Sections 5.12 to 5.14 below.

5.11 EFFECT OF MATERIALS ON RELATIVE CYCLE TIME

In theory, the machine cycle time depends on the material used. In practice, however, there is little significant difference in cycle time between geometrically similar engineering parts made of different materials. Although it is true that some materials will solidify faster than others, there are other factors that tend to cause the actual cycle time to be very similar for the parts with the same geometry but made of different materials. Some of these factors include the following issues.

1. The most important objective for a precision molder is the production of parts with satisfactory dimensional stability and high gloss. Fast molding cycles cause greater variations in mold and melt temperatures than slow cycles. These large temperature variations often result in poor dimensional stability, rejected parts, and resulting lower yield. Furthermore, fast cycles require lower mold and melt temperatures that are likely to cause difficulties in producing parts with high gloss.

Therefore, in order to produce parts with high gloss and dimensional stability, precision molders are likely to manufacture parts at nearly the same rate for rapidly solidifying materials as they would for materials that solidify at a slower rate.

2. Many engineering parts are produced in annual production volumes of 5,000 to 10,000 and in batch sizes of 500 to 1,000. These batch sizes can be produced in two to four shifts (16–32 hours). For such small batches, it is not practical to "optimize" the cycle time for the particular part/material combination.

3. Each machine has its own peculiar characteristics and idiosyncrasies. Thus, a part made of the same material but molded on two different machines under the same set of operating conditions will require different cycle times in order to produce a part of the same high gloss and dimensional stability.

Consequently, optimal operating conditions will vary from machine to machine. The likelihood that a given part would, for each batch, be run on the same machine is very low.

5.12 EXAMPLE 5.1—DETERMINATION OF RELATIVE CYCLE TIME FOR A PARTITIONABLE PART

5.12.1 The Part

For the first example, we consider the part shown in Figure 5.23. In addition to the general overall size of the part, the wall thickness, and the size of the ribs and bosses are given. Although these latter dimensions are not needed in order to estimate the relative tooling cost for this part, they must be known in order to determine the relative cycle time.

5.12.2 The Basic Part Type

In this example, the length of the projections parallel to the surface of the part, c, are 10 mm. Since c/L is less than 1/3 then, as you may recall from Figure 4.3, these projections are considered isolated projections of small volume. Consequently, the dimensions of the basic envelope are

$$L = 160, \quad B = 130, \quad H = 10$$

Since the part is straight, the unbent dimensions L_u and B_u are equal to L and B, respectively. Thus, $L_u/B_u < 10$ and the part is non-slender. We will indicate the fact that the part is non-slender by using the letter N.

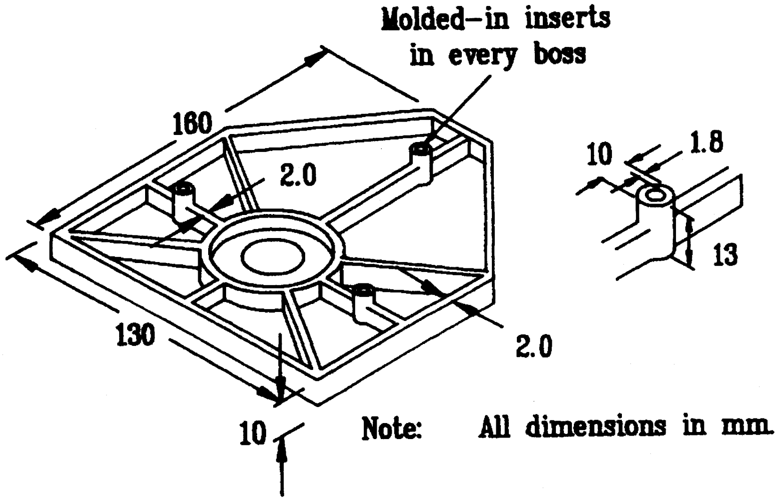


FIGURE 5.23 *Example 5.1.*

5.12.3 Part Partitioning

This part consists of a single elemental plate; thus, no partitioning is needed.

5.12.4 Relative Cycle Time

Basic Relative Cycle Time

The length, l, the width, b, and the height, h, of each projection (boss) is 10mm, 1.8mm, and 13mm, respectively. The plate thickness w is 2.0mm and uniform. Thus, $h/w > 3$, and the projections are considered significant bosses. Since the boss thickness (b) is less than the wall thickness (w) and gusset plates do not support them, the first digit is 6.

The maximum plate thickness is 2.0mm, hence, the second digit is 1, thus, the basic code is N61 and the basic relative machine cycle time, t_b, is 2.52. (Remember, relative cycle time is the cycle time relative to our reference part and is, thus, dimensionless.)

Internal Threads/Inserts

There are no internal threads, but there are three molded-in inserts (one in each boss). Hence, the third digit is 1 and the additional relative time, t_e, is 0.5 per insert or 1.5 for the part.

Surface Gloss/Tolerances

Let's assume that the part requires a low surface gloss (which corresponds to an SPI surface finish of 3 on the mold). Thus, the fourth digit is 0. Because the bosses are unsupported it is difficult to hold tolerances between them, hence, the fifth digit is 1 and the penalty factor, t_p, is 1.20.

Relative Effective Cycle Time

The relative effective cycle time is given by substituting into Equation 5.8, thus,

$$t_r = (t_b + t_e)t_p = (2.52 + 1.5)1.2 = 4.82$$

5.12.5 Redesign Suggestions

The relative cycle time can be reduced in several ways. One method is to provide gusset plates to support the bosses. In this case, the basic code becomes N51, and the fifth digit becomes 0. Thus, the relative machine cycle time is reduced to 2.38, t_p becomes 1, and the relative effective cycle time becomes 3.88—a 19% reduction.

A second method for reducing the relative cycle time would be to reduce the height of the bosses so they become nonsignificant bosses. In this case, the new basic complexity code becomes N41, the fifth digit becomes 0, and the new relative machine cycle time is reduced to 3.74. This is a 22% reduction.

If the bosses are left as originally designed but the molded-in inserts are removed, t_e is reduced to 0, and the relative effective cycle time becomes 3.02—a 37% savings. However, if the inserts are inserted after the part is molded, nothing has been gained by this saving.

Readers should note that although the magnitude of these savings, created by relatively small design changes, might be unimportant for small production volumes, they could become extremely valuable for high-volume parts.

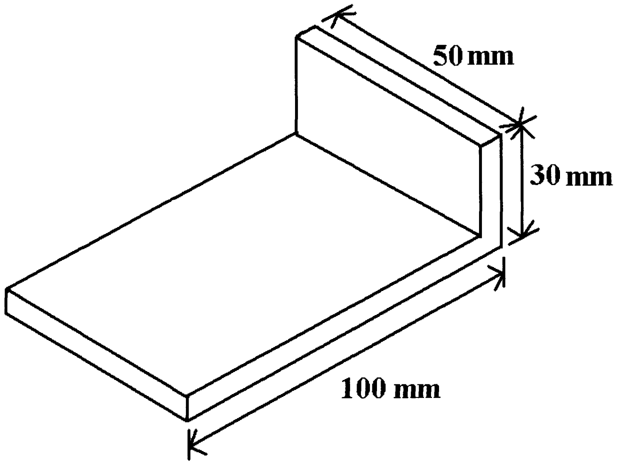


FIGURE 5.24 *Example 5.2.*

5.13 EXAMPLE 5.2—DETERMINATION OF RELATIVE CYCLE TIME FOR A PARTITIONABLE PART

5.13.1 The Part

As a second example we consider the part shown in Figure 5.24. The wall thickness of the part is a constant 3.1 mm. Since the height of the "peripheral projection" in this case is greater than 6w, it will be treated as a wall rather than a rib. (From the point of view of creating the tooling required to mold the part, peripheral ribs and peripheral walls are comparable. Hence, for the purposes of the coding system, all peripheral projections, including ribs, will be treated as peripheral walls.) The part geometry is rather simple and is, thus, partitionable.

5.13.2 Basic Part Type

Since $L_u = L + H = 130\,\text{mm}$ and $B_u = B = 50\,\text{mm}$, then $L_u/B_u = 2.6$, and the part is non-slender, (N).

5.13.3 Part Partitioning

This part can be partitioned in two ways. It can be partitioned as shown in Figure 5.25 into two separate elemental plates. Alternatively, since the wall thickness of the part is constant and both plates are external plates, the part can be treated as a single plate, as shown in Figure 5.26.

5.13.4 Relative Cycle Time—Elemental Plate 1 (Figure 5.25)

Basic Relative Cycle Time

The plate is neither grilled nor slotted, and no projections are present. Thus, the first digit is 2. The wall thickness is 3.1 mm, hence, the second digit is 3. The basic code is N23. Thus, the basic relative machine cycle time, t_b, is 3.39.

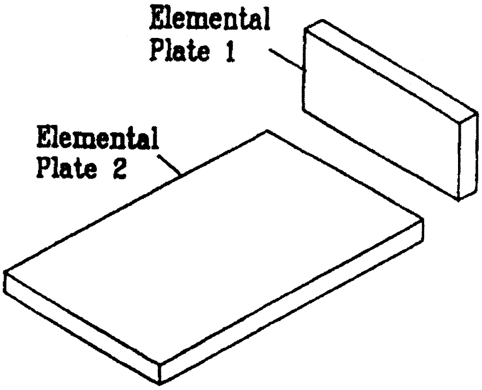


FIGURE 5.25 *Part partitioning.*

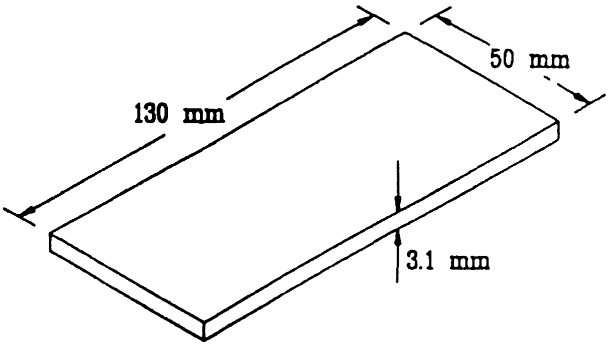


FIGURE 5.26 *Alternate partitioning.*

Internal Threads/Inserts

There are no internal threads or molded-in inserts. Hence, the third digit is 0 and the relative extra mold opening time, t_e, is 0.

Surface Gloss/Tolerances

The part is assumed to require a high surface gloss (SPI surface finish of 1 or 2 on the mold), thus the fourth digit is 3. The 90° angle between the side wall and the bottom is difficult to hold because of the sharp (unradiused) corner and the lack of supporting gusset plates. Thus, the part tolerance is difficult to hold, the fifth digit is 1, and the penalty, t_p, is 1.37.

Relative Effective Cycle Time

The relative effective cycle time for the original design is:

$$t_r = (t_b + t_e)t_p = (3.39)1.37 = 4.64$$

5.13.5 Relative Cycle Time—Elemental Plate 2 (Figure 5.25)

The complete code for this plate is identical to that for plate 1, thus the relative effective machine cycle time is the same.

5.13.6 Relative Cycle Time—Elemental Plate (Figure 5.26)

Basic Relative Cycle Time

Once again, the plate is neither grilled nor slotted and no projections are present. The code for this plate is also N23, and the relative machine cycle time is 3.39.

Internal Threads/Inserts

There are no internal threads or molded-in inserts. Hence, the third digit is 0 and the relative extra mold opening time, t_e, is 0.

Surface Gloss/Tolerances

The part is assumed to require high surface gloss, thus the fourth digit is 3. The 90° angle between the side wall and the bottom is difficult to hold because of the unradiused (sharp) corner and the lack of supporting gusset plates. Thus, the part tolerance is difficult to hold, the fifth digit is 1 and the penalty is 1.37.

Relative Effective Cycle Time

The relative effective cycle time for the design is:

$$t_r = (t_b + t_e)t_p = 4.64$$

5.13.7 Redesign Suggestions

The two cost drivers in this case are the high surface-gloss requirement and the difficult to maintain 90° angle between the side wall and the bottom surface. If the part surface can be replaced by a textured surface (SPI-3 on the mold) the fourth digit becomes 0. If in addition the corner between the two plates can be radiused, or if supporting gusset plates can be used, or if the maintenance of a precise 90° angle is not considered important, the fifth digit becomes 0 and the new penalty is lowered to 1.0. Thus the new relative effective cycle time is 3.39—a 27% reduction.

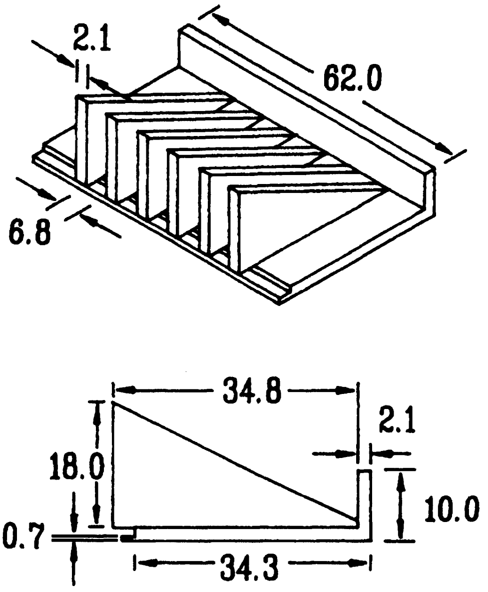
5.14 EXAMPLE 5.3—DETERMINATION OF RELATIVE CYCLE TIME FOR A NON-PARTITIONABLE PART

5.14.1 The Part

The part and all of the dimensions necessary for a determination of the relative cycle time are shown in Figure 5.27.

5.14.2 Part Partitioning

Because the spacing between fins is less than 12.5 mm, the closely spaced fins are difficult to cool. Thus, in spite of its rather simple geometry, the part is considered non-partitionable.



Note: All dimensions in mm.

FIGURE 5.27 *Example 5.3.*

5.14.3 Relative Cycle Time

Basic Machine Cycle Time

Since this part is non-partitionable, the basic code must be found for the thickest easy-to-cool feature as well as the thickest difficult-to-cool feature. However, since the thickness of the part is uniform, only the difficult-to-cool feature needs to be coded. Thus, since the wall thickness is 2.1 mm, the first and second digits are 1 and 2, respectively. Hence, the basic code for the part is NP12, and the basic relative time, t_b, is 4.50.

Internal Thread/Inserts

There are no internal threads or molded-in inserts, thus the third digit is 0 and $t_e = 0$.

Surface Gloss/Tolerances

The presence of the fins makes sink marks unavoidable on the plate to which the fins are attached. Thus, as pointed out in Section 5.9.1, the fourth digit is 2. Assuming that the spacing between the fins is critical, then the lack of gusset plates supporting the closely spaced fins makes the tolerance on the distance between fins difficult to hold—hence, the fifth digit is 1. Therefore, the penalty is 1.41.

Relative Effective Cycle Time

The relative effective cycle time is

$$t_r = (t_b + t_e)t_p = (4.50 + 0)(1.41) = 6.34$$

Table 5.5 Machine tonnage and relative hourly rate. (Data published in *Plastic Technology*, June, 1989.)

Machine Tonnage	*Machine Hourly Rate*
<100	1.00
100–299	1.19
300–499	1.44
500–699	1.83
700–999	2.87
>1000	2.93

5.14.4 Redesign Suggestions

For non-partitionable parts, design improvements are often difficult to make without major changes in part geometry. One possible improvement in the current case, in the sense of reducing processing costs, is to increase the spacing between fins so that the cooling difficulty can be reduced.

It is worth pointing out that the part was coded as though the spacing between fins is critical, and that sink marks are not acceptable. However, practical concerns may be such that stringent tolerance and surface requirements are not necessary. This would change both the fourth and fifth digits to 0, and the relative effective cycle time would also change accordingly.

5.15 RELATIVE PROCESSING COST

The preceding discussion and examples have shown how to compute the relative part cycle time, t_r. This is a critical requirement in estimating relative processing costs. As noted in the Section 5.1.2 of this chapter, the relative processing cost is given by:

$$C_e = t_r C_{hr} \qquad \text{(Equation 5.2)}$$

where C_{hr} represents the ratio C_h/C_{ho}, C_{ho} represents the machine hourly rate for the reference part, and C_h is the machine hourly rate ($/h) for a given part. The relative machine hourly rate, C_{hr}, can be determined from Table 5.5, but it is first necessary to determine the injection molding machine size (tonnage) required to mold the part.

The machine tonnage required to mold a part is approximately two to five tons per square inch, depending on the material to be molded and on the projected area of the part normal to the direction of mold closure. In general, it is assumed that a machine whose tonnage, F_p, exceeds a numerical value equal to three times the projected area of the part (expressed in in^2) will suffice. Thus, the required machine tonnage is approximately

$$F_p = 3A_p \qquad \text{(Equation 5.9)}$$

where the projected area, A_p, is in in^2 or

$$F_p = 0.005A_p \qquad \text{(Equation 5.10)}$$

where the projected area is in mm^2.

5.16 RELATIVE MATERIAL COST

As noted in Section 5.1.3 of this chapter, the material cost for a part, K_m, is given by

$$K_m = VK_p \qquad \text{(Equation 5.4)}$$

where V is the part volume and K_p is the material cost per unit volume, and the relative material cost is:

$$C_m = \frac{V}{V_o} C_{mr} \qquad \text{(Equation 5.5)}$$

Values for C_{mr} are given above in Table 5.2.

5.17 TOTAL RELATIVE PART COST

As stated earlier in this chapter (Section 5.1.4), the total production cost of a part, K_t, in units such as dollars or cents, is now computed as the sum of the material cost of the part, K_m, the tooling cost, K_d/N, and the processing cost, K_e:

$$K_t = K_m + \frac{K_d}{N} + K_e \qquad \text{(Equation 5.6)}$$

where K_d represents the total cost of the tool and N represents the number of parts, or production volume, to be produced using that tool.

If K_o denotes the manufacturing cost of some standard or reference part, then

$$K_o = K_{mo} + \frac{K_{do}}{N_o} + K_{eo}$$

where K_{mo}, K_{do}, and K_{eo} represent the material cost, tooling cost, and equipment operating cost for the reference part. Thus, the total cost of the part relative to the cost of the reference part, C_r, can be expressed as:

$$C_r = \frac{K_m + K_d/N + K_e}{K_o} \qquad \text{(Equation 5.7)}$$

where C_r is, of course, dimensionless.

The total relative cost C_r can be written as follows:

$$C_r = \frac{K_m}{K_{mo}} \frac{K_{mo}}{K_o} + \frac{(K_d/N)}{K_{do}} \frac{K_{do}}{K_o} + \frac{K_e}{K_{eo}} \frac{K_{eo}}{K_o}$$

If

$f_m = K_{mo}/K_o$,

$f_d = K_{do}/K_o$, and

$f_e = K_{eo}/K_o$,

which represent the ratio of the material cost, tooling cost, and processing cost of the reference part to the total manufacturing cost of the reference part, and if

$$C_m = K_m/K_{mo},$$

$$C_d = K_d/K_{do}, \text{ and}$$

$$C_e = K_e/K_{eo}$$

are, respectively, the material cost, tooling cost, and equipment operating cost of a part relative to the material cost, tooling cost, and equipment operating cost of the reference part, then the above equation becomes,

$$C_r = C_m f_m + (C_d/N) f_d + C_e f_e \qquad \text{(Equation 5.11)}$$

The value for C_d is obtained from Equation 4.4, as described in Chapter 4, "Injections Molding: Relative Tooling Cost," while the values for C_e and C_m are obtained from Equations 5.2 and 5.5, respectively.

If it is assumed that only single cavity molds will be used, then from the data given in Table 5.1, the cost of the reference part, in dollars, can be shown to be

$$K_o = 0.124 + 6980/N_o \text{ (dollars)}$$

where the first term is the sum of the material and processing costs for the reference part and the second term is the tooling cost for the reference part. It is seen here that at low production volumes most of the cost is due to the cost of the tooling. At very high production volumes, say when N_o approaches infinity, the cost is due primarily to material and processing costs and approaches $0.124 or 12.4 cents. Thus, the cost of the reference part depends upon its production volume.

Since the main concern here is the comparison of alternative designs for a given part, the actual cost of the reference part is not important. All that is really of interest is a comparison in relative costs between two competing designs. For this reason it becomes convenient to obtain the relative cost of a part with respect to the standard part when its production volume is 7,970 and its total production cost, K_o, is $1. In this case the values of f_m, f_e, and f_d become

$$f_m = K_{mo}/K_o = 0.00182$$

$$f_e = K_{eo}/K_o = 0.1224$$

$$f_d = K_{do}/K_o = 6980$$

and

$$C_r = 0.00182 C_m + (6980/N) C_d + 0.1224 C_e \qquad \text{(Equation 5.12)}$$

5.18 EXAMPLE 5.4—DETERMINATION OF THE TOTAL RELATIVE PART COST

The part shown in Figure 5.28 is made of polycarbonate. The wall thickness is a uniform 3.5 mm and the ribs are assumed to be, according to the classification system, not significant.

As originally designed, the total relative die construction cost, C_d, is found to be 2.32. (See Problem 4.4 of Chapter 4.)

The relative cycle time, t_r, for this part can be shown to be

$$t_r = 3.67(1.20) = 4.40.$$

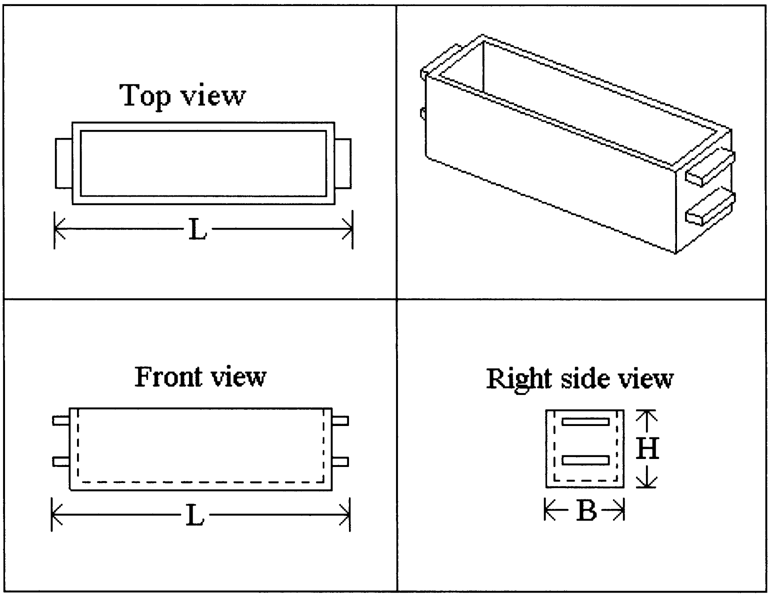


FIGURE 5.28 *Example 5.4. Original design. (L = 180 mm, B = H = 50 mm.)*

The projected area of the part is 9,000 mm^2, hence, from Equation 5.10, the required clamping force is

$$F_p = 0.005A_p = 45\,\text{tons}$$

Consequently, from Table 5.5, the relative machine hourly rate, C_{hr}, is 1.00. Thus,

$$C_e = t_rC_{hr} = (4.40)(1) = 4.40$$

The part volume is approximately 105,000 mm^3. Since the material is polycarbonate, then from Table 5.2 the relative material price, C_{mr}, is 2.96. From Equation 5.5, the relative material cost for the part is

$$C_m = (V/V_o)C_{mr} = (105{,}000/1244)(2.96) = 250$$

where V_o = 1,244 mm^3 is the volume of the reference part.

Production Volume = 10,000

If the production volume of the part is 10,000 pieces, then from Equation 5.12 the total relative cost of the original part, C_r, is,

$$C_r = (0.00182)250 + (6980/10{,}000)(2.32) + (0.1224)(4.40) = 2.61$$

If the bottom rib is removed from each end of the part as shown in Figure 5.29, then C_d is reduced to 1.65 (See Problem 4.4 of Chapter 4). The values for t_r, C_{hr}, C_e, and C_m remain the same. Thus,

$$C_r = (0.00182)250 + (0.6980)(1.65) + (0.1224)(4.40) = 2.14$$

This is an overall savings of some 18% in piece part cost.

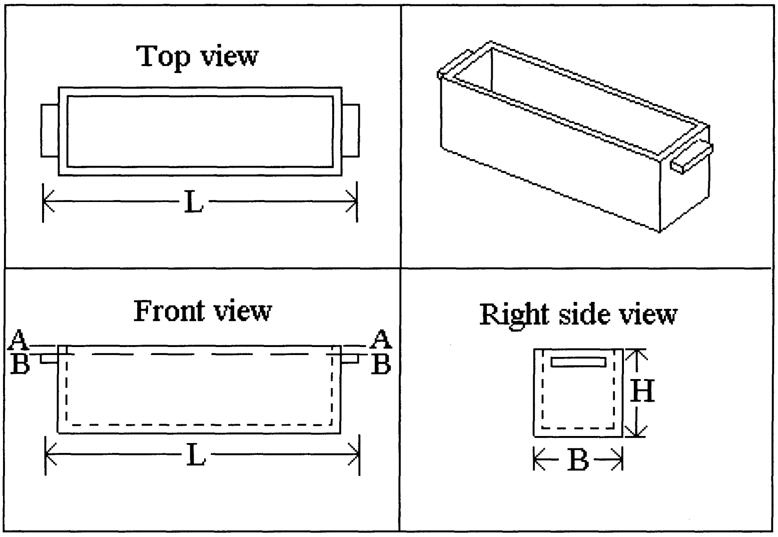


FIGURE 5.29 *Redesigned part.*

Production Volume = 100,000

If the production volume of the part is 100,000 pieces, then the total relative cost of the original design, C_r, is, from Equation 5.12,

$$C_r = (0.00182)250 + (0.06980)(2.32) + (0.1224)(4.40) = 1.15$$

For the redesigned part,

$$C_r = (0.00182)250 + (0.06980)(1.65) + (0.1224)(4.40) = 1.10$$

Thus, for a production volume of 100,000 parts, the savings are only 4.3%. This reduction in savings is due to the fact that, in this particular case all of the savings was due entirely to a reduction in tooling costs whose contribution to overall part cost diminishes with increasing production volume.

5.19 WORKSHEET FOR RELATIVE PROCESSING COST AND TOTAL RELATIVE PART COST

To facilitate the calculation of the relative processing cost and the overall relative part cost, a worksheet has been prepared. The copies shown on the next two pages have been completed for Example 5.1 in Section 5.12. A blank copy of the worksheet is available in Appendix 5.B and may be reproduced for use with this book.

Worksheet for Relative Processing Costs and Total Relative Cost

***Original Design*/Redesign** *Example 5.1*

$L_u = 160$	$B_u = 130$	$L_u/B_u = 1.23$ < 10	Slender/ Non-slender? *NS*	

Basic Relative Cycle Time

	Plate 1	Plate 2	Plate 3	Plate 4	Plate 5
Ext/Int					
1st Digit	*6*				
2nd Digit	*1*				
t_b	*2.52*				

Additional Time

3rd Digit	*1*				
t_e	$3(0.5) = 1.5$				

Time Penalty

4th Digit	*0*				
5th Digit	*1*				
t_p	*1.2*				

Relative Cycle Time for Plate

$t_r = (t_b + t_e)t_p$	$(2.52 + 1.5) \times (1.2) = 4.82$				
Relative Cycle Time for the part = ***4.82***					

Relative Processing Cost

$A_p =$	$F_p =$	$C_{hr} =$	$C_e = t_r C_{hr} =$

Relative Material Cost

$V =$	$V_o =$	$C_{mr} =$	$C_m = (V/V_o)C_{mr} =$

Total Relative Cost

$N =$

$C_r = 0.00182C_m + (6980/N)C_d + 0.1224C_e$

Redesign Suggestions

Support bosses to reduce the first and fifth digits OR reduce the boss height to make them nonsignificant. Could eliminate inserts, but these would need to be inserted after molding, thus little to be gained (i.e., pay me now or pay me later).

% Savings in processing costs:

% Savings in overall costs:

Worksheet for Relative Processing Costs and Total Relative Cost

Original Design/*Redesign* *Version 1*

$L_u =$	$B_u =$	$L_u/B_u =$	Slender/ Non-slender?	

Basic Relative Cycle Time

	Plate 1	Plate 2	Plate 3	Plate 4	Plate 5
Ext/Int					
1st Digit	*5*				
2nd Digit	*1*				
t_b	*2.38*				

Additional Time

3rd Digit	*1*				
t_e	*1.5*				

Time Penalty

4th Digit	*0*				
5th Digit	*0*				
t_p	*1*				

Relative Cycle Time for Plate

$t_r =$ $(t_b + t_e)t_p$	$(2.38 + 1.5)$ $= 3.88$				
Relative Cycle Time for the part = ***3.88***					

Relative Processing Cost

$A_p =$	$F_p =$	$C_{hr} =$	$C_e = t_r C_{hr} =$

Relative Material Cost

$V =$	$V_o =$	$C_{mr} =$	$C_m = (V/V_o)C_{mr} =$

Total Relative Cost

$N =$

$C_r = 0.00182C_m + (6980/N)C_d + 0.1224C_e$

Redesign Suggestions

% Savings in processing costs: (4.82 – 3.88)/4.82 = 19.5%

% Savings in overall costs:

5.20 SUMMARY

The purpose of this chapter is to present a systematic approach for identifying, at the parametric design stage, those features of the part that significantly affect the processing cost of injection-molded parts. The goal was to learn how to design so as to minimize difficult-to-process features.

A methodology for estimating the relative processing cost of proposed injection-molded parts based on parametric information was presented. In addition, a method for estimating the overall relative part cost for this same part was introduced.

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Kuo, Sheng-Ming. "A Knowledge-Based System for Economical Injection Molding." Ph.D. Dissertation, University of Massachusetts at Amherst, Amherst, MA, February 1990.

Poli, C., Fredette, L., and Sunderland, J. E. "Trimming the Cost of Die Castings." *Machine Design* 62 (March 8, 1990): 99–102.

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QUESTIONS AND PROBLEMS

5.1 As part of the same training program discussed in Problem 4.1 of Chapter 4, you are in the process of explaining to some new hires that the processing cost of injection-molded parts is a function of what you have called the *basic relative cycle time* of the part. Explain in detail exactly which features of a part affect the basic cycle time of a part.

5.2 In addition to the basic relative cycle time discussed in Problem 5.1, what other factors affect the overall relative cycle time of an injection-molded part?

5.3 Assuming that the dimensions for the parts shown in Figures P3.2 to P3.5 of Chapter 3 are such that the parts are easily cooled, which parts, if any, are partitionable? For those part that are partitionable, which plate controls the cycle time of the part? Assume that in all cases the wall thickness is constant.

As examples to illustrate both basic complexity and subsidiary complexity, explain which features of these parts, if any, affect basic complexity and which features, if any, affect subsidiary complexity.

5.4 Assume that you are still part of the integrated product and process design (IPPD) team formed as part of Problem 4.3 in Chapter 4. One of the components used in Widget A consists of the hollow cylindrical part shown in Figure P5.4. This component is presently made of nylon 6 in a mold having an SPI finish of 3. What redesign suggestions would you make to your IPPD team in order to reduce the relative cycle time of the part? What savings in processing costs would you achieve by your proposed redesign. Assume commercial tolerances.

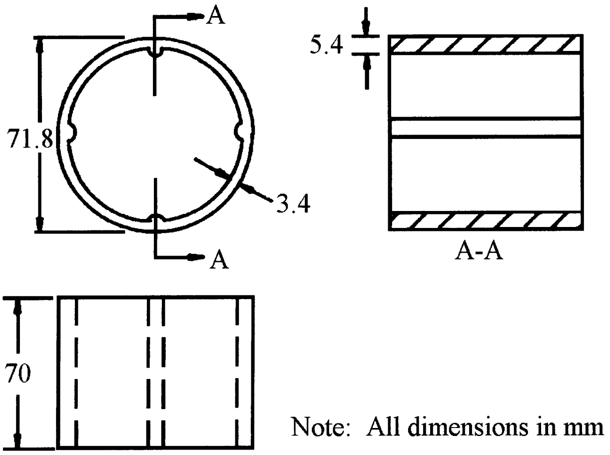


FIGURE P5.4

5.5 Imagine that you are still part of the IPPD team discussed above. You have been asked to roughly estimate the cycle time for the part shown in Figure P5.5 if it is produced with commercial tolerances. What would you estimate the cycle time to be if the part is made of nylon 6 in a mold with an SPI finish of 3. The maximum wall thickness of the part is 2.5 mm. The minimum wall thickness of the part is 1.5 mm.

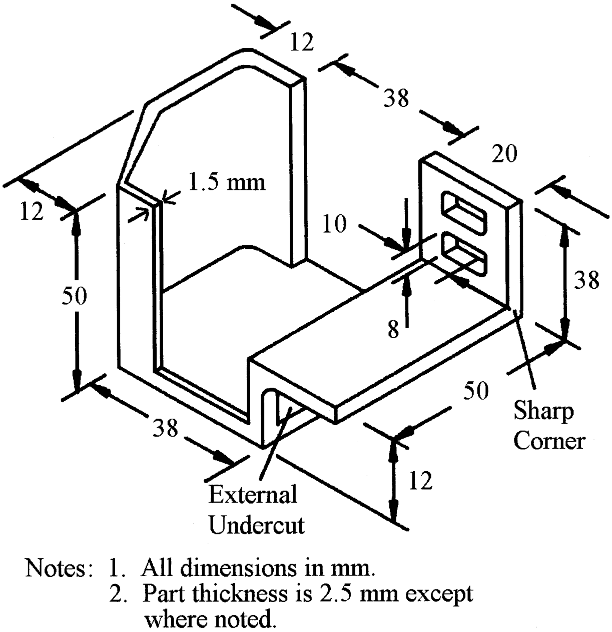
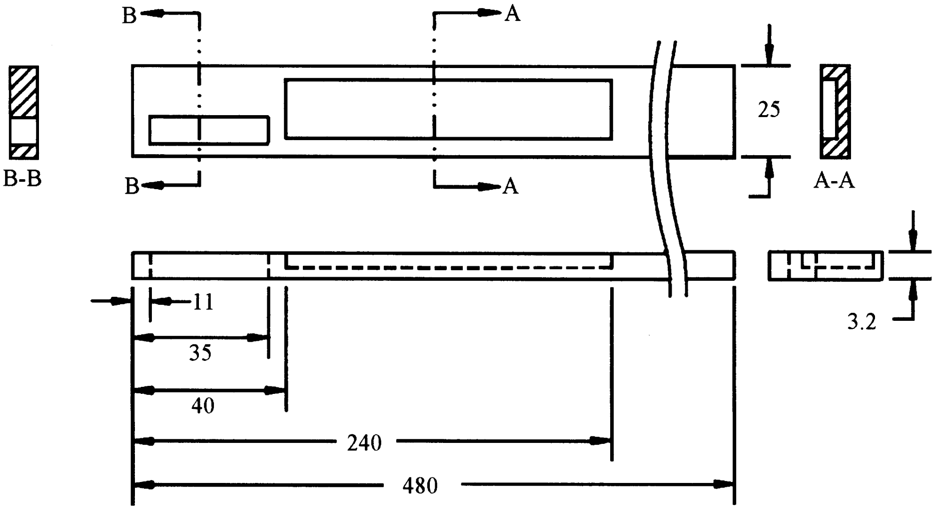


FIGURE P5.5

5.6 In an effort to reduce processing costs, what redesign suggestions would you make for the part shown in Figure P5.5 so that the cycle time of the part is reduced? What is the percent reduction in cycle time due to this redesign?

5.7 Using the methodology discussed in this chapter, estimate the relative cycle time for the transparent part shown in Figure P5.7. Assume commercial tolerances. Can you suggest at least one way to reduce the cycle time?



Notes: 1. All dimensions in mm.
2. Drawing not to scale.
3. Transparency required.

FIGURE P5.7

5.8 The mold used to produce the part shown in Figure P5.8 is assumed to have a surface finish of SPI-3. Estimate the relative cycle time for the part under the assumption that the part is made of polycarbonate. Can you make any redesign suggestions that would reduce the relative cycle time required to produce the part and, hence, the processing cost for the part? The wall thickness of the difficult-to-cool feature is 2.5 mm.

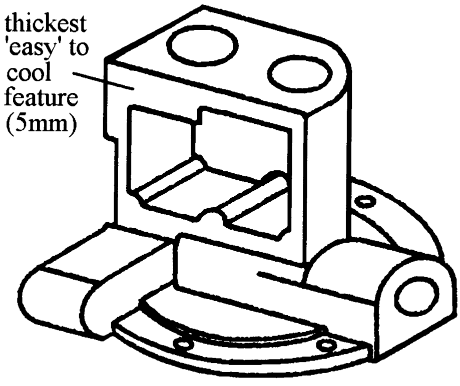


FIGURE P5.8

5.9 Some members of your design team seem unconvinced that overall costs for the part shown in Figure P5.5 can be significantly reduced by applying the redesign suggestions you proposed earlier (Problems 4.8 and 4.9) to reduce tooling costs along with your more recent suggestions for reducing processing costs (Exercise 5.6). Thus, for the part shown in Figure P5.5, determine the percent savings in cost achieved for production volumes of 25,000 and 100,000. Are these significant savings?

5.10 For Example 5.4 (in Section 5.18) it was assumed that the cycle time for the reference part, t_o, is 16 s (see Table 5.1). Assume that the cycle time t_o is 10 s and determine for the part analyzed in Example 5.4 the reduction in costs between the original design and the redesign for production volumes of 10,000 and 100,000.

APPENDIX 5.A

Notes for Figure 5.2 and Tables 5.3 and 5.4

(1) For parts or elemental plates with a bent or curved longitudinal axis, the unbent length, L_u, is the maximum length of the part with the axis straight. The width of this unbent part is referred to as B_u. See Figure 5.6.

(2) Frames are parts or elemental plates that have a through hole greater than 0.7 times the projected area of the part/plate envelope and whose height is equal to its wall thickness. See Figure 5.7.

(3) The thickness of the elemental plate is denoted by w. For parts/plates where the thickness is not constant, w is the maximum thickness of the plate or part.

(4) Lateral projections are shape features that protrude from the surface of a slender plate (rod) in a direction normal to the longitudinal axis. For long slender parts such projections are difficult to fill. See Figure 5.22.

(5) A rib is a narrow, elongated wall-like projection whose length, l, is greater than three times its width, b. Ribs may be located either at the periphery or on the interior of a part/plate. A rib may be continuous or discontinuous or part of a network of other ribs and projecting elements. To avoid sink marks ribs should be designed so that (a) the rib height, h, is less than or equal to three times the localized wall thickness, w, and (b) the rib width, b, is less than or equal to the localized wall thickness. Such ribs are considered as nonsignificant ribs. Ribs designed such that $[3w < h < 6w]$ or $b > w$ are called significant ribs. Significant ribs tend to increase the machine cycle time and make tolerances difficult to hold. For the purposes of this system, peripheral ribs are treated as walls. See Figure 5.17.

(6) A boss, like a rib, is a projecting element; however, its length, l, is less than three times its width, b. It takes a variety of forms such as a knob, hub, lug, button, pad, or "prolong." A boss should be designed such that (a) the boss height, h, is less than or equal to three times the localized wall thickness, and (b) the boss width, b, should be less than or equal to the localized wall thickness. These types of bosses are considered nonsignificant bosses. Bosses designed such that $3w < h$ or $b > w$ are called significant bosses. Significant bosses tend to increase the machine cycle time and make tolerances difficult to hold. See Figure 5.19.

(7) An elemental plate with
   a) multiple through holes,
   b) no continuous solid section with a projected area greater than 20% of the projected area of the plate envelope, and
   c) whose height is equal to its wall thickness

   is called grilled/slotted. See Figure 5.20.

(8) The wall thickness referred to here is the localized wall thickness. (See also Notes 6 and 7.)

(9) The use of foamed materials results in a surface gloss that is generally less acceptable than the one that results from the use of thermoplastic materials. To improve the surface gloss of parts made with foamed materials the parts are usually subjected to secondary finishing operations (painting, etc.). In addition, the minimum thickness achievable with foamed materials is greater than that obtainable with thermoplastics. For these reasons foamed materials are generally not used for parts whose wall thickness is less than or equal to 5 mm.

In addition, engineering thermoplastics are not generally used if the wall thickness is greater than 5 mm because the shrinkage of these plastics becomes difficult to control when $w > 5$ mm.

(10) Features such as holes or depressions that have an internal diameter smaller than 12.5 mm are considered difficult to cool.

(11) Holes or depressions with internal grooves, or undercuts such that a solid plug that conforms to the shape of the hole or depression cannot be inserted, are called internal undercuts. Such restrictions prevent molding from being extracted from the core in the line of draw. When these internal undercuts take the form of internal threads, a special unscrewing mechanism is used. When the number of threads becomes large, the time required to unscrew the mechanism can significantly increase the machine cycle.

(12) Inserts are metal components added to the part prior to molding the part. These metal components are added for decorative purposes, to provide additional localized strength, to transmit electrical current, and to aid in assembly or subassembly work. The use of inserts increases the machine cycle time.

(13) For the purposes of the present coding system, the part surface requirement is considered high when parts are produced from a mold having an SPI/SPE surface finish of 1 or 2, or sink marks and weld lines are not allowed on an untextured surface.

Parts without high surface requirements are considered to have low surface requirements.

(14) Part tolerances are considered difficult-to-hold if:
   a) External undercuts are present.
   b) The wall thickness is not uniform.
   c) A tolerance is required across the parting surface of the dies.
   d) Unsupported projections (ribs, bosses) and walls are used.
   e) More than three tight tolerances or more than five commercial tolerances are required.

APPENDIX 5.B

Worksheet for Relative Processing Cost and Total Relative Cost

Original Design/Redesign

L_u =	B_u =	L_u/B_u =	Slender/ Non-slender?	

Basic Relative Cycle Time

	Plate 1	Plate 2	Plate 3	Plate 4	Plate 5
Ext/Int					
1st Digit					
2nd Digit					
t_b					

Additional Time

3rd Digit					
t_e					

Time Penalty

4th Digit					
5th Digit					
t_p					

Relative Cycle Time for Plate

$t_r = (t_b + t_e)t_p$					
Relative Cycle Time for the part =					

Relative Processing Cost

A_p =	F_p =	C_{hr} =	$C_e = t_r C_{hr}$ =

Relative Material Cost

V =	V_o =	C_{mr} =	$C_m = (V/V_o)C_{mr}$ =

Total Relative Cost

N =

$C_r = 0.00182C_m + (6980/N)C_d + 0.1224C_e$

Redesign Suggestions

% Savings in processing costs:

% Savings in overall costs: