Chapter 1
Successful Design

This chapter gives you an introduction to designing enclosures for electronic products and defines a "successful design."

We'll discuss the designer's role in the setting of product requirements, where the designer fits into the overall product development picture, the importance of communication, and the initial factors to consider when beginning a design.

Before we get started, let's briefly define what we mean when we talk about an "electronic product." It is a product that has a circuit board in it and usually has some input/output device such as an LCD. Examples of electronic products include cell phones, digital cameras, and the ultrasonic toothbrush.

An electronic product enclosure is the item that surrounds and supports the circuit board. The enclosure is what makes the device usable to the consumer. The enclosure is necessary for a number of reasons – to protect the electronics (the circuit board and LCD) from the environment or from a physical jolt (such as dropping the product). The enclosure provides access to input information to the device, via keys or buttons perhaps, and allows information to be transferred from the device. The enclosure provides structure so that the circuit board logic is supported and protected.

Examples of some very effective product enclosures that have been developed in recent years are the Apple iPhone 7 or the HP Spectre laptop computer (both, circa 2016).

In essence, a successful design of an enclosure will be the one in which the design has conformed to the product's written specification (spec) and has been done within the cost and time parameters that were set. Let's now begin our exploration of the process of designing these enclosures.

1.1 Design Guide

This text is intended to place in a single reference, a *design guide* for the *successful mechanical* design of an *electronic product enclosure*.

T. Serksnis, *Designing Electronic Product Enclosures*,
https://doi.org/10.1007/978-3-319-69395-8_1

Let's break down some of the words of the above sentence for further definition (with the word "successful" defined in its own subtopic).

Design Guide
This text is a starting point, a point of reference. The designer will be using many guides in their work; this text is intended to be a general help and serves to augment the designer's entire past experience and their present organization's established processes.

Electronic Product Enclosure (EPE = Electronic Product Enclosure)
The electronic product enclosure consists of both the external and internal structural elements of a product. It includes any of the hardware used for user interfacing, any of the connectors used to interface cables, and any elements that the user will physically feel and see. Many electronic enclosures contain one or more PCBA (Printed Circuit Board Assemblies), and these must be protected against the rigors of normal usage.

An enclosure could be very simple or be extremely complicated with thousands of separate parts. One of the designer's first tasks will be to define the "system" that they are designing, and that is covered in a later chapter. The term "enclosure" (in this text) will be on the less complicated end of the spectrum, and the methodology explained can be extended into the more complicated design situations.

The EPE Designer
This is the person responsible for the design of the enclosure for an electronic product. In many cases, it is a mechanical engineer, but it can be someone with a background in mechanical engineering or who has the experience of the discipline. A good EPE Designer will have the following characteristics:

- Ability to understand and conform to the product specification
- Be able to add to and help create the product specification
- Create inventive solutions to the problems presented by the product

Thus, the EPE Designer must be able to both be creative and still follow the major objectives of the project.

1.2 Defining the Overall Team

The intent of this section is to show that engineering (and mechanical engineering in particular) doesn't design products by themselves; they are certainly a part of a team. Characteristics of the overall team are that the team can be:

- Of a small or large size
- Located in one location or distributed worldwide
- Limited in resources or have access to almost unlimited resources
- In possession of the latest tools, or not
- Motivated by a variety of reasons for accomplishing their goal

- Varying in experience

The entire engineering effort consists of an amalgam of design among several disciplines. These disciplines include:

- Electrical engineering
- Software and firmware engineering
- Mechanical engineering (including structural and thermal)
- Industrial engineering
- System engineering

Therefore, it is recognized that mechanical engineering is only a part of the overall engineering design of an electronic product, and many of the decisions made are in cooperation with the other disciplines. Contemporary product design should balance various trade-offs among all of the factors that go into the production released product.

Indeed, the *entire* engineering effort (all of the disciplines from Sect. 1.2) is only a part of the *overall* effort that goes into the release (sale) of a product.

Besides the engineering effort, contributions result from the following groups:

Each group is defined, followed by how specifically the mechanical design "interacts" with that group. All of this is meant to emphasize that the mechanical design is not done "in a vacuum" but rather as part of a multitasked product delivery team.

Marketing (Including Input from Sales) This organization is responsible for the product definition, that is, defining what the customer wants and what the product will be from the customer viewpoint. This "product definition" usually takes the form of a document that engineering will accept as the product requirements. Marketing also has the responsibility of overseeing how a particular product will fit into the overall product line of the company (or division of the company).

The EPE Designer interacts with Marketing in the effort to define how the product will function, how that functionality will present itself to the customer (user interface), and how the product will look to the customer (industrial design).

Operations (Manufacturing) This organization is responsible for the complete flow of materials for individual components and how those individual components get fabricated, assembled, and delivered to the customer. If engineering's responsibility is to produce the product documentation, operations should be able to take that documentation and get that product produced that meets the product specifications.

The EPE Designer intersects with operations by making decisions on part fabrication techniques, vendor (supplier) selection, and any trade-offs between quality/cost/appearance.

Testing (Design Verification) This organization is responsible for testing both the prototyping and mature designs. This can be accomplished by resources within the mechanical design group (itself) or by an independent group setup for this particular function.

The EPE Designer intersects with the test function by either conducting or reviewing test results. The testing done on the product is actually a part of the product requirements document (PRD) and that it must be proven that the product passes testing as defined in that document. For example, if the PRD states that a product must survive a one meter drop, then a test must be defined that states considerations such as:

- How many drops of a single item (under test)
- Impact faces or corners of that item
- Environment that testing is to take place (such as ambient temperature)
- Statistical concerns (such as how many single items must pass testing)
- Order of testing (among various tests that unit will undergo)
- Definition of “survive” (degree of functionality or appearance after test)

Quality Control/Quality Assurance This organization determines whether the acceptability limits of the individual parts (or entire assemblies) meet the standards both specified in the individual product specification (the drawing) and in the established overall corporate standards. Quality control would be concerned with tactical situations, while (corporate) quality assurance would be more concerned with strategic situations. Most companies have various ways of both controlling and monitoring the quality of the product and certainly get involved with customer satisfaction and service issues.

The EPE Designer intersects with this organization by specifying on their documentation the acceptability limits of each part and can go all up to include assemblies. Typically, acceptability limits take the form of:

- Size (geometry) control as specified in drawing tolerances
- Material and plating specifications stated on drawing
- Cosmetic flaw rejection criteria stated on drawing
- Functional specification as stated on drawing
- Determining the “critical” nature of some aspect of the part documentation.

Service This organization is responsible for the repairing, warranty, and return of product functions. They help determine course of action for field problems with the equipment.

The EPE Designer intersects with this organization by designing-in a reasonable process for the disassembly and repair of the product. Of course, a design with a designed-in high reliability will have less reason to repair. It’s also possible to provide for methodology to determine misuse of the product.

Project Management This organization is responsible for tracking the project for:

- Time allocation – meeting deadlines that are committed
- Resource allocation

- Priority management (for a single project and relative to projects competing for the same resources)
- Compliance to specifications for the product
- Meeting cost goals
- Reporting status of project

The EPE Designer intersects with this organization by reporting estimates of time and resources for all separate line items of the mechanical part responsibility. This starts with product conceptualization, design, prototyping, and testing and continues on into final release documentation. Estimates of time and resources are updated as milestones are met.

Upper Management Included in this group is anyone who is responsible for the project and has a need to understand the project. Project updates would be provided to this group at specific times during the project. Upper management would provide leadership and vision to the project.

The EPE Designer intersects with upper management in an indirect manner. Reporting of project status is relevant at any time and is usually provided thru the project manager.

1.3 Product Requirements

Determining success is a matter of meeting (or exceeding) the requirements of the project. This is a simple statement but is actually very complicated in its interrelated aspects.

A project could be determined successful if it met its goals. These goals can be addressed in (one or more of) the following written documents.

Product Requirements Document (PRD) This document can go by a variety of names (it will vary by company). Basically, it is a "contract" of sorts that attempts to specify the basic functionality of the product. It can be as simple as a few paragraphs or extremely complicated. It can contain:

(a) A description of what the product will accomplish for the customer – it usually does *not* specify exactly how the product will work. That is, details on "how to get there, from here" are not explicit. This description uses words on the "final outside appearance" of the product rather than the details of the "inner workings." Follow-on documents (or specifications) can also specify details of the product. Again, the PRD forms an agreement between marketing and engineering as to what the product will be. The PRD can vary in its content detail. It *is* (should be) updated, during the course of the project, as elements get revised or added to. At each overall product review, it should be compared on the extent of how the design is conforming to the PRD.

(b) A description of how the product will interface with the customer. This would include:

- How information is displayed to the customer or how the information will get from the customer, to the product. This can be visual, auditory, or tactile.
- Various interfaces to the product, such as connectors, switches, or buttons.
- Labeling or icons intended to provide information to the customer.

(c) A description of the various components of the product. That is, if the product (the product being designed) needs additional equipment or cables to function in a larger system, then a description of the various parts of the "system" will need to be described. Thus, one will need to "draw a boundary" around *exactly* what *this* product (being designed) is. What exactly is the "deliverable" to the customer?
(d) Indication of the final aesthetic (visual appearance) of the product. Colors, textures, and industrial design are usually very well-specified.
(e) A listing of the environments that the product will both operate and be stored in. This includes temperature, shock, drop, vibration, humidity, water egress protection, shipping conditions, altitude, and specific corrosive atmospheres.
(f) A listing of any standards that the product will need to pass. This includes both safety and regulatory standards such as Underwriters Laboratory (UL) for safety, federal communication compliance (FCC) for electromotive magnetic interference (EMI), and the (literally) hundreds of other compliance standards that are a real part of today's design world. Some of these standards are country specific, while others are accepted on a worldwide basis. Obviously, anything to do with medical, food, or children's toys will have their own rigorous testing standards to pass.

Internal Test Reports These indicate positive test results. These are the results of testing done to show that the requirements as set forth in the PRD have been passed. If the tests haven't been passed, then there are action plans initiated to improve the product and conduct further testing.

Reports from Initial Customers This is "alpha" or "beta" testing where customer feedback is positive or negative. It is hoped that customers are gaining measureable value from the product. Reasonable improvements to the product can be made when this "real-world" feedback is available. "Alpha" testing is usually done with in-house personnel who are simulating the actual customer, while "beta" testing is usually done with existing customers before shipment to actual (paying) customers.

Project Management Reports

(a) On expenses (expected vs. actual). This includes expenses for salaries, capital equipment, tooling, etc. Monitoring of expenses can lead to analysis of the true "payback periods" of the project and better predictions on expenses for future projects.

(b) Status on milestone dates (expected vs. actual): as with expenses, monitoring of how well the project achieved its time commitments leads to an indication of the true "payback period" of the project. Analyzing where milestones were not met can lead to better predictions for future projects.

Ongoing analysis of "success" (as the product matures in the field) can be measured by:

Quality Assurance Reports These contain information about customer satisfaction and warranty returns: any issues or problems with the product must be *quickly* addressed so as to protect the company's reputation in the industry. If revisions need to be made, they must be implemented with great urgency. Thus, if customer satisfaction reaches some set level of reliability, the product design team will have achieved success.

Analysis of "Lessons Learned" From all disciplines on the project: every project will contain items where things could have been done better. Continuous improvement should be strived for. There should be a way to gather feedback from everyone in the product design process on what items would need to be improved. This will enhance the success rate of future projects. More on this subject is presented in Chap. 13.

Sales Expected vs. actual. Sales figures can indicate the success of the project – in the sense that marketing has predicted the need for the product, engineering/operations has delivered that product to the customer, and the customer does (indeed) value that product. Or, in the opposite case, sales can be less than expected (predicted). This could have happened for a variety of reasons (such as):

- Product is not (exactly) what the customer needed (price too high/performance features too low).
- Product is too late out into the market, that is, it took too long to get the product out into the market, and the customers now have better choices.
- Product is too early into the market (not enough "early adopters"). This happens when the technology of the product doesn't match what customers (at the time) value or other supporting technology isn't available as yet that would make this particular product fully useful.
- Low reliability.

All of the above reasons should be placed in the "competitive arena." That is, most products have competition in their markets. Customers will choose purchases based on their needs for performance, price, and quality. New technology solutions must compete against the older solutions.

It would be rare to have all of the data available at product release to determine how "successful" the product design effort is. Product design usually has increased risk of success if:

- Milestone completion dates are unreasonably shortened.
- The design has a high content of brand new components.
- Changes (additions) to the project occur at an unmanageable rate.

Successful design has been simply described as:

1. Function to specification
2. Delivery on time to project schedule
3. Delivery at predicted costs

Of course, projects can *exceed* functionality, be delivered *ahead* of time, and perhaps be even at a *lower* cost. This would be cause for celebration (although some examination needs to go into why "actuals" didn't match "predictables").

Behind the above "simple statements" for successful design is however some very large implications and that they are *not* so "simple." Let me break down the above three variables a bit. All three are interrelated on several levels.

1.3.1 Function to Specification

Specifications take many forms. They can be written documents, notes from a meeting, or even verbal instructions. The way that projects create specifications varies from company to company and indeed can vary within a company itself. Also, you, the particular Designer, can come in at various stages in an overall project. Therefore, there is no particular way that the work description can manifest itself to you, the EPE Designer.

Although the EPE Designer is not ultimately responsible for setting the full product requirements (in the specification), the designer's input is *critical*. The EPE Designer will be tasked with providing input as to just how far the limits of the design can go. For example, if the Product Requirements "arbitrarily" determine that the shock levels for the product are 40 g maximum, the EPE Designer must do some research (or some initial testing) as to exactly what shock level is possible or what levels have been achieved in the past. Therefore, the 40 g level is initially "proposed," and the EPE Designer must agree to that level or put forth arguments for a different level. It may even be possible that *higher* g levels can be agreed to. Similarly, if cost targets in the Specification seem overly aggressive, the EPE Designer must do some "homework" on their portion of the budget that provides reasonable data back to the project specification.

The important item to concern the EPE Designer is with the writing down of a specification and the later agreement (formal or informal) among the various members of the project. For example, let us say that the general task is one of designing a removable Disk Drive Module. Here are some possible scenarios that lead to its "successful design."

Task (Example): Removable Disk Drive Module **<u>Scenario #1: Minimal Input (to the Designer) – The Beginnings of a Specification</u>**

This would mean progressing with the design without much more than verbal information (as given above). The designer would likely proceed to find out items that would affect the design such as:

1. How many times is the drive to be removed? Will it be just for maintenance or is it more like once a day to secure the data?
2. How large can the module be designed?
3. Is there an existing opening for the module (in the base unit)?
4. Is there a shock concern for the disk drive (what levels of shock)?
5. Will this module be used in other base units?

These questions must be considered at this point to get some agreement as to how the design should proceed. Formal or informal meetings (communications) should now be held to get the answers, even if the present answer is “unknown at this time.”

The important item to do at this point is for the designer to create his/her own “working spec” for the design by writing down what *is* known (and unknown) about the design. This document (again, you are creating the specification) can now be revised as often as necessary, each time with agreement of those persons concerned with the project (at this time). The document at this point does not have to be of any great length. It can be as terse as necessary, for example, in the example of the disk drive that we have started:

Project: Disk Drive Module
Author: (the designer)
Revision Level: 1 (date)

- Design requirements:
  - Disk Drive Module will function under a shock load of 20 g.
  - Disk Drive Module will survive a shock load of 100 g (nonoperating).
  - Ambient air near the Disk Drive Module will be 30 °C maximum (operating).

The above is just the start of the specification, but as more is known (specified), the designer can proceed. The design can proceed because the designer now has some idea when they have been successful, that is, if the design passes testing designed to determine whether or not the design has passed the specification. In this “Scenario,” minimal input, the specification will certainly be added to, and many people involved with the project will need to review and approve the specification. However, the designer can, at least, proceed to make some progress or show some design options.

- **Scenario #2: A Complete Specification**

This specification describes *in detail* all of the requirements of the mechanical design. (The specification actually describes in detail all of the requirements of *all* design elements of the design, not only the mechanical portion, but we’ll concentrate here on the *mechanical* requirements.) It would include:

- Product description
- Product financials
- Product scheduling

It would include in its design requirements such needed detail as:

- Module to plug directly into backplane for power and signal requirements
- Module to slide on a nonmetallic surface for ease of entry/exit

(Plus a whole host of other requirements, including, environmental, ergonomic, electrical interfaces, agency approvals, testing required, etc.)

- **Scenario #3: A Working Specification**

This specification is (by far) the most common specification that the designer is adhering to. The specification's completeness is somewhere between the "Complete" and the "Nonexistent" (beginning) specifications (Scenarios 1 and 2). With the working specification, the project manager usually has some idea of the design constraints, but all aspects have not fully been vetted out. The specification is now under "change control," that is, it is being updated fairly often in the beginning phases of the project, and any changes or additions are being reviewed by the project personnel with signature responsibility. As the project matures, major changes are under extremely tight scrutiny as these changes can greatly affect project completion dates and milestones along the way.

1.3.2 Delivery on Time to Project Schedule

Various schedules are prepared during a project. Each (approved by the project team) schedule is a "snapshot" of what the current project schedule is to be. The first schedule of importance would be the schedule that is used to justify the project. This schedule would be the one that is being used to be the "net present value" (NPV) of the project. This NPV project schedule would include best estimates of:

- Person resources needed to finish the project (by a given date)
- Capital resources needed to finish the project (by a given date)
- Expected sales of product and at what price sold (if product sold by a given date)
- Expected cost of sales of product (if product sold by a given date)

Thus, there is an expected "value" that the project has if that project is completed by its expected date which is the date that the schedule presently states.

However, various considerations can change during the course of a project. They can be:

- Technical issue arises that changes implementation of original design.
- Personnel working on project change (either particular members or the size of team).
- Scope of project is revised (either increased or decreased).

- Revisions to costing of various project components as project proceeds.

As each (above) consideration changes, the project team will meet to determine its effect on the overall project schedule and see how it affects the NPV of the project. A determination is made to either continue the project with the revised NPV or discontinue the project. Usually, as the length of a project is extended, there would be more expenses associated with that extension, and the NPV would be lowered.

Getting back to determining “success” as “delivering on-time to project schedule,” each project can analyze if they have indeed delivered that project “on-time to project schedule” by dissecting the causes for any extension of the time schedule. If the extensions are deemed “reasonable” and “justified,” then the project could be considered to be a success in this regard.

1.3.3 Delivery at Predicted Costs

Just as the schedule can change (in Sect. 1.3.2, above), the costs of either the product or the costs needed to design and deliver that product can change. Costs can change due to the following:

- Personnel resources needed to finish the project are revised.
- Capital resources needed to finish the project are revised.
- Expected cost of sales of product are revised.

So, just as the schedule changes and it is determined whether the changes are “reasonable” and “justified,” the project costs could change in a similar manner. If the changes to the project costs are determined “reasonable and “justified,” then the project could be considered successful from a cost standpoint.

Certainly, all three of the above factors (specification, time, and cost) need analysis during and after the project. Chapter 13 (Continuous Improvement) explores further aspects of determining whether the project can be considered “successful.”

More information on product costing is presented in Sect. 1.7 on Engineering Economy.

1.4 Sketching Versus Detailing

An EPE Designer must know when to shift between either of these modes:

- **Sketching** or brainstorming: this is a very quick ideation phase. It is usually done with a pencil (don’t use an eraser; that will slow the thought process). Nothing is detailed – it all seems to fit perfectly on these sketches. Scale isn’t really important; that will come a bit later. Feedback from others is attained. Speed is the main focus here; the designer is getting major choices on paper so that plusses and minuses of several choices can be decided upon. What are the other choices for orientation? Up? Down? Sideways?

- **Detailing**: that is, providing "some amount" of detail. The amount of detail needed is dependant on the criticality or the uniqueness of the situation. In the sketch (phase), *everything* works, you have "glossed over" the items that may be *stumbling* blocks. You have done that to *speed* the overall design process, but now in the detail mode, more critical analysis is needed. While in "detail mode," you work out (more) exactly some critical parts of the design, the parts that a designer recognizes as "deal breakers." Details usually need CAD design to provide real geometry and scale to the situation. Again, design reviews can be critical to continue quickly down agreed-to design paths.

I'd like to continue the discussion on basic layout, with the assumption that we are working on a brand new design. Many of the concepts will be applicable to the continuation or modification designs. Also, I'd like to proceed with the design discussion as if we are still in the "sketch phase."

1.5 Design Reviews

Along with going back and forth between the "sketching" and "detailing" modes (above), the designer needs a solid feel as to when to get others on the design team to review or comment on their designs (in whatever phase the design is in). Some of these design reviews are *very* formal, while other design reviews can be very informal.

Formal design reviews are usually done to a scheduled milestone on the project schedule. They include specific members of the design team and have definite sign-off by those members.

Informal design reviews happen sporadically and/or spontaneously. It can be as simple as the designer going over to the next office and asking a colleague to "take a look at this" or calling a short meeting among a few people that the designer feels are close enough to the design issues or have previous experience with similar designs.

Some General Comments About Design Reviews:

1. Take attendance, and note who is at the meeting.
2. Take (at least, cursorily) notes on all of the (relevant) issues that are raised.
3. Possibly invite someone to the design review, who is *not* familiar with the basic design. They could be someone from a different function or department within the company. Sometimes, this person can add a different "take" on the issues as they are viewing them from a different perspective.
4. Briefly review the main goals of the design.
5. Some ideas brought up will already have been thought out by the designer; that's fine, and just go quickly thru your rationale.

6. Some ideas may seem (initially) to be not valuable or not "on point." Just note them and move on; it's possible that you may see the value at a later time.
7. You *will* get the value out of the design review – it always happens if you are "open" to it. Thank all of those involved as they have given you their insight and experience.
8. *Publish* your notes on the meeting to those that were in attendance and to the entire project team. This will log further action to be taken by you and others to make progress with the design. Ask for further comments from your Design Review Team.

1.6 Communication

Communication is a necessity for a design to be successful. That sentence stands by itself but is worthy of a more full discussion.

1.6.1 Purpose of Communication

The purpose of communication is to convey information about the design. This is required as that information supplies answers to questions, documents the design as it presently exists, and documents the evolution of the design. Communication can be written, filmed, or verbal. Written documentation takes the form of:

- Specifications
- Drawings
- Project meeting notes/schedules
- Notes in notebooks
- Emails specific to a project or program (any digital communication)

Film documentation are camera recordings of project proceedings, tests, and events. Verbal communications are any of the words spoken to move the project into a completed state. All important verbal communication needs to be put into written form so that all members of the project can review those communications.

1.6.2 Value of Communication

Great communication will make a project more successful. Great communication has the following attributes:

- Accurate – the information is true and backed by testing/documentation.
- Concise – the information is straight to the point without excessive words.

- Distributed – to all those that need the information.
- Speedy – the information is quickly disseminated.
- Offers solutions – proposing a solution to problems invigorates the solution process.

1.6.3 Links in the Communication Chain

One of the goals of communication is to get that information to the people who need the information. As seen in Sect. 1.2, the project team can include a lot of disciplines. Email distributions are easy to create along with document control distributions. The EPE Designer should decide among all of the people involved on the project team, who is critical to making the decisions that need to be made and who is copied for status purposes only.

1.7 Engineering Economy

No chapter on successful design could be completed without a discussion of the basic principles of Engineering Economy. "What something costs" is a paramount consideration in just about any endeavor. In many product designs, it will be one of the main causes of product success or failure. Chapter 4 will include a discussion on the trade-offs between cost vs. time vs. specification, but for now, let's begin the discussion stating that the EPE Designer must be capable of coming up with cost information and some break-even analyses. In Ref. [1], it is stated that "If an engineering project is to succeed in meeting human needs, it must be designed and operated in a way that promises both physical and economic feasibility."

As cost is so important, the designer needs to:

1. Be aware of what the cost goals (for both the individual part and the complete assembly) are for the design.
2. Be aware of what the material and process options are for the part being designed. It shall be the responsibility of the EPE Designer to present various options for attaining (or reducing) cost targets by (perhaps) compromises on functionality. In no cases should the designer ever compromise on any safety considerations. All options must be clearly presented to the management so that any trade-offs can be thoroughly determined. This is one of the most important creativity elements that the EPE Designer brings to the overall design of the product.
3. Propose solutions to materials and processes that are appropriate to where the product is in its overall life cycle. Certain solutions may be more appropriate to early production (where time to market is very critical) than in mature production.
4. Provide cost information, based on the appropriate quantities being ordered, back to the project team so that this important metric is always well-known.

Let's get into an example. As shown in Chap. 4, the choice on whether to "tool" a part is mentioned. This type of problem can be analyzed by choosing between: (200 parts per month needed in each case)

- Choice A: un-tooled part cost is $5.00 from Vendor A
- Choice B: design a tooled part and have Vendor T make the tool. Estimate of costs: tooled part cost is $1.00 and tooling cost is $4000.00

At what time period will the tooling cost and new part cost be *equal* to the old part cost? This is what is known as the "break-even point."

Answer: this is easily calculated or graphed (see Fig. 1.1):

$$(\$5\,/\,\text{part} \times \text{"M" months} \times 200\,\text{parts}\,/\text{month}) = (\$1\,/\,\text{part} \times \text{"M" months} \times 200\,\text{parts}\,/\text{month}) + \$4000\ .$$

"M" is shown to be 5 months. Thus, it will take 5 months for Choice B (tooled version) to "break even" with Choice A (the un-tooled version).

The total cost at 5 months is either:

$$\text{Choice A} = \$5\,/\,\text{part} \times 200\,\text{parts}\,/\,\text{month} \times 5\,\text{month} = \$5000$$

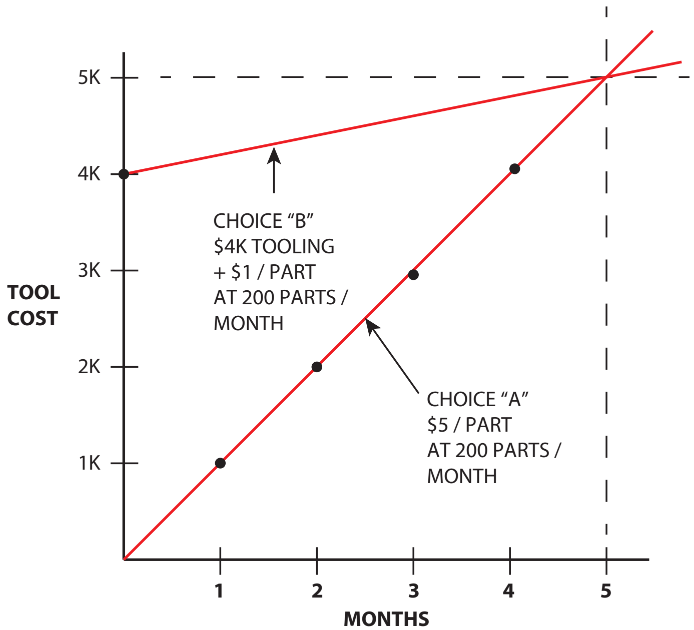

Fig. 1.1 Tooled vs. Untooled Part Break-even Point

$$\text{Choice B} = (\$1/\text{part} \times 200\,\text{parts}/\text{month} \times 5\,\text{month}) + \$4000 = \$5000$$

After 5 months, the total cost will be less for Choice B, the *tooled* part. Clearly, if the product is produced for 5 months or more, we would choose to tool the part.

However, the above "economic reality" actually has some complications.

Choice B costs (above) did not include:

1. The cost to design and document the *tooled* part.
2. The cost of bidding the tool and deciding that Vendor T was the best tool vendor.
3. The cost of prototyping the tooled part (before approving the drawing of tooled part).
4. The cost of getting a first article of the tooled part approved (we'll assume here that the initial first article is approved – hopefully, no tool modification is required as this would be an additional cost).
5. The cost of testing the tooled part (as a replacement for the un-tooled part).
6. The cost of "using up" the un-tooled part and switching over to the tooled part. (Should the assembly where this part is located be date coded to note changeover?)
7. The cost of the money for the tooling. That is, the $4000 cost of the tooling is actually worth more than $4000. Let me explain.

If the $4000 was *not* going to be given to the tool maker vendor, it would be an earning interest for the corporation. A "simple interest" calculation would have the interest earned on $4000 be (at 2%/year): $4000 × 0.02/12 months × 5 months (the break-even time) = $33. But, the question here may be:

What could the corporation do with the $4000 that would be better than just creating the $33 simple interest? Perhaps they could invest it into the development of a new product that could generate much more money or spend it on another tool on a different project that would bring in more money. Yes, this isn't simple.

In the seven items above, the cost to design and document the *tooled* part is not a trivial amount of money. If it takes 1 week to design, document, and prototype, the tooled part could cost the corporation $1000 for the designer's time (say, at $1000/week salary).

Most corporations will not "factor in" the above seven items in their "break-even" analysis, but it is worthy of consideration in some circumstances.

Another term that a designer will need to be familiar with is "return on investment" or abbreviated as ROI. This is similar to the "break-even point" as stated earlier, but that the question is posed slightly differently. In the same problem as above (Choices A and B), the question would be posed as:

What is the ROI on a $4000 tool to bring down the piece price of a $5 part? Once the new tooled piece price is known ($1) and the numbers are ordered (say, per month = 200 parts/month), then the ROI = 5 months. So, basically the return on investment of $4000 will be 5 months.

Chapter Summary

Chapter 1 gave us an introduction to designing enclosures for electronic products. As we are not alone in this endeavor, the chapter also defined the other major groups involved in the design and what their function usually is. The chapter introduces us as to how the design will be deemed "successful" and how the design will meet (or exceed) the (defined) product requirements.

This chapter takes us thru several "design scenarios" where we get everything from a "fully defined" specification to specifications that are minimalistic.

We defined the way to move along designs in either a "brainstorming" or "highly detailed" mode. The needs of both Design Reviews and good communication paths in a general design process were discussed.

Finally, the subject of Engineering Economy was started. This will be further amplified in Chap. 4.

Reference

1. Thuesen HG, Fabrycky WJ, Thuesen GJ. Engineering Economy, 1971, Prentice-Hall Inc., Englewood Cliffs, N.J.

Chapter 2
Building the Design

Our designs will all start with just an idea for a product. Those ideas will need to be proven, so, we'll move on building prototypes, and if those prototypes seem to work via testing to some written specification, we'll document our designs via drawings. We'll need this documentation to be able to build more products in a repeatable manner.

This chapter will take us from the point of just having an idea for a product, all the way to optimally placing all of the individual objects that will make up the final *working* design.

We start out our design with a "blank paper," and that paper will get filled with physical objects. First item of concern will be to determine if the paper is indeed "blank" or are there some beginning constraints. Next item of concern will be to determine exactly what physical objects are to be included. We should then assume that there is an *optimal* placement of those objects based on the objectives of the overall design, so we'll conclude with some words on the choices we have on that object placement.

2.1 Beginning Point

Designers are tasked with either continuing work on existing designs or starting a brand new design. Let's spend a little time seeing what the differences are with those starting points.

- Brand new design: This is a "clean sheet" start for the designer; they would basically have no constraints, other than complying with the specification. We'll have an entire section on what exactly a specification is and its various components.
- Continuation (or adding to) an existing design: This is a variation on the brand new design, but only a *small* part of an existing design is to be modified. The designer here has many of the same challenges of the brand new design, but the

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additional work must utilize the existing design. We will have a separate section on defining what exactly the "system" is in this context.
- Major modification of an existing design: Again, this is a variation on the brand new design, but in this case a large part of the original design is to be modified. The designer here is tasked with changing a part of the overall design, so there will be more constraints than a brand new design.

So, it's important to know where the present design effort will fit into what has been previously done. Our "basic layout" can proceed either with or without the constraints of previous work.

2.2 Defining the Design Boundary: System Description

A few words on defining the "system" being designed: Designs can be extremely complex and large (think space shuttle or large passenger jet), smaller systems (think automobiles), or yet smaller systems such as a personal computer, coffee maker, or cell phone. The scope, cost, time, number of resources committed, and interfaces to other equipment vary with all of these design projects. It is imperative that the designer keep in mind the system being designed. This is important for a variety of reasons, a few of which are:

- Focus on the personal responsibility (scope of work)
- Awareness of other equipment that must interface to this design
- Overall "system" functionality (not just the function of the subsystem)

Even something as "small" as a cell phone functions as part of a larger system. That is, the box that the consumer purchases can contain:

- Cell phone
- Battery charger
- Cables
- Sim card
- Instruction manual
- Other shipping materials (labels, bags, bubble wrap)

(We'll limit the discussion of the "system" here, as one can even think of a larger system that would include the cell phone towers and satellite systems.)

We start here at system description because most electronic enclosures surround and support a product. Sometimes, one product can be thought of as part of a larger product. For example, a network adapter card (a product itself) can be placed into a microcomputer (a second product) and form an entirely new product, in this example, a networkable microcomputer. Things get even more complicated as the networkable microcomputer itself forms a part of the network which may be an even larger product.

Looking at things in another way, we may be tasked to design just a subsystem of a much larger system. Thus, our "system" may be not even a product but just part of a larger "system" that has been broken down into (time) manageable pieces. For

Fig. 2.1 System description

example, we could be tasked to design a data recorder as part of a (larger) surveying system. This system is shown in Fig. 2.1. This system consists of (at least) three major subsystems:

- Data recorder
- Data recorder mounting bracket
- Survey pole (labeled "pole"), which includes another subsystem, the data recorder bracket

There would actually be even more individual portions of this "system" including cables, shipping container (box), and instruction manual (but let's neglect these for this example). As a side note, the system shown in Fig. 2.1 is a photograph of a Trimble Survey system appearing in the Smithsonian Museum in Washington, D.C.

We have become a team member of the "surveyor system design group" and will be designing a portion of overall design (the data recorder portion).

Therefore, the first task for us is to determine (specify) what exactly we are to design (sort of like "building a fence" around the project that we will be responsible for in a given amount of time). To accomplish this task, we will need a specification. (Refer back to Chap. 1 discussion on specifications.)

2.3 The Design Process

2.3.1 Overall Project Start to Project Finish

Designs can proceed in *any* number of ways. All companies vary in how they execute the entire product design process, but they do have some common characteristics. No particular way is absolutely correct; it is the end result (specification conformance) that is a measure of success. A design usually proceeds as:

The EPE Designer will have a "lion's share" of the responsibility of the following tasks. They will be both a "doer" and an "enabler" of much of what is done. If they don't do the work themselves, they certainly are responsible for the work.

1. Sketch of idea – this is the "ideation" stage of the project. Words must be turned into a picture representation of those words. Once the idea takes some form, it can easily be reviewed and revised. Some of the people in the review group need a "picture" of the idea to really see what is being proposed.
2. Review of idea and authorization to proceed to prototype – this action takes the "picture of the idea" and turns it into something the team can actually touch. What seemed fine in sketch form can now be picked up, held, and used in a way a customer will use the product; the prototype is a full-scale, three-dimensional picture. The "authorization to proceed" is important in that projects that are usually limited in time and money, so these expenditures must be agreed to by the team. Steps 3 and 4 (below) actually create the prototype.
3. Drawing (file creation) of idea for prototype fabrication – usually, a sketch is turned into a digitized drawing file that allows the design to be fabricated.

   (Design will now be at Revision 1.) *Italics are included to show "revision level" of the formal documentation, which is further expanded on in Chap.12.*
4. Prototype fabrication (physical parts) – the project team will determine the cost and time constraints of producing the prototype. Sometimes, just a "quick-and-dirty" prototype is needed to make good progress; sometimes a prototype constructed to exacting specifications is needed. The EPE Designer should have very good perspective on what is needed for this stage of development.
5. Prototype analysis and testing – once the prototype is received by the team, it is tested to see how the prototype conforms to the specification. The project team determines just exactly what testing needs to be done to make the decision on how to proceed after that testing.
6. Review of prototype and test result – test results are reviewed by the team, and revisions are proposed.

   (Assuming Revision 1 needs improvement, we'll revise design to Revision 2.)
7. Change to improve prototype (drawing and prototype) – this is the start of an iterative process which will finally result in the design conforming to the product specification.
8. Further analysis and testing of Revision 2

   (Assuming Revision 2 conforms to product specification.)
9. Final documentation produced/final testing/final review
10. Formal approval of design for Production Release

Note that "Production Release" in the above process allows the production of "some number" of units to be produced for sale to a customer or to serve as a larger number of units for a more expansive test program. Corporations can differ in a number of ways on their procedure for releasing and testing their products for their customers. Also note that most projects would have many more revisions than the two revisions shown, but the project generally proceeds as shown.

2.3.2 EPE Designer's Starting Considerations

There is no "absolutely correct" way to proceed with a design for the EPE Designer. Each case has its own unique best way to make visible, required progress. Sometimes, a prototype, being put together in a few days, can spark an incredible new product breakthrough to the market. In other cases, a systematic approach to laying out a few possible solutions, taking months to put together, may be the best path. That being said, the following outline should prove useful to designs at least as a starting point.

1. Determine the use and requirements of the solution not directly related to load. Some of the more important of these requirements are:

   (a) Environment – where will the product be used? Examples are office/outdoors/at altitude/on vehicles.
   (b) Temperature – what are the temperature extremes of the environment?
   (c) Expected life – one usage, years of warranty, service?
   (d) Cost requirements – always an important consideration. Will definitely depend on number of units being produced and tooling budget.
   (e) Finish requirements – cosmetic details can greatly affect cost.
   (f) Size and weight limitations – what are the bounds of the present solutions in the industry? Affects materials/fabrication techniques chosen by designer.
   (g) Safety and regulation requirements – what are the effects of product failure?

   All of the above are very important considerations to be considered at the very beginning of the EPE Designer's design. For example, a different design results from indoor vs. outdoor environments. A different design results from a design expected to last "one time" vs. a design that needs to work after 1000 uses. A different design results from a design that needs to cost under $5 vs. a design that needs to cost under $100. By going thru each element above, the EPE Designer can determine some initial constraints.
2. Determine or estimate the working load from all the various possible types of loads that the individual member (and assembly) may be required to withstand. It is necessary to consider all likely combinations of loads and, if possible, to determine the relationship between load and time. Some of the possible load types are:

   (a) Static
   (b) Steady-state dynamic (vibration)
   (c) Transient dynamic
   (d) Impact or shock
   (e) Body contact, such as point loading or friction

(f) Other loading, such as thermal/gravity/acoustical

The above load determinations are also very important considerations for the EPE Designer's design. For example, a different design results from a 10 pound static load vs. a 100 pound static load. If those loads are changing over time, this will result in a different design solution. Determining the magnitudes and types of loads will directly determine the materials and cross-sectional shapes that are needed to support the electrical components.

3. Determine what the failure mechanism will be. Deformations occur due to loads being axial, shearing, bending, or torsional. Possible failure modes are:
   (a) General yielding (overall inelastic behavior)
   (b) Rupture or fracture
   (c) Sudden – caused by static or dynamic load on brittle material
   (d) Slow – caused by static load on ductile material
   (e) Progressive – caused by repeated load (fatigue)
   (f) Excessive deformation
   (g) Buckling
   (h) Creep – deformation under constant stress
   (i) Relaxation – changing stress under constant strain
   (j) Abrasion (wear)
   (k) Corrosion

   By the EPE Designer determining how their design will fail (in its present state of design), it will be possible to revise that design to protect against that failure. Testing will also reveal some failure mechanisms. However, if some of these failure mechanisms can be thought of *before* testing, much savings of development cost can be saved.

In summary of the above three items, by determining the use cases, loading, and potential failure mechanisms of the design, the EPE Designer can proceed with the design with a solid base of understanding.

2.4 Optimal Object Placement

Most designs can be thought of as the physical placement of objects in space. The individual objects are the separate parts of the overall assembly. Some of the individual parts are completely known (they either are bought off the shelf from another company or are a reuse of parts previously designed in-house). Besides the "known" parts, other parts need to be completely designed new. These new parts can be produced in-house or completely specified to be produced by another company.

Electronic packaging design consists primarily of arranging subsystems into their most efficient arrangement. The first step in deciding upon this arrangement is to look at the separate volumes of the subsystems. These volumes, along with the "gaps" necessary between them for clearance, will generally set the "outer boundary" and, therefore, to a large degree set the overall size of the product. On occasion, the first criterion the designer starts with is the overall size of the product. From here, they must then decide if they can fit all of what is being asked for within the given overall size. That is, our subsystems may indeed be required to shrink to fit within this given overall size.

An aspect of the basic design process is shown in Fig. 2.2. This shows an object (in space) at some distance from an enclosure (shown as "the wall"). I'd like to start my discussion on the design for an electronic enclosure with a description of several

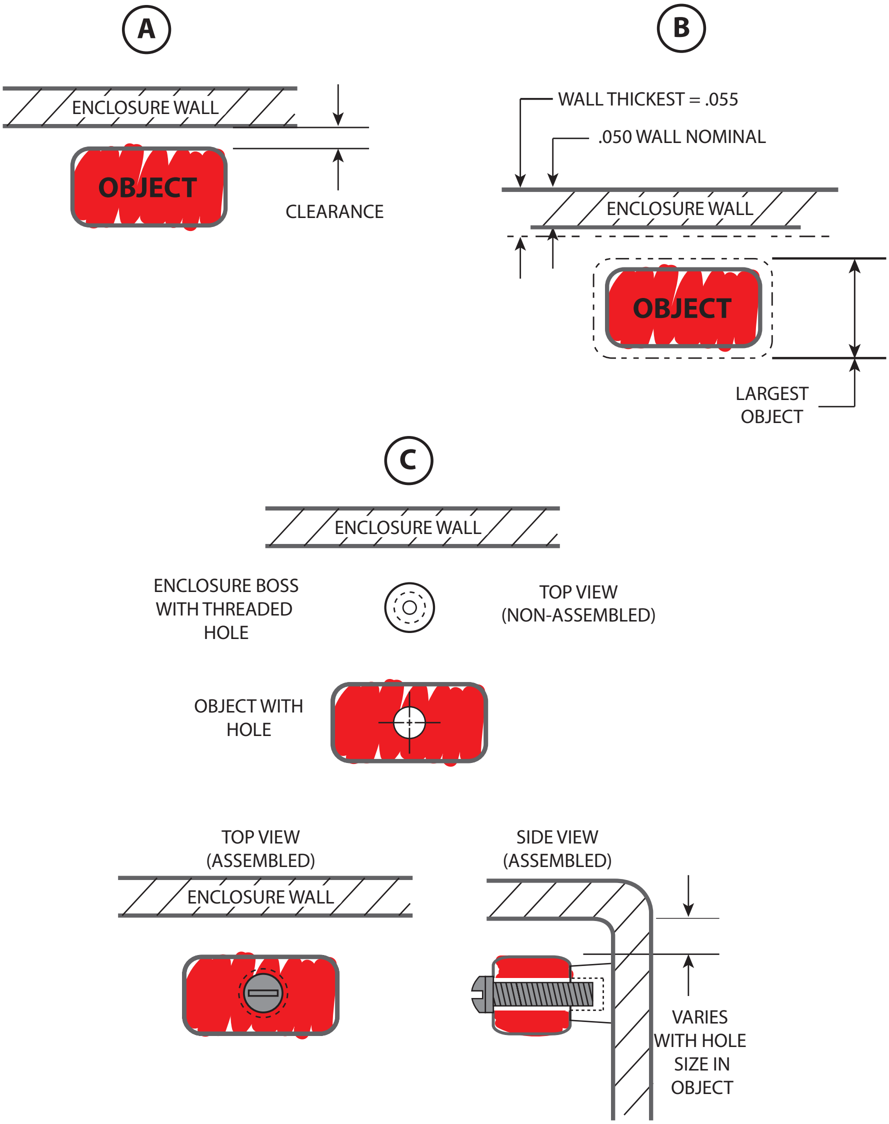


Fig. 2.2 Object/wall clearance

design "scenarios." Much of the discussion is for a 2D (plan view, from above) situation, but this is easily extended to include 3D (side view or the Z-direction), and I'll show some examples of that 3rd view:

Basic Object/Wall clearance: Fig. 2.2 shows an Object and a Wall. The "Object" could be considered just about anything. For example, it could be a printed circuit board assembly, an automobile engine, or any electronic component. The "Wall" can be considered the enclosure outside surface or the exterior of the item being designed. In just about every design, the designer has to determine the distance (clearance) between the "Object" and the "Wall." The idea here could be extended to determining the distance between Object 1 and Object 2. None of these determined clearances need to be the same as each other. The clearance in the X-Direction can be different than the clearance in the Y-Direction, which again can be different than the clearance in the Z-Direction.

2.4.1 Clearance Distance Is a Function Of

1. Tolerances of the object and wall: If one were to maintain a particular distance (let's say 0.100 inch, for example), and a nominal overall (outside) dimension, then the design must allow for:

   - The thickest wall at its extreme of tolerance
   - The largest possible object (at the high extreme of the object's tolerance)

     Note that the 0.100 inch nominal clearance distance has been *reduced* by both the thickest wall and the largest object. (Note also that the 0.100 inch nominal clearance distance could be *increased* by both the thinnest wall and the smallest object.)
   - The fastening of the Object to the box must be considered. That is, how much will the fastening system allow the Object to get closer to the wall? Let's say that the Object has a simple mounting hole in it and the box has a threaded boss in it. The hole in the Object will be (somewhat) larger than the screw used to fasten the Object into the box threaded boss. Thus, the Object could get closer to the wall if the fastener is on one edge of the clearance hole. The location tolerance of the position of the box threaded boss (in relationship to the box wall) must also be considered as the boss may actually be closer to the wall (due to fabrication tolerance). Normally, this "fastening tolerance" can be disregarded, but in some tight-for-space designs with limited clearances, it may be critical.

     So, for our clearance example so far, just considering tolerances, we could have tolerances of:
   - Wall thickness could be thicker by 0.005 inch. (with a "constrained" overall dimension, all of this would add to the wall thickness inside the box).
   - The object itself (mounting hole to object edge) could be at a maximum locational tolerance; this could be 0.010 inch.

- The mounting boss in the box could be closer to the wall due to its positional tolerance; this could be 0.005 inch.
- The mounting hole could be 0.010 inch larger than the (smallest) fastener diameter, allowing for 0.005 inch additional movement.

All of the above (4) tolerances add to 0.005 + 0.010 + 0.005 + 0.005 which would total to 0.025 inch.

Footnote: (Statistical note) Some designers would make a case for some statistical probability, less than 100%, that all (4) tolerances would go in one direction, and we would not (likely) have a total of 0.025 inch. Some conservative designers would assume that *all* tolerance will go in the "wrong" direction, and thus design is a "worst case." I'll generally disregard the "statistical" approach to tolerances for now, but it could be valuable in design situations where space is extremely constrained. See Sect. 4.8 for a discussion of:

- Tolerancing using sum of squares
- Tolerancing using Monte Carlo simulation

2. Movement of the Object relative to the Wall (during product operation): This is also known as "sway" clearance, that is, the object may vibrate in operation while the wall could be steadfast.
3. Growth of the Objects (during operation): This could be the result of thermal expansion.
4. Overall (outside) size constraints: Internal clearance distance will be affected by the overall size. That is, with a given overall size, the distance between objects will have some particular limit. The distance between objects will be a function on the size tolerances of the objects and the tolerances on the Object locations. If the overall size is not constrained (rare instance), Object size and clearances between Objects will determine the overall size.

2.4.2 Object Arrangement

The designer usually works to minimize the overall dimensions of the enclosure by a "productive" arrangement of all of the Objects needed to fit within the enclosure. This can be done in two dimensions (X and Y) and the 3rd dimension, Z. Other arrangements of Objects look to fulfill assembly, servicing, aesthetic, or user interface needs.

In order to minimize the overall dimensions, some distance between Objects is chosen. This distance can be first thought of as a nominal distance. This nominal distance can then be adjusted to suit the design. For example, one could assume a nominal distance between objects of 0.100 inch (in all directions). Of course, the gap size would not have to be the same between all objects. Perhaps the 0.100 "gap" between objects produces an overall dimension that exceeds the expectations of the product (exceeds the product specification). Then, the designer would look to reduce the 0.100 inch gap – but, the gap cannot be less than zero, and it cannot be less than any "worst-case" problem such as an Object being supplied at the upper end of its size tolerance or other factors explored below.

Then, the designer checks to see that all of the Objects in the enclosure have been placed and that the gaps between Objects are such that all interference between Objects is avoided under all environments and user experiences that the design will exist in. The designer will also check to see that the Objects can be assembled into the enclosure in a "forthright" manner and that the service objectives of the product are upheld.

The design is ready for the Design Review Process.

Reviewing, gaps between volumes (or objects) are a function of:

- Fabrication tolerances: A given "box" may be specified as a nominal dimension. However, a slightly larger (or smaller) box results when the supplier fabricates the box to the allowable outer limits of the nominal dimension.
- Cooling requirements: A certain component may have to be spaced a minimum distance from another component so that this component is not thermally affected to an intolerable extent. In some heat-dissipative situations, components must be placed as close as possible (attached to each other).
- Assembly and serviceability requirements: Components may need certain spaces between them due to clearance required to either assemble or disassemble the components.
- Future additions to product (options): Volume may be required for planned additions or product options.

Looking back at our original intention, to locate an object, 0.100 inch from a wall, we can see that, when we get into the *detailed* design, we will have to be careful with this 0.100 inch nominal clearance, (shown by the above discussion on tolerances) as this distance can easily "shrink" (in its worst case) from 0.100 inch to 0.100 minus 0.025 (=0.075 inch). Of course, it could be *increasing* to 0.100 plus 0.025 (=0.125 inch), also. In the "sketch" design phase, we wouldn't be that concerned with this dimension; again, it would become more important as the design moves to the prototyping phase.

All of the above concentration on this 0.100 inch dimension is meant to illustrate that "some distance" is designed between objects (in this case, an object and a wall). In most designs, the overall size of the object must be minimized. This leads most designs to have the *least* possible distance between objects as possible. Examples of designs where overall size (and resulting weight) are minimized would be computer housing, coffee maker, or other household appliance. We live in a world where smaller size (usually) equates to:

- Smaller weight (better fuel savings or ease of use)
- Smaller ecological footprint (savings on materials)
- Saving of space in space-limited situations
- Lower costs (for consumer or producer)

In some cases, it will not be the *least* possible distance that is desired. Complications such as heat dissipation, or mechanical coupling (say, in a gear drive), certainly affect the distance between objects. We have been "simplifying" the design process in our examples.

So, for our example of the 0.100 inch distance between the object and the wall, the designer would actually be challenged to determine what minimal distance this could be (e.g., if this distance was 0.050 inch, our overall product could be smaller). Could this distance shrink even further? (Keep in mind that we came up with an "uncertainty" in this distance in the amount of 0.025 inch.)

In the "sketch phase" of the design, it may not be important to determine this distance *exactly*. In the interests of proving the *overall* design in a very quick manner, the designer may make this distance 0.125 inch and get into the details of reducing this distance as the design proves some success.

The wall thickness is usually a function of:

- Strength required for product operation
- Weight constraints for product
- Fabrication technique

Wall thickness doesn't have to be "constant," that is, it can vary either by the addition of ribs or gussets or the fabrication method that may allow local variation in thickness.

2.4.3 Object Arrangement Example (Fig. 2.3)

So far, in our discussion of locating two Objects (a wall and an object), we have been simplifying the discussion with just two dimensions. We will expand into three dimensions in this section. Let's take our example of Object arrangement a step further. Let's take a look at several ways to locate two objects inside of an enclosure and see what options we have. For the purposes of this example, let's say that the two Objects are both "bricks" (literally a brick), with the approximate dimensions of:

- 2.5 inches thick
- 3.5 inches wide
- 8.0 inches long

In our 2D example, we will forget about the "thickness" and just use the 3.5×8.0 width and length dimensions. So, we basically have a rectangle that is 3.5×8.0. (We will come back to the 3D example, further on, as this adds more choices for us.) See Fig. 2.3.

Now, let's say that our basic starting point in the design is to house two bricks, Brick A and Brick B (both with the same dimensions), in an enclosure. At this initial point, we have no constraints of:

- Overall size or shape of enclosure
- Cost of enclosure material

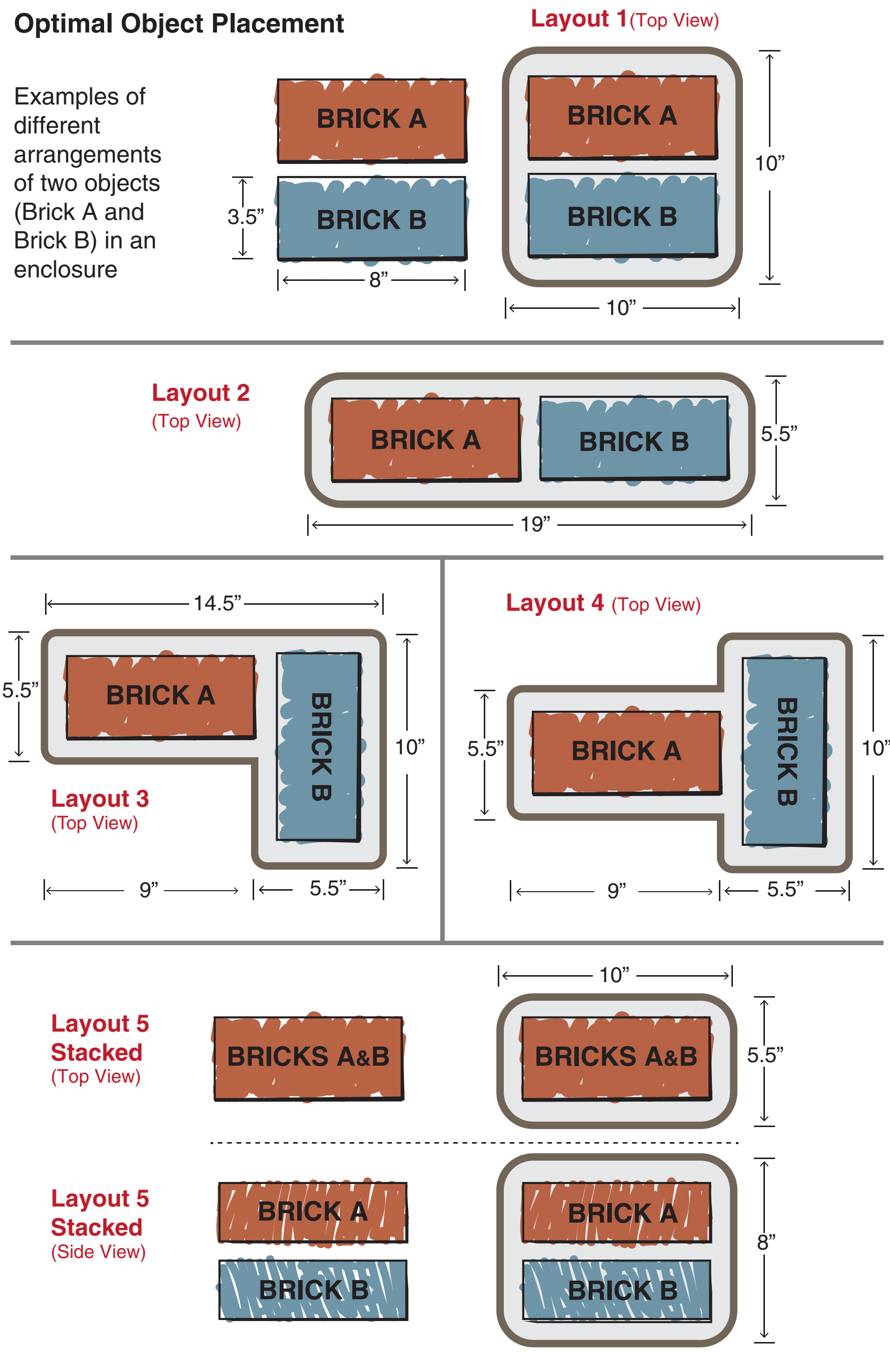


Fig. 2.3 Optimal object placement

We can easily envision (at least) *five* different ways to locate Brick A and Brick B relative to each other, producing very different enclosures. Of course, there are more than five different ways, but I've chosen the standard "Cartesian" arrangement of bricks in which they are parallel or aligned to each other. Let's look at these *five* different layouts and comment a bit about why one might have some advantages (over the other layouts). A constant *one inch* is assumed between Brick A and Brick B, and that same *one inch* clearance is assumed between a brick and a wall (side, top, or bottom).

- Layout 1: Brick A and Brick B side by side along width
- Layout 2: Brick A and Brick B aligned along length
- Layout 3: Brick A and Brick B in "L shape"
- Layout 4: Brick A and Brick B in "T shape"
- Layout 5: Brick A and Brick B "stacked" (a 3D version – this is the only layout that has used the "3rd Dimension")

Now, let's analyze the five layouts. (For all of the layouts, let's assume a very thin-skin for the enclosure that adds essentially zero to the enclosure width, length, and height. Also, we'll neglect the rounded corners that an enclosure might have, and just assume square corners).

- Layout 1 is seemingly the simplest layout, ending with a relatively square shape for an enclosure. Resulting enclosure is 10 × 10 × 4.5 high. The six sides (areas) are 2 × (10 × 10) + 4 × (10 × 3.5).
- Layout 2 is "long," rather than "square." This type of enclosure may have unique applications, such as for better utilization of desk space. Resulting enclosure is 19 × 5.5 × 4.5 high. The six sides (areas) are 2 × (19 × 5.5) + 2 × (19 × 3.5) + 2 × (5.5 × 3.5).
- Layout 3 may be better suited for "corner" applications. Resulting enclosure is (5.5 × 10 × 4.5) + (5.5 × 9 × 4.5). The eight sides (areas) are 3.5 × (4.5 + 9 + 10 + 4.5 + 5.5 + 14.5) + (9 × 5.5 × 2) + (10 × 5.5 × 2).
- Layout 4 is similar to Layout 3 but with a more symmetrical look (same Volume and same perimeter as Layout 3).
- Layout 5 offers minimal "floor plan" but results in the tallest of the layouts. Resulting enclosure is 10 × 5.5 × 8 high. The six sides (areas) are 2 × (10 × 5.5) + 2 × (10 × 8) + 2 × (5.5 × 8).

These simple layouts illustrate that even the placement of two Objects, in this case, two bricks, represents quite a few possibilities. If one would add a 3rd Object or Objects of different sizes, one can see that this gets quite complicated. Sometimes, there is a fundamental reason for the placement of one object relative to another, as one object's "in" should be close to the other object's "out" (nesting of objects). In any case, let's continue to discuss some relative merits of the five layouts, above.

There may be a fundamental aesthetic rationale for a choice between the layouts. That is, Layout 1 could be chosen because it is deemed "more direct" (more "honest"), and it is possible that Layout 3 is deemed more "interesting." So, the choice of layout could come down to a marketing decision that the customer will find a particular enclosure shape to be more pleasing (and, thus, results in higher sales of the product).

How about optimization (minimization) of the surface area of the enclosure – which layouts results in the minimum surface area? Again, the enclosure surrounds both bricks on their sides, top, and bottom.

	Volume (Cubic inch)	Perimeter area (Total square inches)
Layout 1	450	340
Layout 2	470.25	380.5
Layout 3	470.25	377
Layout 4	470.25	377
Layout 5	440	358

Some Conclusions to Object Arrangement

If weight is to be minimized, Layout 1 is best as the weight is primarily due to enclosure perimeter area. (Bricks have the same weight in all layouts, and the air is negligible.)

If volume is to be minimized, Layout 5 is best. This may be advantageous for some designs where size is restricted.

Volume is the same for Layouts 2, 3, and 4.

Largest perimeter area is Layout 2. An iteresting "Layout 6" (not shown) would be a enclosure that would be a sphere. A 6 inch radius sphere could house Layout 5 with the resulting volume of about 900 cubic inches while only having a perimeter area of about 450 square inches - perhaps a "creative" solution?

Obviously, as more "Objects" are added, it will get more difficult to optimize the objects for volume and perimeter area. The designer's ingenuity comes with "nesting" various geometrical objects in a given layout area.

Various techniques can be used to optimize the layout's compactness. Once all objects within the enclosure are determined, the designer can model those objects and start placing them in an orientation that:

1. Utilizes the space in an efficient manner.
2. Places objects that require nearness to each other, as closely as possible to each other. This may be due to mechanical, thermal, or electrical reasons to do this. For example, if a cable connects two Objects, it may be advantageous to have these two Objects as close as possible – how about eliminating the cable by connecting (directly) Object 1 into Object 2?
3. Places objects that need as much distance from each other, as far away as possible from each other. Again, there may be mechanical, thermal, or electrical reasons to do this.

It should be noted that Layout 3 and Layout 4 could be more complicated to produce (manufacture). The nonsymmetrical enclosure could be more difficult to fabricate than straight walls. This is not necessarily so if the enclosure is a tooled (molded or cast) product. However, if the enclosure is sheet metal, the extra walls provide a bit more of an issue to fabricate.

A note about designing in 3D: As all of the objects we design are actually 3D objects, we will actually need to design in 3D. A quick sketch in 2D may solve a portion of the design intent, but all of the details will need to be shown as the design moves to 3D. This makes working in CAD essential to the accuracies and speed required in the contemporary design world. Creating 3D models of all of the objects makes checking clearances and fits simple to change and optimize. An example of this is how a mechanical designer views a printed circuit board assembly (PCBA). It basically has a 2D layout of many components mounted on a printed circuit board. However, all of those components are at various heights, thus clearances above and below the PCBA will vary in many areas. Thus, the PCBA, while primarily thought of as a "2D area" (in the "sketch phase"), has a "thickness" to it that makes it a 3D volume.

Chapter Summary

This chapter takes us from the beginning point of a design where we have just an idea. It shows us how we transform that idea into the geometric placement of objects into space that gives us a physical manifestation of that idea.

We started by looking at our starting point and defining the boundaries of the design – what do we start with and what is the "outer edge" of the design. We have to define what the product is that the customer will need.

We saw how designs proceed from Revision 1 to Revision X, where X is the design that provides what we believe to be what the customer will need.

Finally, we took a look at seeing how the individual objects that need to be in the design can be optimally placed to solve customer needs. There are trade-offs to be considered, and we must be aware of how we determine the best choices between these trade-offs.

Chapter 3
Structural Considerations

In the previous chapters, we defined what a successful design is and then moved on to determining the placement of the objects that will be in the design. We'll now take up the structural considerations of the design. Why consider the structural considerations at this juncture, and why not the thermal aspects, or the user interfaces? It's probably only because I have a mechanical engineering background so I "naturally" first see how the design must be "structurally sound." I feel we must build upon a "solid foundation," so that the rest of the design can build upon that. The electronic enclosure (itself) is, of course, a structure that must be strong enough to work in the various environments that the customer (user) will be using the product in. So, let's begin with a discussion of the main considerations of providing this "solid foundation." This chapter will focus on:

- Using strength of material concepts to propose structural solutions
- Defining a generic process for considering the structural design of our electronic enclosure
- Look at some examples that specifically illustrate the general concepts We'll close this chapter with a section titled "Bonus Section". This last section is meant to add some complications to our problems on strength of materials and also to show how other considerations besides strength will be important to our design choices.

3.1 Introduction: Strength of Materials

This chapter is not an attempt to review all of the principles of strength of materials or of mechanical engineering. Entire texts have been devoted to stress, strain, and strength alone; therefore, we will just "scratch the surface" of knowledge and emphasize how some basic equations help our job to design electronic enclosures. However,

T. Serksnis, *Designing Electronic Product Enclosures*,
https://doi.org/10.1007/978-3-319-69395-8_3

in the course of design of these electronic enclosures, an exacting knowledge of the structural considerations will be essential to the overall success of the design.

The reader does not need a mechanical engineering degree or be an expert in strength of materials to benefit from this chapter. I'm hoping that some of the basic principles are touched-upon, enough to give the EPE Designers some value no matter where they are in their career. It was my belief that the more that designer understands basic strength of materials, the better the enclosure design would be.

For example, the EPE Designer can design an enclosure using 1/8-inch-thick aluminum for the enclosure material. Testing may prove that 1/8-inch-thick aluminum does indeed pass the shock and vibration testing. However, here are some questions to ask about this choice of thickness and material for the design:

- Could we have used 1/16-inch-thick aluminum instead, which would have saved weight and possibly been easier to fabricate?
- Could we have used 1/8-inch-thick plastic instead, which would again have saved weight and possibly been easier to fabricate?

So, as you can see from the above questions, it is not enough to just solve the problem, we need to solve the problem in the most *cost-efficient* manner possible. We'll get into the detail of "the most cost-efficient manner" at the beginning of Chap. 4. But for now, we'll concentrate on determining suitable designs that are at least structurally successful.

One of the biggest contributions that a designer will make to the design of the electronic enclosure is data to prove that the design will hold up "structurally" to the rigors of the customer product environment. I'm hopeful that whatever the reader's background is, they will be able to propose a design for an electronic enclosure that will be strong enough to pass the rigors of testing. I'll introduce some of the basic equations and concepts involved to help even the beginning EPE Designer, and hopefully it will also help the veteran EPE Designer.

The fundamental approaches for designing a suitable structure for an electronic enclosure break down into *four* basic approaches:

1. Take a look at similar products that already exist, and use the solution already designed as a quick starting point for the design at hand. Pluses for this kind of approach are speed, but the downside is that your design may suffer due to lack of creativity toward solving a unique problem that your specific product should solve.
2. Quick, "back-of-the-envelope" design. This approach uses some rudimentary design equations on simplified structural elements. We'll explore some examples of these design approaches with some example problems later on in this chapter.
3. More complex analysis. This is explored a bit more in Sect. 3.3 on "Analysis Required." Again, this text will not cover much ground for designs requiring complex analysis. What I would like to emphasize in this chapter is a feel for the structural elements of the design and what some "quick fixes" would be for improved designs.

4. Overdesign – Of course, *overdesign* is not the correct answer for all of the designs. I've already touched upon this above in the example on the solution using 1/8 inch aluminum. I'll go into another example of overdesign below. In a *competitive* product market, where customers make buying decisions mainly on price, overdesign will likely lead to increased product cost (or, certainly, increased weight and size). Structural overdesign is basically starting with a design that has a very good likelihood of success of passing structural testing, that is, surviving the customer usage environment for shock and vibration.

A lot can be said for *overdesign*. The EPE Designer could determine that a bracket that is 18 gauge (0.048) thick metal would "do the job" but, *instead*, choose 16 gauge (0.060) thick metal. Increasing the thickness of the bracket gives one some comfort for a couple of reasons:

- That the design will stand up to some of the forces that are *not known* to a high degree of precision. This will be further explored in Sect. 3.2 on "Design Process."
- That there is just a "factor of safety" greater than 1.0 in the design. A factor of safety *equal* to 1.0 means that your design *just* meets the design criteria. A discussion on the considerations of designing with increased factor of safety is covered in Sect. 3.2 of this chapter.

Also, it is possible that there may be some economical reason for placing 0.060 thick metals in the design. For example, if the majority of the design is 0.060 thick already, and if the bracket can be made out of a piece of "scrap," a savings might result.

It is very possible (in the above example) that using 0.048 thick metals *with the addition* of some simple "ribs" or bends would make the design *much stronger* than 0.060 thick metals. This is what I would like to spend some time on, and this issue of adding ribs to a design is explored in the problem shown in Sect. 3.4.2.

3.2 Design Process for Structures

I'd like to give the reader a generic process for designing the electronic enclosure (or, an *individual part* in the enclosure) that will satisfy the structural considerations of the design. By going through these six steps, the designer should be ready to propose a material and cross section that will work. I'll individually break out the six steps as subsections.

3.2.1 Similar Designs

How have other designs in the industry handled similar situations? The other designs could be from examples within your own company (past products) or from competitive products outside of your own company.

3.2.2 Forces on Part

Determine the forces (static and dynamic) on the object – amplitude and direction of those forces. The part's own weight generally doesn't come into consideration in electronic enclosures for static forces but does get considered for dynamic forces. In this text, I refer to "objects," "parts," and "members," but they should all be considered being one-in-the-same.

3.2.3 Existing End Conditions

Determine the "end conditions" of the object, that is, its degrees of freedom of movement, and how the member will be supported. Common end conditions are "fixed" (not allowed to move) or "free" (allowed to rotate). End conditions have an effect on determining the amount of stress that loads will create.

3.2.4 Propose Material and Cross Section

Determine the material and cross-sectional combination needed to support those forces (from Sect. 3.2.2), keeping in mind that "strength" is an inherent aspect that belongs to materials (so, the higher the yield strength of the material, the more load-bearing ability that material contains), and forces produce stresses in those materials. All materials have limits for maximum stress where we either have the start of deformation (yield strength) or complete failure point (ultimate strength).

Maximum stress in the member is generally known by the "common equation" of

$$\sigma = Mc / I$$

where:

σ is the maximum stress in the member.
c is the distance of extreme "fiber" from bending axis.
I is the moment of inertia. This is a property of the cross-sectional area of the object.
M is the maximum moment in the cross section furthest from where the force is applied. It is that force times its distance from an end-point condition to where the force is applied.

Basically, only *two* choices initially exist to design higher load-bearing members (as the terms "c/I" are both related to cross-sectional area and that area's "dispersal" away from the "neutral plane" of bending).

- Change the material, which allows a change to the stress limits. So, choosing a material with higher stress limits allows more loading to be placed on that member.

- Change the material's cross-sectional property, basically the member's second moment of area (also known as the moment of inertia, I) and the amount of area that can be concentrated away from the member's "neutral axis" or centroid. Increasing area will essentially increase a member's ability to carry more loads. Increasing that area away from the member's "neutral axis" will also help the member carry more load (which is why "I-beams," which have a lot of the member's cross-sectional area very far from the "neutral axis," are excellent load-carrying members).

I've illustrated the interrelation between changing both material and cross section in Fig. 3.1. Here, we have a very common load situation, one where a force is acting on the end of the member, and the member has a fixed end condition. We will be showing how various changes in (either or both) material and cross section can solve a problem. The basic problem is finding a member strong enough to survive this load, a 2000 pound force. The EPE Designer is tasked with determining both the material and cross section of the member so that the maximum stress *in* the member will be under the maximum stress (let's say yield stress) *allowed* by the particular material. So, we can utilize the equation from above as a starting point in the design:

$$\sigma = Mc / I$$

We can calculate the maximum moment, M, as being equal to 48 inch × 2000 pounds, which we'll then say is 96,000 in-lb (this will be the same value for any material and cross section that we choose). Let's put forth two candidate materials:

Pine wood, which has a yield stress of 1200 pounds/in^3 (psi)
Aluminum, CR H-18, which has a yield stress of 22,000 psi

Let's keep to simple rectangular shapes, which have the moment of inertia value of (for either material):

$$I = bh^3 / 12$$

where

b is the width of the member and *h* is the height of the member in cross section.

In this example, *c*, which is the distance from the extreme fiber to the bending axis, will be *h*/2.

Thus, our equation for stress becomes:

$$\sigma = Mc / I = \left(96000 \times \left(h / 2\right)\right) / bh^3 / 12 = 576{,}000 / bh^2$$

(Note that the stress in this member is dependent on the height of the member *squared*, which underscores the need for high "aspect ratio" (the ratio of height to width) cross sections.)

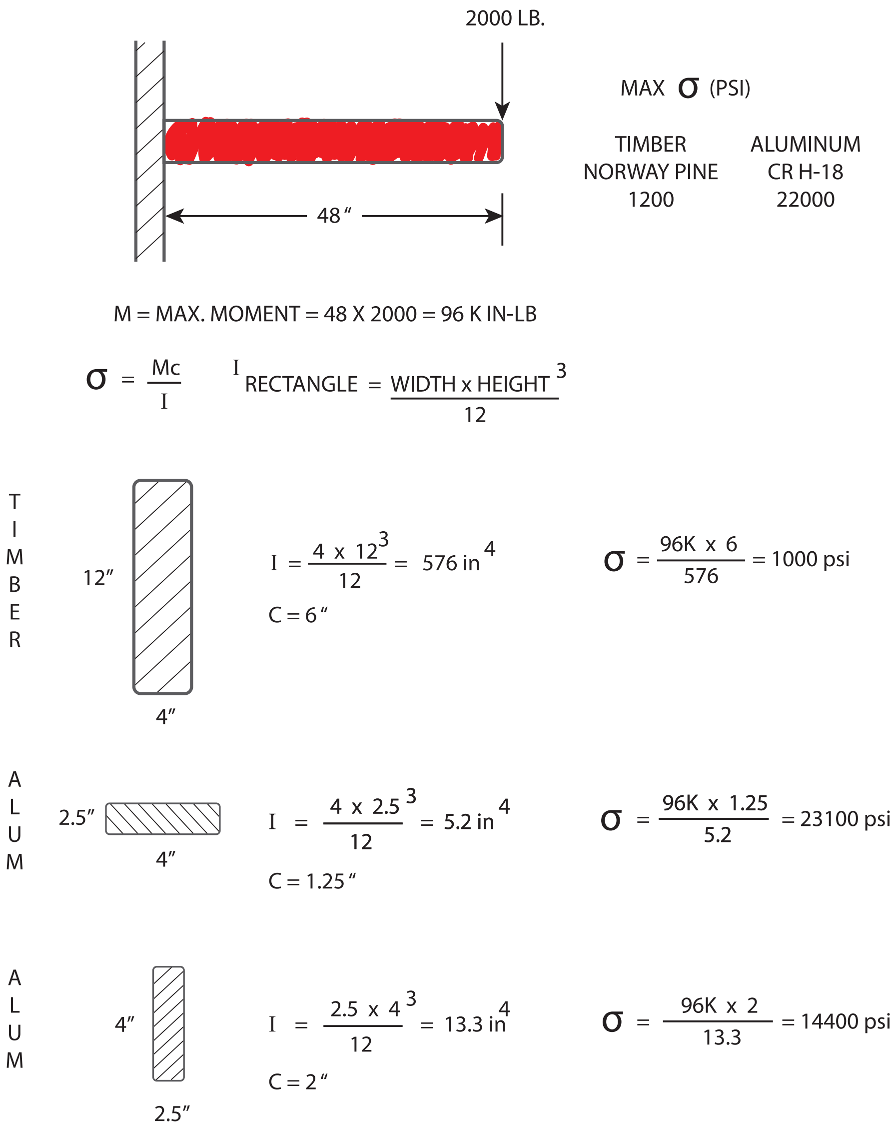


Fig. 3.1 Material & cross-section choices

3.2.4.1 Pine Wood Solution

Let's try to design the member that will be made of pine wood. By putting in:

$b = 4$ inch and $h = 12$ inch, we see that the maximum stress will be 1000 psi. This member (pine wood, with a cross section of 4×12) has a "stress limit" of 1200 psi, and the load on it is only 1000 psi. Nice, we have "overdesigned" the member (with a factor of safety of 120%).

Now, the EPE Designer needs to look at "other" design constraints (like weight or cost) to make a decision to see if this pine wood beam will be a good candidate for our electronic enclosure.

Spoiler alert: We'll discuss the 15 considerations for determining material selection for any part in Chap. 4, but for now, just look at weight as another consideration for the "final choice" of material and cross section.

Let's look at the weight of this pine wood beam. At 30 pounds/ft^3, the beam will be 40 pounds. Fine (for now).

3.2.4.2 Aluminum Solution

Design is all about presenting some logical choices, so let's look at an aluminum beam.

We can choose,

$b = 4$ inch and $h = 2.5$ inch. We can see that the maximum stress will be 23,100 psi. This is *above* the maximum yield stress for the aluminum, so *this will not be* structurally *satisfactory* in our design.

But what about remembering that the height of the beam is the larger "factor" in our calculations for moment of inertia,

$b = 2.5$ inch and $h = 4$ inch? This will be the *same* cross-sectional area as the previous example for the aluminum beam. Now, the maximum stress will be 14,400 psi, well within the maximum of 22,000 psi for this aluminum. Thus, "rotating" the same cross section, where the thicker aspect is in the direction of the load force, allowed this choice of material and cross section to be structurally successful.

Let's look at the weight of this aluminum beam. At 169 pounds/ft^3, the beam will be 47 pounds. This compares to 40 pounds for the pine wood.

In summary, we have looked at how two different materials (pine wood and aluminum) could be used to solve the structural problem. We can develop cross-sectional areas for each material that solves the structural problem.

In design, deformation often shares an equal importance with strength. A load member may have sufficient strength to withstand a particular load, but it may deflect an unacceptable amount beyond the elasticity of the engineering material. Problems, where deflection (and thus the material's modulus of elasticity, E) is also under consideration, are shown in some examples further on in this chapter.

The economics of the above choices (change material or change material cross section) pose an interesting problem to EPE Designers. Many combinations of material and cross-sectional area will work, but a choice must be made that fits the overall goals of the project. Besides functioning, it must meet project goals of cost, manufacturability, risk, weight, time to market, etc. These choices will be further investigated at the beginning of Chap. 4. It is possible that alternative solutions would need to be reviewed, tested, and prototyped. One of the biggest assets a designer can bring to the design would be to quickly find the logical choices to be made among the viable candidates for material/cross-sectional choice that will solve the problem at hand.

3.2.5 Combine Function

Can the part being designed be *combined* with another part in the assembly which is adjacent to this part? Basically, can two *separate* parts (being envisioned) be combined into a *single* part? This is illustrated in Fig. 3.2.

The "alternative thinking" aspect of looking at the part being *combined* is to actually look to create two *separate* parts from a (envisioned) single part. This could result in a lower overall cost reduced solution to the *combined* design.

One of the main choices (for a candidate material/cross-section solution) will be determining how to fabricate this solution in production. For example, some of the choices involved here are:

- What is the tooling budget for the project? Can the project "afford" spending an amount of capital needed for casting, injection molding, extruding, or other fabrication techniques that may be under consideration? Is there existing tooling that can be utilized? A determination must be made to find the "payback period" of a tooled solution. For example, knowing:

  1. How much tooling will cost
  2. How many parts will be needed (over the product "lifetime")
  3. How much un-tooled part will cost
  4. How much the tooled part will cost

will determine when the "payback period" of the tooled solution. For example, if tooling will cost \$50,000, and the un-tooled part cost is \$10, while the tooled part cost is \$1, this would result in a savings of \$9 per part needed. Thus, the tooled part pays for the tooling in 50,000/9 = approx. 5500 parts. If 5500 parts are expected to be sold in a year, then the "payback period" will be approx. 1 year. See previous discussion on tooling "breakeven" in Sect. 1.7.

- Are there "off-the-shelf" or "previously designed" solutions that could be used in the design? This could save the tooling cost, and the increased volumes of this "new" usage (when combined with the "old" usage) will lower the individual piece cost.

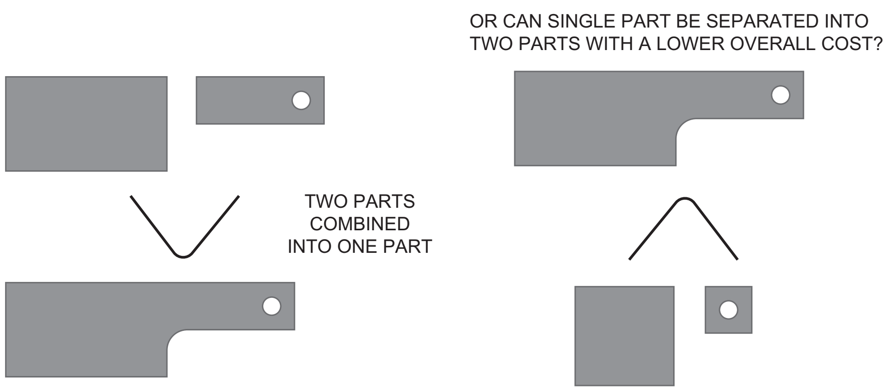


Fig. 3.2 Combining (or separating) parts to improve design

- Can the fabrication technology be phased-in over the course of the project? That is, can we use one fabrication technique in the prototype/first production stage (e.g., CNC milling) and then switch over to a tooled solution (e.g., casting) after first production? With this scenario, cost reductions are phased-in, and the savings doesn't occur near term (but, rather, in a longer time period).

3.2.6 Determine Factor of Safety Needed

A determination of "factor of safety" must be reviewed at this time. That is, answers to the following questions must be known:

- If the part fails, does anyone get injured? What is the cost of an unpredictable failure in lives, in dollars, and in time?
- How critical is this particular part in the overall function of the product? If this part fails, does the entire product fail?
- How well are the forces known (from Sect. 3.2.2 above)? Do we know the "error bars," that is, how much the forces can deviate from the assumed nominal value?
- Determine the "critical aspects" of the chosen design (material or geometry), and how in-production will they be specified, certified, and inspected? Make notes to assure these steps (certification/inspection) will be done. Determine the testing required in the various stages of the design that will be required to assure that the final design will be adequate for shipment to the customer in production.
- There will be an optimized solution which generally can be found by analyzing the major components of the design and determining where the "weak links" in the design exist. This can be found by utilizing some testing methodologies that induce failures by testing beyond the environmental limits (such as highly accelerated life testing, HALT). By first identifying where failures might occur, then by testing design prototypes, data can be generated to determine whether certain segments are near their design limits.

If any of the above six steps in the design process do not have answers known to some degree of confidence, the designer is faced with:

- Making further inquiries to get better information.
- Going forward with the design. It would be rare for designers to know about all of the forces and interrelation of parts at the very beginning of the design process. Certainly, the designer can list the assumptions made and the additional information that would be essential. It is certainly possible to design parts, prototype the parts, and test them under the conditions that they will need to function in. Several approaches to this dilemma of "going forward with the design without knowing all of the information" can be taken; let's explore an example where:

Design 1 has a weight that is 110% of target weight but has a 95% chance of being structurally successful. Design 2 is 100% of target weight but has a 75%

chance of being structurally successful. So Design 1 is 10% over the target weight, but with a much lower risk of failing to meet the design goal of working from a structural point of view.

So, what is being "traded-off" is the time needed to optimize the design. Certainly, the product must work from a structural basis. It will be difficult to determine the "margin" in the design at the very beginning of the program. Going forward with the design *without knowing all of the information* has value in that the "basic design" can be tested. It is hoped that the "basic design" can be modified in a quick time frame that allows the program to continue as the rest of the information is attained. We can move forward quickly by "overdesigning" the parts or invest more time to "marginally" meet all of the requirements. These two paths are investigated a bit more below:

A. "Overdesign" the parts – this approach probably guarantees that the parts *will structurally function* under testing. The idea here would be to iterate back to a *less* conservative design as testing reveals where material and weight savings are appropriate. This approach at least maximizes the chances of the design meeting the structural functionality requirements very early in the test phases of the project. However, weight changes to the design to bring these parts closer to "marginal" structural success will require time (and money) to retest the design to validate the changes. Most projects have limited time for iterative approaches to attain parts that are "perfectly" designed.
B. Design parts with the more time-consuming path of "just marginally" meeting both the weight and strength requirements. So, this stratagem is different than overdesign (above) in that the parts are designed that have a chance of (just barely) working. For example, if space and weight reduction are highest on the list of product requirements, a design that is "marginally" acceptable from a structural strength factor, but has a greater material and weight savings, may be what is needed. This approach attempts to balance both "risk and reward" and should have the agreement of the design team to go forward. With this design, the material and weight goal would be met. However, risk of this design *not structurally working* goes from 5% to 25%. So, the "B" design path shows higher risk of not meeting the product requirements for structural strength but will meet the product requirements for weight.
C. Blends of the above two approaches may be appropriate. That is, some parts of the design would be conservative, while other parts of the design would be more risky. This perhaps allows an "overall risk tolerance" to be a part of the overall design. Experienced design teams will know the best places in the design to "push the envelope" of acceptability.

3.3 Analysis Required

There are certainly many designs that warrant the most exacting analysis in the design of electronic packaging. In any highly competitive product design area, it will be the company that does the most productive job with a given technology that will maximize its chances for success. The very highest degree of analysis will be needed if the product has:

- A "high" production quantity. If hundreds of thousands of a particular unit are to be produced, then the savings of a dollar per unit could result in substantial total savings. An analysis that saves even a small amount of cost will result in a lot of overall profit due to the larger production quantities. If, however, only a few units are to be produced, the potential for savings is greatly reduced, and, once a design is deemed to be functional, a large investment in cost reduction will not bring substantial savings.
- A high degree of safety as a requirement due to the environment that the product will be placed into. Examples of this are products that are in the transportation, utilities, medical, or educational industries. All customers need to have a safely operating product.
- A "mission" that is critical to the customer. This would include products needed for military, space agency, or government in general.

Note here that there can be no excuse for a design that is so overdesigned that it lowers the profitability of the company. Designers and engineers should be ever vigilant to the possibility of cost reduction. The elimination of parts, the design for manufacturability, and the overall elegance of design lead to product leadership. It is in the first stages of design that present the *most* cost reduction possibilities. As the design progresses to even the prototype stages, the cost of redesigning for cost reduction starts to rise exponentially. More on this aspect will be presented in Chap. 6 on "Assembly and Serviceability."

Also, a note on safety is appropriate. There can be no excuse for underdesigning a product in any area where safety is an issue. Underwriters Laboratories (UL) and other safety agencies, of course, certify electronic equipment for safety considerations. That is, a safety agency will take a product (specifications and working units) and subject them to both review and testing. Most electronic products, certainly those sold worldwide, will have to pass rigorous agency approval certification. More on this aspect will be presented in Chap. 10, "Safety by Design."

The number one design consideration is still and will always be *functionality*. That is, the part must *function* as it is intended. It doesn't matter how well it looks or how elegantly it can be produced, IF the part will fail under load. This is a major reason why the loads must be understood by the designer.

Modern analysis software solutions using finite element analysis (FEA) are very ubiquitous. A search on Google reveals introductory material such as:

A. *Finite Element Analysis*, by David Roylance, MIT. Describes the three principal steps as:

   - Preprocessing, where a model of the part to be analyzed in which the geometry is divided into a number of discrete subregions, or "elements," connected at discrete points called "nodes"
   - Analysis, where the dataset prepared by the preprocessor is used as input to the system of linear or nonlinear algebraic equations that calculate the stresses and displacements

- Postprocessing, where the results are graphically displayed to assist in visualizing the results

B. *Linear Analysis*, by Professor K. J. Bathe, from the MIT *open courseware*, MIT. This video series is a comprehensive course of study that presents effective finite element procedures for the linear analysis of solids and structures.
C. *Finite Element Analysis*, Dr H. J. Qi. Describes the FEA process as:

- Formulating the physical model, that is, describing (perhaps, simplifying) a real engineering problem into a problem that can be solved by FEA
- Using the FEA model by discretizing the solid, defining material properties, and applying boundary conditions
- Choosing proper approximate functions, formulate linear equations, and solving these equations
- Obtaining results in both numerical and visual formats

There is no doubt that using FEA can provide much useful information about engineering problems involving structural analysis (along with solid mechanics, dynamics, and thermal analysis). Any answers coming out of this analysis should be first tested by using simplified models and forces to see if the answers make some sense. Testing should be used to verify the assumptions made and the resulting answers. Another attribute of using FEA analysis is that small changes in the design can also be inputted into the analysis to see how the results vary. In this manner, it can be shown very quickly how to make the design better.

Some companies are large enough to have an entire department devoted to FEA analysis, while others operate with the expectation that the designer will be analyzing the structures using FEA on their own.

3.4 Structural Problems: Static Loads

Again, as this text is not meant to cover all of the various structural considerations or problems encountered, I'd like to highlight a few problems (I kept it to three) that highlight the following:

- Problems that can be thought of as either "individual" in that loads and forces are applied to *single members* being designed or the "structures as a whole," that is, it could be an analysis of the entire (assembled) structure.
- Many suppliers of individual parts (or sub-assemblies) offer design guidance in their own literature that is certainly available to the individual designer. Much of this information is based on both empirical and analytical experience gained over the years. The designer is cautioned to understand the background and limitations on any of this information. Some of the information that is presented in graphical or tabularized formats is rooted in fundamentals, but this may not be apparent. Some examples of this type of available "supplier data" is in the design of plastics, seals, EMI components, and bearings (to name a few).

Static loads on members in electronic enclosures are due to:

1. The member's own weight
2. Loads applied by other members
3. Loads due to thermal effects, residual stresses, etc.

Static loads will induce members to fail either by applying a force resulting in:

1. The yield strength of the material being exceeded.
2. An over-deflection of the member which results in the member performing outside of the design intent. As all loads produce some deflection, it must be known at some point in the design just how much deflection by the member is to be allowed.

Failure by fracture under static loading is not as common in ductile materials as in brittle materials. In a ductile member, failure usually occurs as a result of excessive inelastic action which leads to very large overall deformations long before fracture.

Dynamic loading will be covered in Sect. 3.5. Dynamic loads are generally those that vary with time, whereas static loads do not change significantly in a relatively short time period. Some dynamic loads common in the design of electronic enclosures are repeated loads, impact loads, and energy loads. Energy loads are loads that are expressed more easily in terms of the energy transmitted during the impact period (than in terms of applied force).

Fracture caused by a repeated load is commonly referred to as a "fatigue" failure. Vibration can be a cause of a fatigue failure.

Topics generally covered by the following three problems are:

1. What is a beam (vs. a plate)?
2. Stress formulae and maximum stress.
3. Deflection formulae and maximum deflection.
4. Section modulus.
5. Modulus of elasticity.
6. End conditions.
7. Load conditions.
8. Worst-case loading.
9. Combined loading.

3.4.1 Cantilever Beam Analysis (from **Tecknit EMI Shielding Products** *Manual)*

A majority of electronic enclosure stress analysis can be characterized by calculations of a "simple" beam. But, first of all, let us define a beam. Roark and Young (see Ref. [1]) make the following assumption for the application of beam flexure formulae:

- The beam must be long in proportion to its depth, the span/depth ratio being 8 or more for metal beams, and 15 or more for beams with relatively thin webs. This

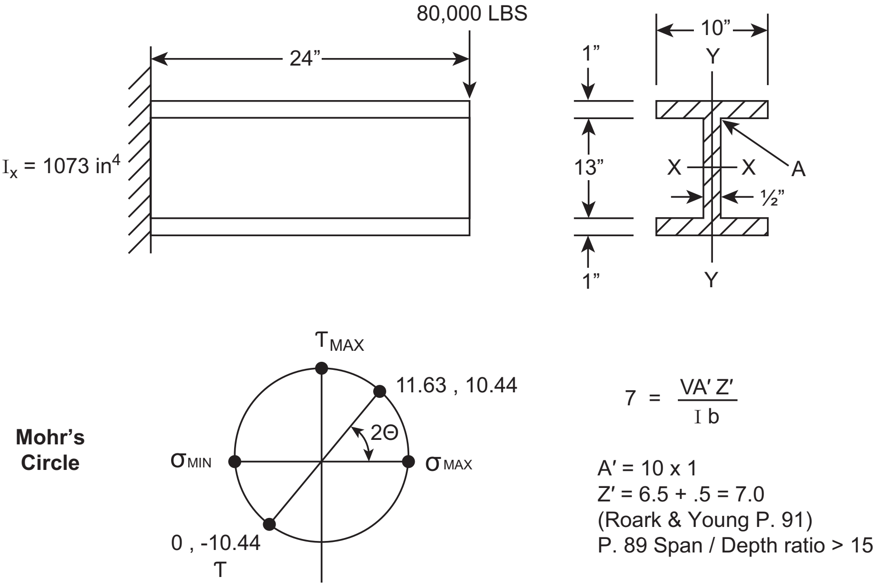


Fig. 3.3 Cantilever beam analysis

is shown in an excellent example by Byars and Snyder (see Ref. [2]), a cantilever beam as shown in Fig. 3.3. Determine the principal normal and shear stresses at Point A just below the flange. Assume elastic behavior and neglect any stress concentration at the wall.

Solution: The bending moment at the left-hand end of the beam is:

$$M = (80{,}000)(2)(12) = 1{,}920{,}000\,\text{in} - \text{lb}$$

and the vertical shear force is:

$$V = 80{,}000\,\text{lb}$$

Hence, the flexure stress at Point A is:

$$\sigma = My / I = (1{,}920{,}000)(6.5) / 1073 = 11{,}630\,\text{psi}\,(\text{tension})$$

and the transverse shear stress at Point A is:

$$\text{T} = VQ / It = (80{,}000)((10)(1)(7)) / (1073)(0.5) = 10{,}440\,\text{psi}$$

Mohr’s circle for this state of stress gives:

$$\sigma\,\text{max} = 17{,}750\,\text{psi}\,(\text{tensile})$$

$$\sigma \min = 6{,}130 \,\text{psi} \left(\text{compression}\right)$$

$$\mathrm{T} \max = 11{,}940 \,\text{psi}$$

(Mohr's Circle is used to find the total stress when bending stress and shear stress are considered in the problem) Note, however, that in such a short member as this with its thin-web cross section (span/depth ratio = 24/15 = 1.7), the validity of the flexure formula is questionable. Notice, for example, that the shear and normal stresses are of the same order of magnitude. Also, note that the length of this beam would have to be on the order of 19 feet, for the correct span/depth ratio to apply.

The importance of the above example is the emphasis on the effect of transverse shear stresses on maximum stress. In determining maximum stresses in beams, don't be satisfied with your results until you have exhausted all possible combinations of flexure and shear stresses which could give the maximum principal stresses. Often, the construction of the shear and moment diagrams and a comparison of the orders of magnitude of the flexure stresses and transverse shear stresses will greatly simplify the problems.

Using some of the beam stress formulae from the example above, we will continue with the "main thrust" of a problem that an electronic enclosure designer may face. That is determining the (maximum) fastener distance ("C") for a "cover plate" onto a housing chassis. This type of problem involves an environmental seal along the housing that will provide (see Ref. 6)

- Protection from dust, moisture, and vapors
- Adequate EMI shielding

We'll take up the shielding portion of the problem in Chap. 9. Right now, we'll tackle the "structural problem" of designing the basic seal design geometry in regard to maintaining adequate strength to provide a moisture seal. I'll be quoting some material from the Tecknit EMI Shielding Products Manual (see Ref. [3]). Note here that I am using some reference material from a "manual." This remains, even in the "Google Search" age, a very valuable source of information for designers. Many of these manuals are hardbound and were available from original equipment manufacturers for designing in their particular components. Now, a lot of this "design guide" information is available online (as opposed to being available in a hardbound manual). Usually, sales personnel of the component manufacturer are aware of the various "guides" and online information available to designers today.

Now, returning to the structural considerations of this enviromental seal problem:

A. Material of seal: covered later in Chap. 7, "Product Environments (Sealing)"
B. Cover and chassis material: modulus of elasticity covered here (corrosion covered later in Chap. 4, "Materials and Processes." Surface finishes are covered in Chap. 7, "Product Environments (Sealing)"
C. Cross-sectional area (moment of inertia needed), covered here
D. Bolt spacing, covered here
E. Compression stop, covered here

The "fastener distance" problem is solved (approximately) here in the Tecknit manual by the use of an equation (where C is the spacing between bolts).

With the three assumptions of:

1. Gasket width = cover plate width.
2. Maximum pressure (exerted by gasket) equals three times the minimum pressure (exerted by gasket).
3. Minimum pressure is 20 psi.

Comparing an enclosure made of aluminum (vs. made of steel):

$$C = 59.6\left(t^3 \Delta H\right)^{1/4}$$

For aluminum plate (E = 1 × 10^7 psi).

For ΔH = 0.01 inch, a reasonable gasket deflection, and t = 0.125 inch, C = 4.0 inch

$$C = 78.5\left(t^3\ \Delta H\right)^{1/4}$$

For steel plate (E = 3 × 10^7 psi).

For ΔH = 0.01 inch, a reasonable gasket deflection, and t = 0.125 inch, C = 5.2 inch.

A few further observations about the equations (and answers) are:

1. We see that the bolt spacing for a steel enclosure is more than an aluminum enclosure – this makes sense that the stiffer material would allow less flexure. A bolt is needed every 4 inches for an aluminum plate, while if we use steel for the plate material, a bolt will be needed every 5.2 inch.
2. We see that the bolt spacing varies as the cube of the thickness – we would expect that the equation (for bolt spacing) is probably based on the moment of inertia of the "beam," with resulting "cube function" for thickness.
3. We would expect the bolt spacing to be a function of a "power to the ¼" as the general equation for a beam with a uniform load along its length to have deflection as a function of its length to the fourth power (see Ref. [2]). That same general equation for a beam with a uniform load would also have deflection as a function of its material modulus of elasticity (E) to the ¼ power (3 ¼ = 1.3, which = 78.5/60).

Thus, as a designer, we would start with an estimation of bolt spacing at 4.0 inch (for an aluminum housing design). Obviously, we could (and should) prototype this spacing in our design and test under as real conditions as possible. Of note is that we have also made assumptions of cross-sectional area of our gasket seal areas and gasket changes in thickness as the gasket goes from:

A. Uncompressed state (before fasteners are tightened).
B. Compressed state (after fasteners are tightened down to set "stops" in the design, that is, design features near the fasteners that specifically limit the gasket from

being over-compressed. All gaskets require these “stops” to allow the fasteners to have a specified compression limit.

We could also look at similar designs where the level of ingress protection (air or water) matches what we design. If we see that 4.0 inches works for these designs, that would give us some confidence that we have certainly a chance at success.

It should also be noted that one of the factors of the *overall* design would be to have a *minimum* amount of fasteners. Thus, a 5.0 inch distance between fasteners would be better than a 4.0 inch distance (with resulting savings of fasteners and the labor to tighten those fasteners). However, the 4.0 inch spacing will increase the likelihood of the gasket design sealing under additional loads that were not a part of the calculation (like shock or thermal) and thus provide the design some margin of safety.

3.4.2 *Deflection Formulae and Maximum Deflection (from* **Injection Molding** *Magazine)*

Another problem that illustrates the relationship between stress, deflection, moment of inertia, and area is shown by a method to allow the designer to determine the stress and deflection ratios of a ribbed plate compared to an unribbed plate of the same base thickness, W (Fig. 3.4). This problem will point out the importance (and ease!) of adding a rib to the design. This rib will greatly increase the strength of a section. Ribs, such as this, are easy to add in the injection molding process, casting process, or even in standard sheet metal design. Fig. 3.4 shows two charts. For the chart marked “stress ratio (ribbed/unribbed)”, the ordinate is the stress ratio and the abcissa is the rib height/base thickness. This chart shows how the maximum flexural stress changes as ribs are added to a flat plate. Each curve represents a particular rib spacing ratio, with the curve labeled “.01” representing very widely spaced ribs while other curves have more densely spaced ribs. The chart marked ‘deflection ratio’ is similar and shows a curve labeled “.01” representing very widely spaced ribs. More detail is available in Ref. [4].

Procedure

1. Calculate the equivalent base width, $B\text{eq} = B/N$, where

$$B\text{eq} = \text{Equivalent base width}$$

$$B = \text{Total width of plate}$$

$$N = \text{Total number of ribs}$$

2. Calculate the rib tip thickness, $t = T - 2H\ (\tan a)$, where

$$t = \text{thickness of rib at the tip}$$

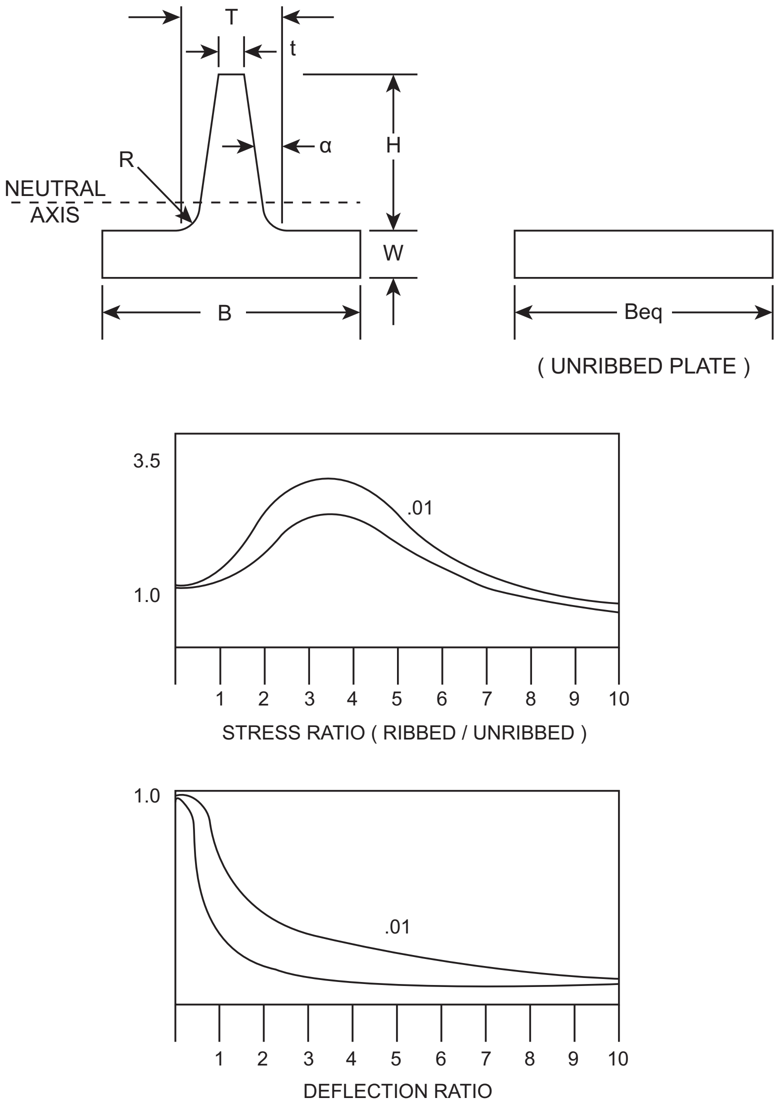


Fig. 3.4 Ribbed vs. unribbed plate

$$T = \text{thickness of rib at the base}$$

$$H = \text{height of rib}$$

$$a = \text{draft angle per side of the rib}$$

3. Calculate the cross-sectional area of the equivalent base section, $Ar = B\text{eq}W + H\ ((T + t)/2)$ where:

$$Ar = \text{Cross} - \text{sectional area of equivalent base section}$$

$$W = \text{Thickness of base}$$

4. Calculate the distance from the extreme fiber to the neutral axis, $Y = H + W - (3B\text{eq}\ W^2 + 3Ht\ (H + 2W) + H(T - t)(H + 3W))/6Ar$
5. Calculate the moment of inertia of the equivalent base section, $Ir = (4B\text{eq}W^3 + H^3(3t + T)/12 - Ar(H - Y)^2$
6. Calculate the moment of inertia of the equivalent base section without ribs, $Io = (B\text{eq}W^3)/12$
7. Calculate the ratio of the stress of the ribbed plate to the stress of the unribbed plate, $S\text{ratio} = 2(Io/Ir)(Y/W)$
8. Calculate the ratio of the deflection of the ribbed plate to the deflection of the unribbed plate, $Y\text{ratio} = Io/Ir$

So, we know that adding ribs to "unribbed" structure will increase that structure's ability to handle more loading. Generally, strength can be increased by adding thickness to the "general" wall thickness as:

$$\sigma = Mc / I$$

where:

σ = the stress that the member under consideration
M = the maximum moment in that member (usually a function of force times "distance," that is the "distance" from the force to the section of the member)
I/c = Z, which is a property of the section under consideration, also known as the section modulus
c = distance from neutral axis of member to "outside fiber"
I = moment of inertia (about the centroid) of the member

Thus, to increase the amount of load-bearing ability of a member, you could:

Increase I and/or decrease c (increasing Z).

The I for a rectangle (a rectangle being a common choice for a fabricated member),

$$I\text{rec} = bh^3 / 12, \text{and}\ c = h / 2$$

Thus,

$$I\text{rec} / c = bh^2 / 6$$

where b = the length of the rectangle's base and h is the *thickness* of the rectangle.

Note that increasing the thickness (h) has a large affect due to the "squaring function."

Thus, doubling the thickness essentially makes the beam stronger by *four* times.

The above being said, doubling the thickness will increase the weight of a member (of a "standard" cross section) by *two*. This can be a "disaster" for weight-sensitive designs (which are most prevalent in the electronic enclosure industry).

However, by adding ribs, which are "intermittent" additions of thickness, the strength goes up considerably (while the weight goes up by only a small amount). The designer may be surprised to see that adding ribs may actually increase the maximum stress. Why is this? Although a rib increases the overall moment of inertia of the plate, the distance from the neutral axis to the extreme fiber of the cross section (c) can increase more rapidly for short ribs. This effect is most pronounced for widely spaced ribs.

Let's go back to the seven steps in calculating Sratio (ratio of maximum allowable stress for both an unribbed and single-ribbed design) for a very simple rib addition where the "rib" is *not tapered*, that is, $T = t$:

Width of the plate (B) = 1 inch
Single rib, height of rib (H) = 0.375
Thickness of base (W) = 0.125 inch
Wr = 0.0.125/1.00 = 0.125 rib height/base thickness = 0.375/0.125 = 3.0

$$B\text{eq} = B = 1.00\,\text{inch}$$

$$t = T = 0.125\,\text{inch}$$

$$Ar = B\text{eq}W + H\left(\left(T + t\right)/2\right) = \left(1 \times 0.125\right) + \left(0.375 \times 0.125\right) = 0.172\,\text{in}^2$$

$$Y = \left(0.375 + 0.125\right) - \left(\left(0.047\right) + \left(0.053\right) + \left(0.035\right)\right)/1.032 = 0.5 - 0.131 = 0.369\,\text{in.}$$

$$Ir \quad = \left(0.0078 + 0.026\right)/12 - 0.172\left(0.375 - 0.369\right)^2) = 0.00282 - 0.00001 = 0.0028\,\text{in}^4$$

$$Io = 0.00016\,\text{in}^4$$

$$S\text{ratio} = 2\left(0.00016/0.0028\right)\left(0.365/0.125\right) = 2\left(0.057\right)\left(2.92\right) = 0.33$$

Thus, the addition of the rib to the design makes the section approximately three times stronger.

The *Injection Molding Magazine* (Ref. 7) article also compares the deflection ratio for a ribbed/unribbed section.

3.4.3 *Another Deflection Problem, This Time Snap-Fitting Hook (from* **Mobay Design Manual, Snap-Fit Joints in Plastics***)*

This problem is a great example of what an enclosure designer faces when designing a commonly used feature, the "snap-fit." Snap joints are a very simple, economical, and rapid way of joining two different components. As this eliminates fasteners from joining the two components, it is used quite frequently. The design utilizes a protruding feature from one of the parts (the "hook"), while the other part contains hole (or "undercut"). The idea here is that the hook is deflected briefly during the joining operation and catches in the undercut to complete the mating operation.

This introductory problem has been chosen as it:

A. Shows a common fastening methodology (for plastics).
B. Shows the use of common strength of materials formulae being used in a manner that utilizes the elastic nature of material, deflection being used as an advantage in a design, and optimization of cross-sectional area and uniform strain.
C. Introduces some of the aspects of designing with plastic materials.
D. Utilizes available literature from suppliers (in this case, Mobay Plastics). Instead of solving some of the more complex (yet, common) problems by first principles, the use of tabulated options and nomograms can greatly reduce the design time needed.

This calculation example is for a snap-fitting hook of rectangular cross section and with a constant decrease in thickness from h at the root to $h/2$ at the end of the hook (see Fig. 3.5). This is therefore design type 2 (see Table in Reference). General design goal is to permit maximum deformation with minimum material.

Given:

Material = Polycarbonate

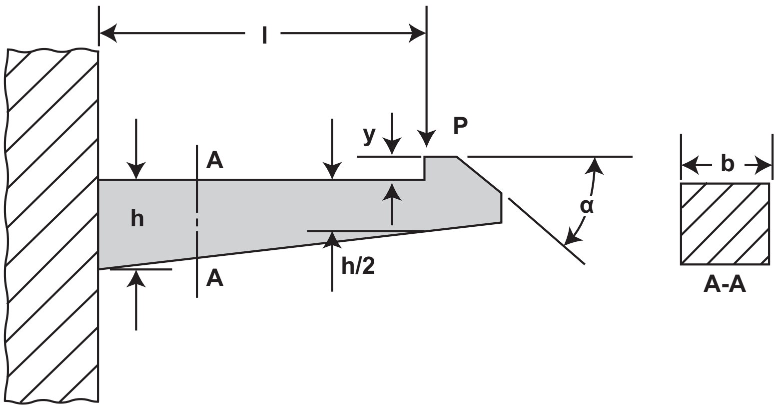


Fig. 3.5 Snap – fitting hook

Length (l) = 0.75 inch
Width (b) = 0.37 inch
Undercut (y) = 0.094 inch
Angle of inclination (α) = 30°

Find:

Thickness (h) at which full deflection (y) will cause a strain of ½ the permissible strain.

From table (for polycarbonate), ε (permissible) = 4%; therefore, ε (allowable) =2%.

From table (type 2 designs)

$$y = 1.09\varepsilon l^2 / h = 1.09 \times 0.02 \times 0.75^2 / 0.094 = 0.13\,\text{inch}$$

Deflection force (P)

From table (force equation)

$$P = \left(bh^2 / 6\right)\left(E\varepsilon / l\right)$$

From graph for polycarbonate (ε = 2%), E = 264,000 psi

$$P = \left(0.37 \times 0.13^{\dagger}\right) / 6 \times \left(264{,}000 \times 0.02 / 0.37\right) = 2.9 lb.$$

Mating force (W)

$$W = P\left(\mu + \tan\alpha\right) / \left(1 - \mu \tan\alpha\right)$$

Friction coefficient from Table (PC against PC) $\mu = 0.50 \times 1.2 = 0.6$.

From figure, $(\mu + \tan \alpha)/(1 - \mu \tan \alpha) = 1.75$ for $\mu = 0.6$ and $\alpha = 30°$

$$W = 2.9 \times 1.75 = 4.3\,\text{lbs.}$$

3.5 Dynamic Loads

Dynamic loads on members in electronic enclosures are due to loads that bear on the member in a nonsteady-state manner. They include, but are not limited to:

A. Vibratory loads that have amplitude and frequency (includes wind forces or inertia forces associated with earthquake ground motion)
B. Discrete shock loads

Some problems considering these vibration and shock-loading situations will be explored in Chap. 7 on “Product Environments.”

Chapter Summary
In this chapter, I've introduced the EPE Designer to some of the basic considerations of the structural considerations of the enclosure. We can start this design by proposing materials for these outer hulls. Also our design disposal will be the choice of the cross section of the hull. The best choice for these cross sections and materials are made by using strength of material equations which are readily available. However, there are choices to be made among various solutions, and it will take more considerations than just structure alone to determine the best design.

Also, we have introduced a generic process for designing the structure for the electronic enclosure. This starts with looking at previous designs, determining the forces on the structure, and continues on to determining the factor of safety in our design.

From there, we looked at some examples that illustrate common problems in designing the structure. We finished with a short section on additional complications and considerations to be noted which serves as an introduction to Chap. 4.

References

Again, this chapter has been a review of structural considerations as they relate to structures encountered in the design of electronic enclosures. The reader may have many other sources of information, but the main ones I have used (over the years) are:

1. Roark RJ, Young WC (1975) Formulas for stress and strain. McGraw-Hill Book Co., New York
2. Byars EF, Snyder RD (1969) Engineering mechanics of deformable bodies. International Textbook Co., Scranton
3. Design guide to the selection and application of EMI shielding materials. TECKNIT, EMI Shielding Products (1991)
4. Injection Molding magazine, May 1998 issue, R. Cramer of Dow Materials Engineering Center

Chapter 4
Materials and Processes

Now that we have the structural foundation for the design, we'll actually start this chapter with a "return to basics." We've already touched upon the need to define and then conform to the product specification, but now we'll return to cost considerations of the design. With that reestablishment of this design "touchstone," we'll continue on with more "building blocks" that will be available to the designer to determine the best materials and processes for their enclosure parts. The choice of material and process for the individual parts that make up the assembly will get the designer also thinking about the assembly and servicing of the product (which is taken up Chap. 6).

4.1 Cost Versus Time Versus Specification

This chapter will start with a return to the basic consideration of the design, and that is an emphasis on *cost* being the deciding factor (ultimately) in the decision to make one choice over another in the design process.

A designer of electronic enclosures faces a certain "practicality" in their design in that the design must be produced on a scale that assures financial success for the owners of the company. There would be certain designs that would be considered "one-offs," where cost considerations are less important, but I'd like to address those designs that will produce assemblies (parts) that are at the very minimum, in the hundreds. I have worked at an experimental laboratory where only *one* assembly was to be produced, but again, I will not be addressing that case. Cost can even be extremely important in the case of a "one-off," such as a space satellite, but the cost of failure could then dominate the design rationale. This is also true in matters of safety or public health.

Let's further explore the above *cost* emphasis on design. There are cases where prototypes required for the final design need to be developed. These "prototypes" are

T. Serksnis, *Designing Electronic Product Enclosures*,
https://doi.org/10.1007/978-3-319-69395-8_4

certainly less cost-sensitive, as it is *time* that is usually the critical factor here. However, even though the prototype itself may not have a cost-sensitivity, the *overall* project cost is impacted in the sense that cost is sacrificed for speed *just* in the prototype portion of the project, as that time saved (by the "high-cost" prototype) results in the product being tested and approved for production in a shorter length of time, which usually translates into an *overall* lower cost (for the project).

Let me give an example where a certain aspect of the design is originally thought to be the *most* important, but it is really *cost* that turns out to be the #1 consideration. If a corporation chooses "aesthetics," that is, how a product looks and feels to the customer, as the #1 consideration, here is how that "plays out" in the marketplace. What is being decided by choosing "aesthetics" is actually a choice saying that these products will *sell more* with that look. So, the product development team's investment in "aesthetics" will actually result in increased profit to the corporation (over a product with "lesser" emphasis on aesthetics).

So, when I say *cost* in the above paragraphs, that can be also thought of as *profitability* or (increased margin), that is, lower cost = higher profits.

Time plays into this "cost picture" very much. The "time-to-market" can be a *huge* driver in product development. That is, if a certain product isn't released in some specific time frame (such as the spring planting season or the electronic show before the holidays), that can mean a huge difference to the total sales of the product. So, *coupled* with cost is the aspect of time. This leads to certain scenarios that are likely to play out in the life cycle of the product as:

1. Emphasis on *time* in material/process/manufacturability choice for the early stages of the development process
2. A "high-production" and cost-reduced product release can come occur in the later stages of the development process

All of this really still goes back to *cost* because it could have been determined (by the project management) that the overall cost is minimized by a "two-stage" product release (above). The *overall* sales, from the beginning of product release, to the end of product life, will be increased by this methodology. The concept of tooling needed for the project, and at what stage it is required, was explored in the section on Engineering Economy in Chap. 1.

Cost can also be broken down into several time frames, such as:

1. Development cost (until first shipment to customer)
2. Ongoing production cost of the product: materials/assembly/overhead
3. Service and warranty costs after production
4. End-of-life costs such as recycling

All of the costs *added together* make up the *total* cost – so minimizing cost in only one product phase doesn't minimize the *total* cost.

"Cost" is not only related to the cost of the individual part or assembly but also refers to the development (design) cost.

Another example where cost is still the #1 driver of the project is a project where *weight* needs to be minimized for the product to succeed. This is rationalized by the following logic (for this made-up scenario):

1. The specification of the product clearly calls out the:

   - Time required for the project delivery (expected)
   - Cost of product
   - Weight target of product (difficult to achieve)

2. Product is designed. Iteration #1 results in weight target exceeded.
3. Design is iterated; iteration #2 results in (slightly) exceeded weight target.
4. Time allotted to deliver product has been exceeded at this point.
5. Decision is made (by project management) to either:

A. Accept iteration #2 (deviate from original specification)
B. Move on to iteration #3, with a specified length of time needed for completion and notation that original delivery time has been exceeded

The above problem has its "roots" in weight minimization, but the solution is actually a matter of time (with time equating to cost). It's the cost of the project budget "overrun" that needs to be balanced with the need of product shipment.

So, again, as time is related to cost, the product designer must have these two related project aspects (time and cost) at the forefront of their design "mind space." Those two, plus "conformance" (meet or exceeds) to specification, make for an integrated approach to successful design.

Designers, if given any problem/challenge, must *always* be asking:

1. What is the acceptance criterion for the design? (How do I know I've been a success?) This usually is in the form of a specification, which may be formal or informal. The design should be working to formalize the acceptance criterion so that this is completely transparent to the project team.
2. What is the budget for the design in terms of dollars?
3. What is the project schedule for individual parts, as it relates to the entire product, and what is the "critical path" of the schedule? If the time estimated to complete the task is too short (not enough time left), other solutions such as getting more resources must be suggested as soon as known. The detail of the schedule should be such that every time-intensive activity is noted, including design reviews needed to move forward and potential issue resolving time (second iterations of design) needed.

all of the above is so important to the choice of:

- Materials of the individual parts.
- Process needed to produce the above parts.
- Assembly procedure needed to assemble above parts.
- Testing procedure needed to test above parts and assemblies.
- Quality control procedures in place to assure parts and assemblies are produced and assembled to specifications.
- Service (expected or unexpected) requirements are met.

that this will bear repeating over and over in Chaps. 4 and 5, so I'll just put the code "Cost (Chpt4)" in the text (the reader can just refer back to this general discussion as a refresher if needed).

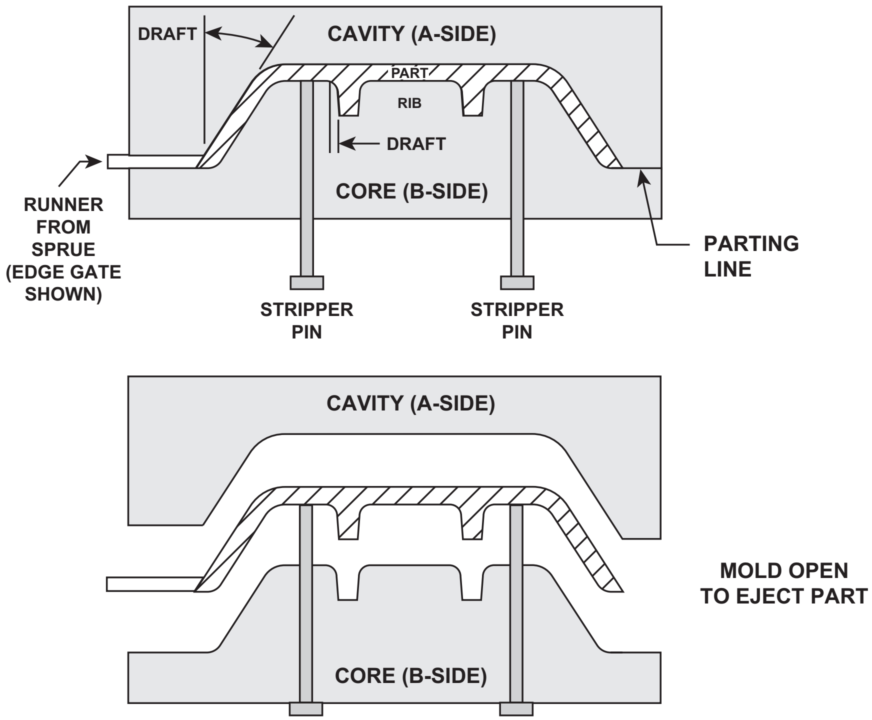


Fig. 4.1 Injection molding – mold schematic

4.2 The Designer's Mind Space

The designer has to "think ahead." When faced with designing an electronic enclosure, here are some things that go on in the mind of a designer, hopefully, all at the same time (Cost (Chpt4)). I consider these the following questions to be "ever-present" in the designer's head, which is why I use the term "designer's mind space" to describe these ever-present questions:

- How big?
- How many parts are needed to accomplish purpose?
- Has this (or a slight variation) been done before? Here, or at another company? How has the product purpose been accomplished by the competition?
- What is the "user interface," that is, how will the customer use this product (buttons/displays/lights/doors/connections for power, input, and output)?
- I am designing this portion of the product, what are the other portions that I am not (directly) responsible for?
- How quickly can I present some ideas that will solve the problem? How quickly can I prototype these ideas to check out the feasibility of an idea? Who else can I brainstorm with to critique these ideas?

- Once the idea has been reviewed and the prototype seems to work, what parts of the design are:
- The most risky (may not work as intended)?
- The most simple?
- The longest lead items for a preproduction run of parts, that is, what are the parts that are in the "critical path" of project completion?

For the prototype, how close is it to the production version? What testing will determine whether the prototype "succeeds" or "fails," and are several rounds of prototyping required (each round perhaps nearer to the production version)? How many prototypes does the project team need? And when?

How will I convey project progress or issues with the design to the rest of the design team? Who needs to be there for a design review?

4.3 Materials and Process Choice

Once a designer has designed a part, the designer must determine the "best" Cost (Chpt4) way for that part to be produced. The general items to be determined for *each* part are:

- Material of the part.
- Finish required for the part (see next section).
- Dimensional accuracy needed for the part.
- Process by which that part will be produced (perhaps one process for early needs, prototyping, and preproduction of parts and a different process for mature production of the parts).
- Quantity needed of the part (say, per quarter, per month, per year).
- Second operations needed for the part (beyond finishing).
- Cost requirements for the part.
- Can this part be combined with another part in the design? Essentially, what needs to be determined is whether a single (combined) part can fulfill the functionality of the separate parts (Cost (Chpt4)).
- Can the part be made symmetrical (for assembly ease)? Should the part that is *almost* symmetrical be made a more obvious nonsymmetrical part? These two questions deal with the assembly of this part and the chances of being assembled in an incorrect way. Holes or notches (superfluous) can be added to the part solely for the purpose of making that part symmetrical.

Considerations for determining material selection for a part:

The designer should choose a material that will satisfy (meet or exceed):

1. Strength requirements
2. Weight requirements
3. Reliability requirements
4. Regulatory requirements
5. Safety requirements

6. Thermal requirements
7. Shielding requirements (EMI/RFI)
8. Compatibility requirements for metals (galvanic corrosion)
9. Elastic requirements (durometer)
10. Conductive (or insulating) requirements
11. Opaqueness requirements
12. Wear requirements
13. Aesthetical requirements (touch, visual)
14. Acoustical requirements
15. Ultraviolet (UV) transmission and resistance requirements

Let's go thru a few examples and see how the 15 requirements above get determined (Cost (Chpt4)).

Example 1 Cell Phone (Outer) Case
For the choice of material, two major candidates come to mind; this would be either a metal or a plastic. Either can fulfill the 15 requirements, with these notations:

1. Metal will provide adequate EMI shielding but may be difficult to fabricate. The case needs to be smooth and elegant, which is expensive for a metal to accomplish – even a casting can require many "second operations" (such as machining or grinding) that can be labor-intensive.
2. Plastic (injection molded) will be adequate for alleviating the "smoothness" and "elegance" criteria but will need an additional EMI shielding scheme. Either the plastic case must be "metalized" or another nonaesthetic part needs to be added to the design just under the plastic case to function as an EMI shield. We also will need to investigate some safety issues with plastics (UL regulations for "flame class"). A plastic case as an exterior part could have much lower costs required for finishing (no painting required, at least that is the hope).
3. If weight (and size) is a factor (usually is with a cell phone), both metal and plastic should be examined more closely to see what may be better. Normally, ribs can be added to a plastic design to augment strength.
4. Thermal issues can be a factor in choice of material. A plastic will function as an insulator (keeping in the heat), while a metal will take the internal heat generation away to the ambient air resulting in a lower "case ambient" temperature. However, the metal case may feel too hot to the touch.

Calculating equivalent rigidity (or stiffness) of a material is shown quite succinctly in Ref. [1], where (temperature-dependent qualities):

T1 = cube root of ((E2/E1) × $T2^3$) = Thickness of Material 1
E1 = Flexural modulus of Material 1
E2 = Flexural modulus of Material 2
T2 = Thickness of Material 2

Let's compute the equivalent thickness of a plastic (say, SABIC Cycolac) to a 0.03 inch thick aluminum part:

$$\text{Tplastic} = \text{cube root of}\left((100/4)\times(0.03)^3\right) = 0.088\,\text{inch}$$

Let's compute the equivalent thickness of titanium to a 0.03 inch thick aluminum part:

$$\text{Titanium} = \text{cube root of}\left(\left(100/160\right)\times\left(0.03\right)^3\right) = 0.026\,\text{inch}$$

Now, if we look at strength (all of the above are "equivalent" strengths) to weight ratios for (looking at thickness to density ratio):

$$\text{Plastic} = 0.088/0.04 = 2.2\,\text{in}^2/\text{lb}$$

$$\text{Aluminum} = 0.030/0.10 = 0.3\,\text{in}^2/\text{lb}$$

$$\text{Titanium} = 0.026/0.16 = 0.16\,\text{in}^2/\text{lb}$$

Therefore, if weight (for equivalent strength) is an issue, titanium would be a much better choice (than aluminum or plastic). This is why titanium is extensively used in aircraft (Cost (Chpt4)); however, titanium has some inherent fabrication difficulties which make it very expensive as a choice for an electronic enclosure.

Discussion on molding plastics is in a following subchapter.

No decision will be made here of using "metal vs. plastic" for the exterior case of the enclosure. Enough ambiguities have been raised as to warrant a much more in-depth analysis, and we need to move on to another example of material choice. The Apple 5s phone case was made of (machined) aluminum, while the later released Apple 5c phone case was made of plastic. The plastic was made EMI compliant with the addition of a metalized coating in some areas and metal shields in other areas. The plastic version was thought to "bend" in the shirt pocket much more easily, but not enough to stub sales. Machined aluminum was a much "sooner to market" choice over molded plastic, as long lead time tooling was not required. Also, changes can be made much more adroitly with a machined piece than a molded part due to the longer time needed to modify the tool and test the new change. Again, each design will likely be unique to material and process choice – this is an example of something the mechanical engineer (working with other teams in the corporation) can make to the overall product design.

The optimum choice between plastics and die castings requires careful analysis of all product requirements.

Aluminum, magnesium, zinc, and zinc-aluminum (ZA) die castings are often preferred over plastics in electronic enclosures where strength, stiffness, and minimum packaging space are required. They often eliminate the need for inserts to received threaded fasteners. Their thermal conductivity often eliminates the need for cooling fans, which is essential in battery-operated portable electronic equipment. Die castings are also preferred over plastics where strength and rigidity are required and for medium to large size decorative components operating at elevated temperatures.

EMI and RFI (electromagnetic interference and radio-frequency interference) shieldings are inherent with die castings as they are metal. Plastic parts need a layer of metal shielding to provide EMI/RFI compliance. These shielding additions for plastic parts (painting, coating, resin fillers, metallic barriers, multilayered electroless nickel plating) can have performance problems and quality control issues.

Aluminum die castings are frequently chosen over plastics in designs that are subject to continuous pressure, particularly at elevated temperatures, and hand tools such as drills that require minimum weight, rigidity, and good surface quality. Magnesium die castings are frequently chosen in applications that require minimum weight combined with strength, stiffness, and minimum packaging space. Components for high-speed printers, which require rigidity at minimum weight; cases requiring mounting features, high-quality surface, and impact resistance; and decorative trim pieces are frequently produced by magnesium die casting.

Plastic components that are subjected to continuous loads, such as a part being used to environmentally seal, often require support from metal stampings to develop stiffness and creep resistance.

Also, it should be noted that even a "simple" material such as aluminum is much more complicated to actually specify in an engineering drawing. Many grades and alloys of aluminums exist, either "commonly" or "exotically," and this text is not going to address that complication, only to say that much attention is deserved to actually specify the specific "grade" of the material. Picking one grade over another is a function of that particular grade's ability to (Cost (Chpt4)):

1. Possess the 14 characteristics (stated above) of the design.
2. Be available to any of the supply chain members for meeting delivery times.
3. Be fabricated in a repeatable manner with specified quality control measures.

For example, if I wanted a part to be made of stainless steel, items to be considered would be:

1. Choice between chromium nickel stainless steels (austenitic) and straight chromium stainless steels (martensitic). Chromium nickel stainless steels are Types 20X and Types 3XX. For example, Type 302 is (from Ref. [2]):

   - The basic 18% Cr. 8% Ni, analysis, possessing excellent corrosion resistance to many organic and inorganic acids, and their salts at ordinary temperature.
   - Has good resistance to oxidation at elevated temperatures.
   - Can be readily fabricated by all methods usually employed with carbon steels.
   - Cr-Ni grades are nonmagnetic in the fully annealed condition and cannot be hardened by conventional heat treatment.

   In Ref. [2], Tables of Information (for the various grades of stainless steel): chemical composition, physical data, and the mechanical properties (both in the annealed and heat-treated states) are shown.
2. *Availability* must be considered for the candidates (choices) of material. In this example for stainless steel, by checking a reference such as Ref. [3], Type 302 *is not readily* available. Types 304, 309, 316, and others are available in stock (from Ryerson, a large resource of stainless steel stock). For example, Type 316 (cold rolled, annealed, pickled, 2B and 3 finish. Spec: QQ-S-766), ASTM-A240, is available in 16 gauge (0.060 thick) × 30 inch × 96 inch size stainless steel sheet.

3. Material choice should be made with fabrication technique in mind. If the part is envisioned to be turned on a spindle machine (lathe or mill), then a free-machining grade needs to be considered. If the part is to be welded, various grades may or may not be very weldable.
4. As usual, information about the material choice can be utilized using experience from:

   - Your codesigners within your own group (or other corporate resources),
   - Your supply chain fabricators

Once the material choice is made, it must be fully specified, that is, specified so that it will be unambiguous on the part specification. Materials and finishes are usually specified to some standard such as ASTM, MIL-standard (US government), or international standards such as ISO/IEC. There must also be in place some methodology of assuring (thru standard quality control procedures) that the material specified is the material being fabricated into the final part.

Example 2 Cover for a LED
Let's take another example of a material choice and the "thought process" that one would go thru to make a rational choice among candidate materials.

How about the need for a clear (optically transparent) part that will cover an LED? This part is envisioned to be flat and not needing much structural strength, basically supporting its own weight and preventing the user from "poking" the LED with their finger or a pencil. Let's name the part "LED *window*" for now. The piece will "seal off" the LED (from moisture) and is not generally replaceable (must last the product lifetime without being serviced).

Immediate questions that should come to the designer's mind are (Cost (Chpt4)):

1. How many are to be produced, what is the schedule for part production (prototype/preproduction/production), and at what general cost? The cost is usually not specified up front in the design, that is, it may be something ambiguous such as "as cheap as possible." As the design proceeds, certain choices in the design may increase the cost of the part, so trade-offs with alternatives are usually helpful.
2. Will it be designed to fit into a recess or "stand out" from the enclosure? How far away will the window be from the LED? These are the general "geometry" issues of the design. What are the aestetic considerations of the window?
3. The light from the LED shines thru this part. Is there a need for the light (from the LED) to be "diffused" – what kind of look do we want aesthetically? How does this part look in the "overall" design? Is it in the user's view all the time or only occasionally? Is "clear" the right choice of color, or is there another color that is wanted (red/green/amber/blue)? What color is the light from the LED?
4. Go thru the 15 requirements for the material from the above characteristics. For example, how is the part (right now, a nonmetal) going to adversely affect the EMI shielding requirements? This could possibly lead to the new part being as small as possible to create a minimum hole for EMI.

5. How will the LED *window* be assembled to the enclosure? Can it be assembled without any extra hardware? Candidates for assembly may be the use of ultrasonics, tape, or adhesive to bond the piece into place.
6. Are there multiple (more than one) "windows" in the overall design? Look for commonality possibilities with these windows.
7. Material candidates (with some issues for that choice):
   - Lexan plastic: Molded or cut from sheet? If molded, can we see mold flow lines? If cut from sheet, it probably will be flat (no other geometric features), while molding allows a design feature to be added (such as an ultrasonic weld bead). How thick? Is there an "anti-scratch" or "antiglare" requirement (and how would that be solved?)? If molded, can the *window* be assembled to the enclosure at the enclosure fabricator? Plastic will have some safety considerations such as being a burn hazard or having sharp edges.
   - Glass: Hardest and toughest material candidate, probably the most expensive (Cost (Chpt4)).
   - Polyester film as part of a label: Usually under 0.010 inch thick. Label could incorporate other information on the enclosure including identifying what the LED functions are.
8. Present to the project team with whatever detail is warranted. This could be price/time estimates, prototypes, or sketches to base going forward with a design choice for material.

4.4 Finishes and Coatings

All of the choices made when selecting a material (previous selection) are directly "coupled" with the choice of finish for that material. Practically all engineered parts *need* a finish. There would be some exceptions to this, for example, a "sculpture" (artwork) or building façade that is intended to corrode (and have a "corroded" look). The designer will be specifying *both* a material *and* a finish to every part they design.

Finishes (including coatings in the broad sense) are required to:

1. Retard corrosion in storage (from fabricator, to assembler, to customer) or in final usage by the customer.
2. Provide anodic protection when metals are in contact with dissimilar metals. Basic to this, dissimilar metals in contact must have adequate protection against galvanic corrosion. This is accomplished by interposing inert material or that which is compatible to each. The table below lists similar metals by groups. Contact between a material of one group and another material of the same group shall be considered as similar. Conversely, a critical electrolytic stage is set (requiring only humidity as the agent) whenever materials of different groups are in intimate contact. (This is particularly disadvantageous when either magnesium or aluminum, unprotected, is in contact with any other metals of different groups (Table 4.1).)

Table 4.1 Material groups

Group I	Group II	Group III	Group IV
Magnesium alloys	Aluminum	Zinc	Copper
	Aluminum alloys	Cadmium	Copper alloys
	Zinc	Steel	Nickel
	Cadmium	Lead	Nickel alloys
	Tin	Tin	Chromium
	Stainless steel	Stainless steel	Stainless steel
			Gold
			Silver

Note that the uses of lead, cadmium, and, in fact, all finishing materials have very serious environmental concerns. Many of these materials are banned or limited by various legislative statutes and laws. Please see the RoHS requirements as an example of these international laws that limit the use of one or more of the above finishes.

3. Appearance (aesthetics).
4. In the case of bonded connections, the protective coating will actually be omitted (masked). For such areas, moisture entrance must be prevented by forced ventilation or adequate sealing.

Finishes are usually listed into three main types: (See Ref. [4, 5])

- Chemical: those finishes resulting from chemical reactions on the surface of the metal.
- Electroplated: those finishes consisting of a film or plate deposited on the base metal of electrolytic action.
- Organic: finishes consisting of an organic coating over a base material, applied usually by brushing, dipping, or spraying.

Coatings can be applied by:

- Sprayed metal: A thin layer of metal is sprayed onto the surface for several purposes. Examples are aluminum being used for corrosion and heat resistance or copper for electrical conductivity.
- Powder coating: A dry painting process in which powder particles are applied directly to the surface to be coated without the use of solvents or water. Either thermosetting or thermoplastic powders are used. Parts are electrostatically powder sprayed at room temperature and then heated above the melting point of the powder to attain a fused surface finish.
- Electrodepositing: A thin coating can be deposited electrically to improve appearance, increase electrical qualities, and increase resistance to wear, corrosion, or specific environments.
- Ceramic, cermet, and refractory: Fixed porcelain enamel frits and refractory materials are used as corrosion-resistant coatings and also for color appeal and decorative effect.

- Hot dipping: These coatings, used principally on steel, cast iron, and copper, provide corrosion resistance at low cost. Materials used are aluminum, zinc, lead, tin, and lead-tin.
- Immersion: These coatings can be applied to most ferrous and nonferrous metals, with a few exceptions. Materials used are nickel, tin, copper, gold, silver, and platinum. Examples of use are for conductivity, facilitation of soldering, and brazing.
- Diffusion: These coatings are produced by the application of heat while the base material is in contact with a powder or solution. Most diffusion coatings are intended to obtain hard and wear-resistant surfaces and to increase resistance to corrosion.
- Vapor deposited: This is depositing vaporized metal in a vacuum chamber, where it then condenses on all cool surfaces. Most metals and nonmetals can be used as base materials to be coated. Examples are mirrors and optical reflectors, metalized plastics, lens coatings, and instrument parts.
- Organic: These consist of alkyds, celluloses, epoxies, phenolics, silicones, vinyls, rubbers, and others.
- Chemical conversion: These are chemical coatings which react with the base metal to produce a surface structure that will improve paint bonding, corrosion resistance, decorative properties, and wear resistance. Phosphate, chromate, anodic, and oxide coatings are common.
- Rust prevention: These are oils, petroleum derivatives, and waxes that form a film which will resist attack, principally from industrial and marine atmospheres.

Finishes or coatings that will be applied to engineering materials are usually called out on the (part) documentation with a MIL *specification* (MIL SPEC) Cross Reference. This is mainly done because most (common) finishes already are standardized and calling out an existing specification:

1. Saves time in that standards already exist that are “universally” accepted.
2. Suppliers already have these processes in place to economically produce these finishes.
3. The finish can be checked (verified by the specifier) using acceptable, in-place quality control procedures.

For example, a chemical film for aluminum may be called out to comply with a chemical film per MIL-C-5541.

An example of a callout for engineering documentation for a material and finish is:

- Material: 16 Ga. (0.060) 1010 CRS (with CRS standing for cold rolled steel and the “1010” a shorthand for AISI M1010 Steel). AISI M1010 Steel is a low carbon, general purpose merchant quality steel, featuring economy plus formability and weldability.
- Finish: Zinc plate clear chromate per QQ-Z-325. Class 2, Type II (with QQ-Z-325 being a common MIL SPEC for zinc and the “class” and “type” specific choices for attributes such as minimum thickness).

One of the most extensive finishes for metals is paint. Painting can be very much a complicated process. Difficulties occur with:

- Surface preparation
- Color matching
- Identification and control of defects

Ref. [9] is included as further information.

The material and finish callout on the engineering documentation should be unambiguously stated. It is a good idea to see how your company usually calls out these common materials and finishes, check with the supplier as to how the callout fits in with their processes, and what the quality control procedures for "guaranteeing" the material and finish will be handled by both at the supplier and at incoming (to your facility) inspections. Sometimes this is handled with a material/finish "certification" that is supplied to the incoming inspection by the supplier.

4.5 Punching and Forming Metals

The basic processes by which metals are punched, notched, formed, and bent has changed in recent years. Old fabrication techniques like (non-CNC) lathes, milling machines, and drill presses have been relegated to "garage shops" or "quick-turn" prototype shops (of the past). Contemporary fabrication is done on CNC (computerized numerical controlled) multi-axis machines or high-speed strippet punch presses. Your CAD file is electronically transferred to the shop, the shop "converts" the file as input to their fabrication machine, and the machine creates the part (in specified quantity).

A strippet punch press takes a flat piece of stock and positions a rotating turret (pre-loaded) with round punches, rectangular punches (for cutting the periphery), and just about any shape punch (customized or already in the shop catalog), over that piece of stock. The table that the stock resides on moves in x and y, and the turret rotates to put the proper punch in place. A flat piece of metal can be completely punched out with a complex design in minutes. Specialized "punches" that punch and form louvers can also be programmed on the strippet. Tolerancing (which we will expand upon in the following section) can be very tightly controlled with CNC as there is no "manual" setting of dials, stops, or machine feeds/speeds.

Multi-axis spindle machines are commonplace in today's fabrication environment. The term "5-axis" is typically referring to the ability of a CNC machine to move a part or a tool on five different axes at the same time. 3-axis machining centers move a part in 2 directions (X and Y), and the tool moves up and down (Z). 5-axis machining centers can rotate on two additional rotary axes (A and B) which help the cutting tool approach the part from all directions.

As with all fabrication techniques, the more the designer is familiar with the machine and machining process, the better the design will be Cost (Chpt4).

I've included a section on Sheet Metal Practices in Appendix. These show very common practices of bending and punching metal that sheet metal fabricators use and are commonly found in corporate drafting standard manuals.

4.6 Molding Plastics

A designer of electronic enclosures must have solid knowledge of the plastic molding process and how to design plastic parts. Most engineering degrees do not place much emphasis on this skill, so it is likely attained and honed while on the job. There is much in the literature on the proper design of plastic parts, and I'll provide some good references on the subject, a lot of which come from the plastic suppliers (of raw pellets) themselves. The plastic suppliers themselves have learned a great deal over the years on the use of their resins, and it benefits everyone to share that experience. Also, Ref. [6], by Glenn L. Beall, can be considered a "bible" as Mr. Beall is a well-known expert in this field. I will be providing a list of the "top ten" guidelines for plastics design, but these will be just the highlights of an extensive list that each designer can add to.

The probable #1 capability of the plastic part designer is understanding the tooling that will used for their parts and having an understanding of what options are available with injection molding tooling. With an understanding of injection molding tooling, the following six concepts will help in the design of injection molded parts (see Ref. [7] for additional information):

(See Fig. 4.6)

1. The idea of draft needed to eject the part from the mold.
2. The location of the main gate (or "sprue") that will "inject" plastic into the mold. This gate location (and subsequent need of "degating") will be a large consideration for the cosmetics required for the part. Gating can be done at the edge or either the core (reverse gating) or cavity side of the mold.
3. The idea of "mold flow" needs to be well understood. The need for *radiused corners*, generally an *equal thickness* design, and *limitations on rib heights* are highlighted. As the melt cools, it turns from a viscous liquid into a semisolid and, eventually, into a solid part. It is more difficult to fill the areas of the part the furthest away from the part gate.
4. Stripper bar locations are shown, again, highlighting the cosmetic surface need.
5. If "undercuts" are required by the part, the tooling will show how this is to be achieved (and how much this can complicate the mold).
6. The mold "parting line" as shown in the tooling is a reflection of the part design and thus shows the difficulties with those designs.

The above tool design features are learned from experience. In all cases, the part design needs to be reviewed by the tool designer (usually resident or contracted by the molder), and the part designer should get assurances that their design is "moldable" in a straightforward manner. Both the part design and the tooling need serious review by the designer and the project management team, as mold tools have:

1. A large capital expense (K$)
2. Very long lead-times (they need weeks to complete)
3. Difficult (both in time and money) revision processes

One of the largest advantages of a molded plastic part is that it needs less second operations to become a finished part (as compared to a "like" metal part). Usually, the molded plastic part does not need cosmetic painting on the exterior. Most (customer visible) plastic parts end up with a molded-in texture on the exterior which is usually achieved by etching the mold with a "texture pattern." Note that this mold texture results in undercuts to the part (which is achieved by adding a small amount of draft to the part).

Some common second operations are needed to a molded part (these are operations done outside of the molding operation and usually done by the molder (or contracted out by the molder)):

1. Holes or cuts needed to the parts that were not deemed doable in the mold itself – sometimes holes are easier to be added by a second operation rather than tooled as part of the mold. Thus, drilling or tapping operations may be added.
2. Machining may be required to repair the "gate mark" if gate is in a cosmetic area. Gates may also be removed (by hand) if the gate area is not a cosmetic surface (and that surface doesn't require machining).
3. Inserts (metal, threaded fasteners) may be ultrasonically placed into the part (or these inserts can also be molded in).
4. EMI shielding can be applied to the plastic part. This takes all sorts of forms:
    - Painting
    - Plating
    - Bonding of metal shielding
5. Bonding operations (ultrasonic or adhesive) can fuse one or more molded parts together.
6. All sorts of decorating (silk-screening, painting) can be done. Some in-mold operations can be done to incorporate graphics in that manner.
7. All fixturing needed for any of the above operations need to be clearly identified, costed, and placed on an accountable time schedule.

All of the above second operations need to be clearly called out on the finished part documentation which would include any quality control acceptability criteria. These second operations can add to the piece price of a part in a very *significant* way, so they need to be a part of the total design process, with alternatives to that design clearly presented by the designer. The second operations need to be discussed in great depth with the molder to see that they are achievable in the most cost-effective manner.

Choice of plastic for the part: The designer must review all of the 15 characteristics previously listed (for *any* material) to decide what resin to choose. Creep data (long-term viscoelastic behavior) is also important for plastics. Some other unique aspects include:

1. There are many molding processes: Injection molding/blow molding/compression molding/thermoforming (pressure or vacuum forming)/reaction injection molding (RIM). I've been mainly addressing the injection molding process.
2. Snap-fits require materials with specific limits on stress vs. strain.

3. Data exists for the common choices of plastic with the plastic pellet suppliers (See Ref. [8]). These suppliers can also review the design and possibly indicate if a customized solution is needed for your application. The suppliers are a large reservoir of information on materials and molding.

As previously "promised," here are my top ten recommendations for proper plastic part design. Most designs can be analyzed with a mold-filling "program" that is resident in-house or at the molder. These programs take the CAD geometric data of the design, the proposed material, and determine an optimization process to properly fill the mold:

1. All attempts must be made to maintain a *uniform wall thickness*. Thicker areas will likely result in a cosmetic defect known as a "sink." Ribs with large draft can result in a thick wall section where the base of the rib meets the main wall (this can limit rib "height"). This is also a common occurrence with screw bosses where the boss base meets the main wall. Screw bosses also incur an additional complication as the insert in the boss requires a wall thickness needed for structural requirements. Where it seems that a larger (than nominal) wall thickness is needed – look to "core out" the large area with an added feature in the tool that will result in a (more) uniform wall thickness. Always think of the part in *three* dimensions. Commonly, the design is a series of 2D sections that are used to accomplish a purpose. However, plastic parts can have contours that result in curved areas that result in areas of nonuniform wall thickness.
2. *Radius* all transition areas for several reasons. The melt flow is easier with these radiused sections. Also, sharp corners can only be produced by mold tooling which, in itself, would be sharp. These sharp edges are difficult to maintain over the life of the tool. Inside radiused areas should "match" outside radiused areas, that is, inside radius + nominal wall thickness = outside radius (of part). The ratio of inside radius to wall thickness (R/T) should be as high as possible to reduce the stress in the cross-section, R/T > 0.75 is recommended. Some notes on plastic part drawings include a statement such as "Radius All corners 0.030 Radius or as Specified"; however, care must be taken as with any note intended to cover all occurrences on the drawing.
3. *Selection of tool maker/molder* is *critical* to overall satisfaction with the part. Other factors (besides "cost") enter into this selection, such as:

   - Quality of tool – selection of material and heat treatment of the tool.
   - Delivery schedule of tool – first article and production quantity parts.
   - Communication path openness – how well supplier can communicate with the part designer, the communication of suggestions about the part design, and any ongoing issues that may arise. Regularly scheduled milestone publication is essential. A face-to-face discussion can help communication, but the Internet can also be used effectively.
   - Total cost of part – includes delivery (molded/boxed/shipped), any fixturing required for the part, secondary operations, and quality control.
   - Supplier chosen from current approved suppliers – the cost of "qualifying" a new supplier must be considered. Also, problems with current approved suppliers are already known, while unapproved suppliers likely mean unknown problems.

4. Look to *reduce the amount of secondary operations* required for the part. Look at the trade-offs involved with tooling slides. Features in the part that can be produced by adding slides to the tool (or revolving inserts in the tool) offer a way to reduce second operations. However, these slides or revolving inserts make the tool more expensive and complicate the molding operation. For example, if a large thread is needed in the part, these can be formed within the tool by including a revolving portion of the tool (that "unthreads" to remove the part from the tool), thus eliminating a (secondary) threading operation (done outside of the tool). However, it may be less expensive to tap the threads as a secondary operation than to include the threads in a more complicated tool (that has "moving" parts). Certain holes in the part can be formed in the tooling by what is known as a "cross shutoff." This cross shutoff "pierces" a side wall with pieces matched on an angle. However, the negative to the cross shutoff is a "stepped" parting line in the tool that slightly complicates the tool. Again, discussions with the tool vendor/molder are invaluable for deciding on trade-off choice.
5. *Draft* should be as generous as possible, without compromising uniform wall thickness or the design. Zero draft is possible in some areas – please talk to the molder! (For example, texturing actually produces "undercuts" that don't need side pulls if the draft allowance allows the part to "spring" away.) How much draft that is required is a function of:

   - Material
   - Shrink
   - Part design need
   - Roughness of texture

   Minimum draft on ribs allows higher ribs while maintaining relatively uniform wall thickness where the rib meets the wall.
6. Be liberal with the amount of *reinforcing ribs* in the design. This is one of the advantages of using a molded plastic part in that part-strengthening ribs can be added with very little overhead to cost. These ribs increase stiffness and control melt flow. Patterns of ribs, such as circular and rectangular, should be explored. Connected ribs, to each other, or side walls can increase overall stiffness of the part.
7. Be careful of exactly where the "*weld lines*" will occur on the part. Weld lines occur where the material flows within the part and meets (itself) on the opposite sides of where the plastic originally enters the part (at the tool gate). These weld lines result in structurally weak areas of the part (as the material has cooled at this juncture of two meld paths). Also, the weld line shows up as an actual "line" on the exterior of the part resulting in an aesthetical issue that must be addressed.
8. Think of areas in the part design which will result in areas that produce a *very* thin section of the tool itself (or even a bent core pin). These thin tool sections can be difficult to maintain, and breakage can result to delay part molding. Always look to add "sections" to the mold which can be easily removed. These sections (*tool inserts*) can be utilized for either:

   - Easy maintenance
   - Easily producing another part variance, for example, a part with a hole and a part without a hole

For example, it is very common to put the part revision level on a tool insert so that, as the revision level changes, only the (small) insert needs to be modified.

9. Consider *adding features* into the design which will help align (or structurally help) a mating part. For example, adding a round recess in a part that can mate with a part that has a round positive pin can help the overall design of the mated pairing of these two parts.
10. Consider where the *mold stripper pins* will be placed, and "how many." The stripper pins will help eject the part from the mold after the part has (just about) solidified. However, they will usually leave a mark on the (hopefully) non-cosmetic side of the part. These locations should be reviewed by the designer to make sure they are optimally placed. For example, the stripper pins should not be placed where a gasket will be in the design (as the gasket surface will not be flat).
11. (Yes, the 11th listing in a top ten.) Search both the literature and look at other plastic parts to gain knowledge. Over the years, much "tribal knowledge" has been acquired in the areas of:

    - Snap-fit design
    - Fastening processes (assembly methods) and fasteners used for plastic parts
    - New material blends
    - In-mold decorating

The *general* plastic design process follows these six steps: Correct revision control of the documentation is assumed here – see Chap. 12 on documentation. Design review is broadly meant to include any and all people that should be on the review cycle for both the individual part and the overall project (should include in-house reviewers, contractors, and suppliers):

1. Part is designed. Design is reviewed.
2. Bids for tooling are placed. CAD files sent (as appropriate). Design is reviewed by tooling vendors and resin manufacturers. Any changes to design are again reviewed. Schedule for tool development and first article run are agreed to. Plan for first article acceptance is agreed to. All pricing for part known (including fixturing required) is agreed to.
3. Final design is approved; tooling purchase order is placed to a particular (and agreed to) revision level.
4. Tool maker inputs CAD file and adds correct shrink factor (parts will shrink out of the mold) to assure correct part geometry.
5. Meetings regularly scheduled to review project milestones. Updates are given to the project management. Any changes to part and/or time schedule are clearly broadcasted.
6. First article is produced and reviewed. Modifications considered including ramifications to project schedule. Preproduction run of parts scheduled as appropriate.

4.7 Casting Metals

Casting metals has a lot in common with the previous section on molding plastics; however, there are some clear distinctions. First of all, as in above section where there are actually quite a few processes for forming plastics, the same can be said for the casting process. There are many casting techniques. The casting techniques generally vary by:

- Metal cast
- Size range of part normally cast
- Tolerances expected to be held by process
- Cost of tooling
- Part price
- Surface finish expectation
- Minimum draft recommended
- Normal minimum section thickness
- Ordering quantity
- Normal lead time

The common casting techniques are described below (Ref. [10], and additionally in Ref. [11, 12]):

- Die casting: Molten metal is injected, under pressure, into hardened steel dies, often water cooled. Dies open and castings ejected.
- Permanent mold: Molten metal is gravity poured into cast iron molds, coated with ceramic mold wash. Cores can be metal, sand, sand shell, or other. Molds open and castings ejected. New LPPM method pressure pours with up to 15 psi.
- Investment (lost wax): Metal mold makes wax or plastic replica. These are sprued, then surrounded with investment material, baked out, and metal poured in resultant cavity. Mold is broken to remove castings.
- Plaster mold: Plaster slurry is poured onto pattern halves and allowed to set; then mold is removed from pattern, baked, and assembled, and metal is poured into resultant cavity. Molds are broken to remove castings.
- Ceramic mold: Ceramic slurry poured over cope and drag patterns, allowed to set, then molds removed from pattern, and baked (at 1800 °F), producing hard, stable molds. Molds assembled with or without cores and metal poured into resultant cavity. Molds are broken to remove castings.
- Graphite mold: Similar to ceramic mold, except graphite mold used instead. Core pins are usually steel.
- Resin shell mold: Resin-coated sand is poured onto hot metal patterns, curing into shell-like mold halves. These are removed from pattern, assembled with or without cores. Metal is poured into resultant cavities. Mold is broken to remove castings.
- Sand casting: Tempered sand is packed onto wood or metal pattern halves, removed from pattern, assembled with or without cores, and metal is poured into resultant cavities. Various core materials can be used. Molds broken to remove

Table 4.2 Table of casting techniques (from [6])

Technique	Metals	Size range	Tolerances (inch)	Surface finish (rms)
Die casting	Al/zinc/Mg	<2 ft^2	0.001–2	32–63
Permanent mold	Al/zinc/brass	Oz – 100 lbs.	0.015 basic	150–250
Investment	Most castable	Oz – 150 lbs.	0.003 basic	63–125
Plaster mold	Al/zinc/brass	<3 ft^2	0.005 basic	63–125
Ceramic mold	Most castable	<350 lbs.	0.005 basic	80–125
Graphite mold	Zinc or zinc-Al	Oz – 10 lbs.	0.005 basic	63–125
Resin shell mold	Most castable	<4 ft^2	0.008–10 basic	125–350
Sand casting	Most castable	Oz and up	0.03 basic	150–700
Metal injection mold	Ferrous	Under ¼ lbs.	0.003 basic	45
Powder metal	Ferrous/SS/Al	20 in^2	0.004 basic	16–90

castings. Specialized binders now in use can improve tolerances and surface finish.

- Metal injection molding: Very fine metal powder combined with binder material is injected into die. Part is ejected, the binder melted or dissolved, and vacuum sintered, resulting in 94–99% theoretical density.
- Powder metal: Metal powder is compressed in die barrel between moving upper and lower punches. Lower punch ejects part which is then sintered and sized if close tolerance is required.

The Table 4.2 below summarizes the above differences for the various casting techniques.

Casted parts are *generally* designed with the similar constraints of injected molded parts, that is, constant wall thickness and radii required at all corners, but there are some important differences. As most casting materials are more brittle, they are more prone to developing stress in sharp corners, so larger radii are needed. Sink that occurs with injection molding is not a huge problem with castings; however, parts still need to be cored to keep a constant wall (and save weight).

The casting process, although similar to injection molding, results in unique problems that must be addressed:

A. Porosity Castings are not homogeneous. The "skin" of castings (the outside layer, perhaps 0.020 inches thick) is relatively smooth and continuous. This results because the mold surface itself is relatively cool as compared to the "molten" flow of metal, and a skin forms on this outside edge of material that is dense. Right below this skin can be an area of air (gases) trapped within the metal that is relatively "porous." If one takes a machine cut on the outside surface, an area of porosity (uneven metal) can be exposed. Machine cuts are sometimes taken on the outside of a cast part, as the tolerance on any particular dimension can be quite high. For example, an outside dimension that is nominally designed to 4.000 inch may be cast at +/−0.010 inch. Thus, if the casting ends up at 4.010 and 4.000 inch is needed for the design, 0.010 may be needed to machine off of the casting. Machining 0.010 off of the part may take away the hard skin, revealing the underlying porosity.

Also, an “as-cast” surface may not be “smooth” enough for the design if the design needs a low surface roughness (as for a surface being used for a pressure seal). If the “as-cast” surface roughness is 500 μ-inch and a 32 μ-inch surface (for example) is needed to provide a sealing surface (with an O-ring), the surface in question would require machining.

Impregnation is sometimes used to develop pressure tightness and smooth surfaces in die castings. Systems employing anaerobics and methacrylates are currently used when impregnation is specified. These systems produce sealed castings ready for pressure testing.

Porosity, in castings, also creates a serious quality control issue. As porosity can be the result of the casting process (proper settings of temperature and pressure, plus feedstock material consistency), porosity can occur in a part at some point even though some parts in the batch were without porosity. If porosity occurs in a part, at a critical cross-section under load, the part may fail. Thus, porosity must be screened for, and the process must be controlled and monitored. If the part was a “mission-critical” part involved in safety or of a national defense need, the part would need some methodology to be employed to assure the part strength.

B. Secondary Operations Required Castings usually require some “large” operations after the casting process to make them ready for final assembly. These operations can be divided into machining and decorative/corrosion preventative coatings.

Similar to an injection molded part, the area where the material “enters” the part (at the “sprue”) must be removed. That is, a machining operation is required to remove the vestige of material that remains with the part, from the injection sprue. This machining operation may be as simple as hand clippers to remove the vestige but may be more elaborate if this vestige is on a cosmetically visible surface. Unlike an injection molded part, the casting process usually also involves a “trim die” to remove material at the die parting line that either gets out as “flash” or is intentionally allowed out to help fill the entire part with solid metal. This “trim die” can consist of a press plus fixture to control the trimming process or be rather “uncontrolled” (such as a grinding wheel done “by hand”). “Flash” occurs due to tiny mismatch between the upper die and lower die. Where the upper and lower die “come together,” the pressure of the casting process forces some small amount (0.001–0.005 inch) of material to be “squirted out,” and as the dies get more used, this situation gets worse. A trim die (and fixture) can cost thousands of dollars to avoid trimming by hand. So, this is another cost/time decision to be made substantiating any tooling expenditure.

A variety of surface treatment systems can be applied to die castings to provide decorative effects, corrosion protection, or increased hardness and wear resistance. It is recommended to seek specific information on surface treatments from suppliers and references, as these vary by cast material and purpose of the surface treatment. For example, for cast aluminums:

- Decorative finishes can be achieved by paint, polish/epoxy, plating, and powder coating.
- Environmental corrosion barriers can be achieved by paint, anodizing, chromate, and iridite.

- Fill and seal surface/subsurface can be achieved by impregnation.
- Improved wear resistance can be achieved by hard anodization.

No designer of castings should be without the reference material of Ref. [13]. The NADCA product specification standards for die castings is a "bible" showing required background information including:

- Process and material selection
- Tooling for die casting
- Alloy data
- Engineering and design (specific to die castings)
- Quality assurance
- Commercial practices

4.8 Dimensioning/Tolerancing

4.8.1 Choice of "Nominal Dimension"

This may be an unusual section in this book, but I believe it will help greatly in the journey to designing great parts. I'd like to start with some basics about why we choose "the numbers" like we do, and how that choice of numbers leads to a design. How the designer ends up dimensioning a part can lead to years of trouble-free assembly and very happy customers. If this is not done correctly, the parts are in a rather constant state of "not fitting" and "out of tolerance," and assembly line stoppage will occur. In some sense, this section of the book is a precursor to Chap. 6 on assembly and serviceability, as properly dimensioned and toleranced parts will lead to very smooth manufacturing assembly of those parts.

Some comments about the English system of units vs. metric system of units are also appropriate (see separate discussion). I even want to start this discussion with how I actually started design "parts" (which were actually tooling fixtures and jigs to perform machining or welding of parts). This was before CNC'd parts, computers, and CAD were a part of the "standard toolbox." We actually designed parts with *fractions* in mind. That is, we tried to design parts using the common markings of a "ruler" (or more correctly, a scale). A scale is divided (commonly) into marks on each 1/32th of an inch, that is, there is a mark at every 0.03125 inch. There would also be marks noting 1/16th of an inch (0.0625 inch), the 1/8th inch (0.125 inch), ¼ inch (0.25 inch), and ½ inch (0.50 inch) spacings. Thus, our designs could "shoot for" numbers like:

- 3.00
- 3.50
- 3.625 (3.62)
- 3.6875 (3.68)
- 3.71875 (3.72)

Note that these numbers get more "uneven" in the sense that they are increasing by some smaller fractional amount (1/2, 1/8, 1/16, and 1/32). Also note the "rounding" of the numbers to *even* numbers. Why choose an even number? Well, if the overall part was chosen to be 3.68 inch, if one wanted to place a hole half way across the part, that hole would be placed at 1.84 inch. If the overall part was chosen to be 3.69 inch, then the hole that is half way across would be at 1.845 inch, but this 3-place dimension "implies" a "tighter" tolerance than is actually required (more on this later in the section).

Also note that this scale with the fractional markings actually had a scale (on the other side) that had graduations in 0.020 inch increments. So, parts could have been designed in increments of "tenths," such as 3.120 inch, but again, fractions were more commonplace.

This brings up a discussion on *nominal* or "evenness." Designers are more apt to choose even numbers, and by that, given the choice between:

- 3.00
- 3.10
- 3.25
- 3.26
- 3.27

I would say that a designer would choose them in the order above (top to bottom), without consideration to size, *just* by the numbers. I believe that 3.25 could be chosen over 3.26 because 3.25 is 3 ¼. 3.26 does have an advantage in that it is an even number (easily divided in two). 3.27 "suffers" in that it is not a common fraction and an odd number. Above discussion assumes that one wants the numbers at two decimal places.

4.8.2 United States Engineering Units Versus International System of Units

My comments about dimensioning/tolerances are useful in either system of units (inches or millimeters). In the United States, we may start a design thinking that 3.000 inches is nominal or "the place to start." In Europe, the "same" place to start might be 75 millimeters (which is equal to 2.953 inches).

If a design starts in the United States at 3.000 inches, those drawings are exactly *converted* to $3 \times 25.4 = 76.2$ millimeters if the product is to be manufactured in Europe. I'm trying to make a distinction between "conversion factor" (inches to millimeters) and "designer origin mindset." So, if I was a designer in the United States (with a US education), who was designing a part for a European firm, I would probably create a design that had its start with an "even" millimeter nominal dimension, so I would start with 75 millimeters as that size (instead of choosing 3.000 inch). My choices in that general range of numbers would be among:

- 70 millimeters
- 75 millimeters
- 80 millimeters

4.8.3 The World Before and After CNC-Controlled Machine Tools

With machine tools before the computer was added to them, a machinist would "dial in" by hand a reading on a dial and then "make the cut." For example, on a lathe turning machine, if a 2.000 inch diameter rod (2.000 nominal, with a tolerance of +/−0.002 inch) was to be the "final" diameter, an initial cut would be made on the rod; a measurement taken (physically) of the part might be, say, 2.015 inch diameter (initial cut would always be made so that it resulted in the part being slightly larger, in a sense, "sneaking-up" on the wanted dimension). The tool on the lathe would then be "zeroed" on the part diameter, and then the dial would be moved to 0.0075. A cut, 0.0075 deep on the part, would theoretically take that part down to 2.000 inches. If another measurement were to be taken on the part, it would likely measure close to 2.000 inches diameter. Of course, the complication of adding knurling, plating, or paint is another factor to consider, but let's keep it simple for now and not consider other finishing operations. After the part was removed from the lathe, it would be inspected. If the part was between 1.998 and 2.002 inches, it would be "passed" as correct and meeting specification. This general procedure, of zeroing, dialing, cutting, and inspecting, produced "industry acceptable" standards for attaining parts (within a tolerance of +/−0.002 inch) in a productive manner. That is, the machines, machinists, and inspection processes provided parts in a "reasonable manner." If the tolerances were made tighter, say, +/−0.001 inch, the parts would be more expensive due to either of the machine, machinist, or inspection process being more difficult, resulting in a slower time to produce acceptable parts. Also, asking for parts with looser tolerances, say +/−0.003 inch would *not necessarily* result in less expensive parts, as +/−0.002 inch would be "standard practice." Of course, machine shops would enjoy looser tolerances as their rejection rates would go down, but these savings were likely not passed on to the customer. Again, I'm making an argument here as to specify tolerances in cooperation with your suppliers to find a balance between what the part needs and what can be reasonably (or typically) produced.

Note that (see Ref. [14], Machinery's Handbook) a turning machining operation, under normal conditions, would produce work in the range of Grades 7–13. For a 2.000 inch diameter, a tolerance of +/−0.002 inch is reasonable (but difficult). From Ref. [9], "normal consistent accuracy" would be +/−0.005 inch.

Now, with CNC-controlled machines, part costs have been reduced. This is due to several factors:

1. Total time is reduced to produce part. Once the machine is programmed, the machine will move according to that program, basically eliminating the "machinist." So, no "dial moving" is needed. (Of course, a machinist is still needed to "oversee" the operation in a general sense.)
2. Less inspection is required as the machine has eliminated "operator error." Inspection is still needed of course.
3. The "machine" can change tools, speeds/feeds, axis of machining, and just about any machining operation in a machine-controlled manner. This is faster than can be done with a human operator.

4. Small changes to the part design are very easy to accomplish – a quick revision to the program, and the new revision parts are quickly produced. Even extensive changes still only mean relatively simple program updates.
5. Machining "factors" can be built into programs to *adjust* for any machining situation that might occur. For example, if a punch results in a hole being out of tolerance in an x-y coordinate, the program can be "adjusted" to bring that hole position into tolerance.

Flat metal punching by a CNC-controlled machine (a "strippet") allows x-y table movements and tool changes via head rotation. This allows reduced set-up time, elimination of fixturing, and machine changes at tremendous time savings over the previous generation of machine tools.

As input to a CNC-controlled machine is a computer program, parts are the result of only digital data that is transferred to those machining programs. This allows extremely quick (and "error-free") transfer of "design intent" to "finished part."

4.8.4 Overall Size and the Design

To continue the general topic of dimensioning and how it relates to design, Some constraints will usually be the start of a design. Here are some examples:

The general assumptions for the examples are:

Minimum size and weight, Cost (Chpt4), are required in the design.
Minimum clearance between one object and another is 0.010 inch. This obviously varies in a real design and depends on the objects and environment that the enclosure will be used.
Nominal thickness of enclosure is 0.050 ("thickness tolerance" will be discussed separately), but the thickness will simply be at 0.050 for now.

State-of-the-art designs may require everything from custom sheet metal gauges to "fixtured" solutions that include "go/no-go gauges" that essentially allow parts to be constructed with *no* (or,*very* little) tolerances. The examples will not consider these types of situations but, rather, more "normal" design circumstances. Again, given an unlimited amount of time and money, just about any exception can be taken with the examples. Designs usually proceed with one of the following two types of thinking: See Fig. 4.2.

"Size-goaled" Design: An enclosure must be smaller than 3.5 inches. This is because the previous product was 4.0 inches (or the competing product is at 3.6 inches). In this case, we start with an overall enclosure size of 3.5 inches. If a single component that is 3.0 inches long is to be put into our enclosure, we immediately know that the "nominal" distance between the inside of the wall and the component will be: 3.5 minus 3.0 minus (2 times .050) divided by 2. This equals 0.2 inch. We have "accepted" the 3.5 inch outside dimension and are "accepting" the 0.2 inch clearance between wall and component.

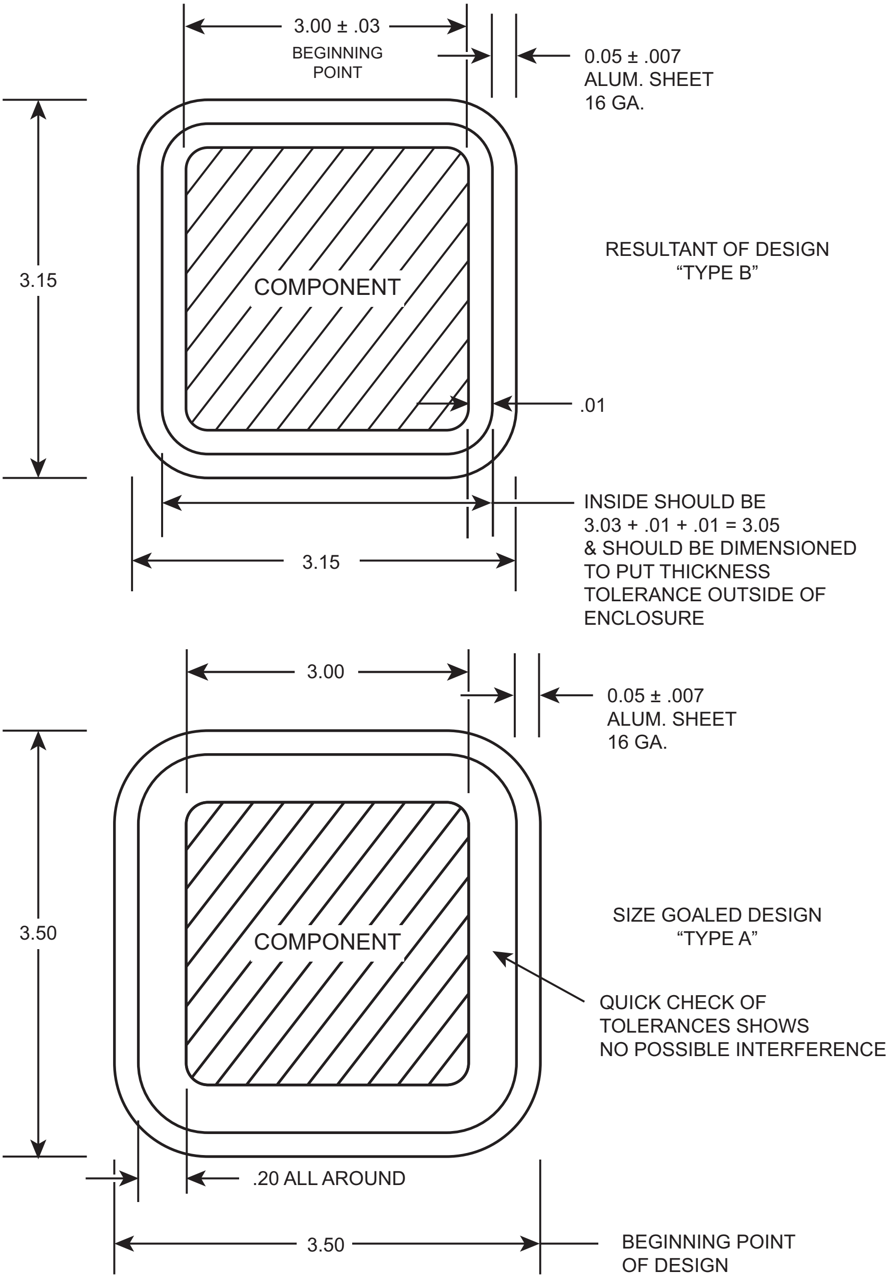


Fig. 4.2 Overall size and the design given

"Resultant of Given" Design: A single component that is 3.0 inches long is to be put into an enclosure. That "sets" the (minimum) size of the enclosure at 3.0 + clearance per side (0.010, estimated for now) + thickness of both walls of the enclosure (in just the "x" direction); thus the overall size of the enclosure is:

$$3.0 + 0.010 + 0.010 + 0.050 + 0.050 = 3.120\,\text{inches}$$

However, we haven't stated the tolerance on the "3.0 inch component." Let's say that this component's *maximum* size is actually 3.03 inches. That takes the minimum size of the outside of the enclosure to 3.12 + 0.03 = 3.15 inches.

Let's take a look (more closely) at both the clearance and thickness numbers and investigate what the tolerance actually is on those numbers.

There will actually be a tolerance on the thickness of the enclosure. Let's investigate this for various materials:

Sheet metal thickness: Sheet metal is normally available in standard gauges that have standard tolerances on thickness. 16 gauge aluminum sheet, which is "nominally" 0.050 inches thick, has a +/−0.007 inch tolerance on its thickness (5050 alum, 100 inch stock width) per [10]. It's been my experience that the thickness will "always" come in on the "thin side" of the tolerance (but could come in on the "thick side"). General deburring of a plate (before punching) will take 0.001–0.002 inches off of the thickness, while some plating will add back the 0.001–0.002 inches. The designer should plan on a nominal gauge thickness (for most designs) unless it's actually warranted taking a specific thickness tolerance into consideration. Note that clearances should be checked at both their maximum and minimum conditions to ensure proper fit both in assembly and customer use.

So, designs usually proceed as either the Size-goaled or "Resultant of Givens" type of design. The Size-goaled design may result in some saving of time, however, the Resultant of Givens design usually is a better methodology for getting to the *minimum-sized design*.

4.8.5 Theory of Tolerancing: The Need

Tolerancing on part dimensions is needed as parts cannot be produced *perfectly*. Manufacturing techniques do not produce perfect parts. This is probably obvious. The actual amount of tolerance is based on a few (probably competing) factors:

1. Cost (larger tolerances are less expensive to manufacture).
2. Like parts (the same part) need to be *interchangeable* – all parts made to the tolerances must work.
3. Parts that mate with other parts must do that with all parts at the extremes of their tolerances.

So, the "default procedure" for specifying a tolerance is to:

1. Choose the tolerance for the reasonable or most common manufacturing process. For example, if the part is a 0.25 inch diameter part, say 2.00 inches long, a common way to produce this part would be with a CNC-controlled spindle axis machine (or a lathe). The "industry-accepted" tolerance on the diameter might be + or −0.002 inches. If the part was to be an *investment casting*, the tolerance on the diameter might be + or −0.001 inches.
2. If the above is acceptable to the design, look to increase the tolerance even more, checking back to acceptability in the overall design. Increasing the tolerance will allow more parts to pass inspection, which should (could) result in overall cost reduction.
3. Tighten the tolerance even though the most common manufacturing process will not produce that tolerance *if the design dictates that tighter tolerance*. Check with the part manufacturer if that tighter tolerance will be achievable (reasonably) or at what cost.

Each dimension (location, hole size, angle, etc.) must have a tolerance, either explicitly stated on the drawing or as being a part of an overall notation on the drawing.

Some designs require parts with *very* low tolerances. That is, if parts are manufactured that exceed those tolerances, they will not work!

Most designs should allow "standard industry" tolerances to be cost-effective. These "standard industry" tolerances are found by:

- Consulting with part manufacturers
- Researching standards available in various industries
- Using previously attained knowledge by the designer (i.e., experience)

Tolerances are listed on drawings (documentation) in several manners. An individual dimension on a drawing may carry its own tolerance; there may be notes that define the tolerance on several dimensions or there be a note on the drawing that covers every dimension. In any case, *every* dimension does indeed have a tolerance (that should be specified).

There are several methods of dimensioning. For example, a dimension that is nominally 2.000, with a tolerance of +/−0.005, can be specified on the drawing as:

- 2.000 +/− 0.005
- 2.005/1.995
- 2.005 + 0.000 – 0.010 (unilateral dimensioning)
- 1.995 + 0.010 – 0.000 (unilateral dimensioning)

If the tolerance was an odd number (say, 0.003 *total*), this will produce an example of *bilateral* dimensioning, as

- 2.000 + 0.002 – 0.001

But, this would be a rather rare occurrence.

Unilateral dimensioning is advantageous when a critical size is approached as material is removed during manufacture, as in the case of close-fitting holes and shafts. Thus, for a shaft (where material is removed), the high side of the limit is shown first as:

- 2.005 + 0.000 – 0.010

However, it would be much more common to list this dimension as

- 2.000 +/− 0.005

The number of decimal places for the tolerance should match the number of decimal places shown for the basic dimension. For example, a dimension given as 2.000 would have a tolerance listed as +/−0.010 (not +/−0.01).

4.8.6 Theory of Tolerancing: Accumulation of Tolerances

Every individual part has overall dimensions (length/width/thickness) as a minimum. Parts usually have, in addition, features (cuts, holes, etc.) that need to be dimensioned. In dimensioning, it is very important to consider the effect of one tolerance on another. When the location of a surface in a given direction is affected by more than one tolerance figure, the tolerances are *cumulative*. For example, in Fig. 4.3, the location of Surface A can be controlled from either Surface B or Surface L:

In the "cumulative tolerances," the tolerance of the location of Surface A from Surface L is 2.000 + 0.000 – 0.010.
In the "base line dimensioning," the tolerance of the location of Surface A from Surface L is 2.000 + 0.000 – 0.005.

Thus, if the feature (Surface A) *needs* to be held more closely to Surface L, then that feature should be *directly dimensioned* from that same feature.

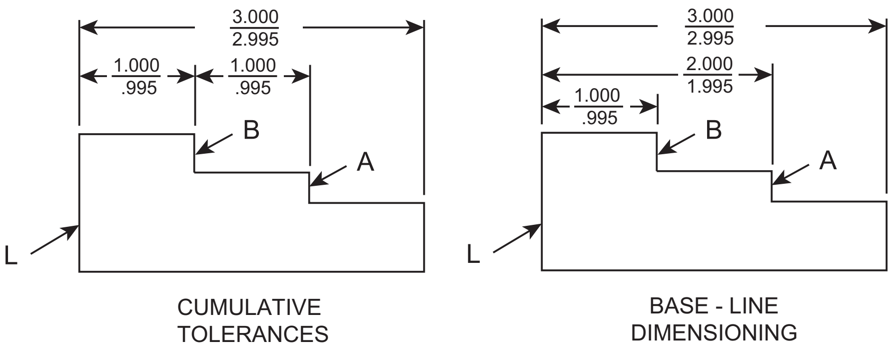


Fig. 4.3 Accumulation of tolerances

Every dimension should be analyzed to determine exactly what feature it should be controlled from (dimensioned from) so that tolerances don't accumulate from "irrelevant" features.

4.8.7 Inspection Dimensions (Critical Dimensions)

Parts can have hundreds of dimensions. To fully specify every feature on some parts takes a fair amount of time. Historically, every feature on a drawing was dimensioned to enable that feature to be inspected and found either in compliance with the specification (drawing) or non-compliant. With the advent of 3D CAD systems for designing and creating drawing documentation, it is completely possible to transfer all of the part information digitally, without any dimensions being specified actually on the drawing, and have that part manufactured at the "nominal specified dimension." That is, features that are 3.000 inches apart are "drawn" exactly 3.000 inches apart, and that number is an integral part of a file that the part manufacturer gets. Anyone who brings up that part file on their CAD system can query that file and see those features need to be 3.000 inches apart (with a stated tolerance as a part of the CAD file). In fact, inspection departments, if they had access to the CAD file, could inspect the part (perhaps with a 3D computer-controlled inspection system) and determine whether that dimension (3.000) was within tolerance.

So, the question becomes who exactly needs to know the dimensions and to what purpose is it that the dimensions are shown on the drawing documentation? The answer to that question is probably different for each organization. Some organizations have settled on not specifying every dimension but rather a subset of the dimensions.

It has become common practice to label dimensions on a part drawing those dimensions that determine whether the part has "passed inspection." On parts with only a (relative) few dimensions, that might mean that *all* of the dimensions are considered "critical." On parts with hundreds of dimensions, a subset of those dimensions could be considered "critical" and must be verified by standard inspection procedures. Those procedures could be 100% inspection or some agreed-to sampling process that is less than 100% inspection.

What dimensions would be considered "critical" and thus inspected? Candidates for specifying this subset (of all of the dimensions) are:

1. Is the feature critical to the function of the part? If a feature (holes, cutouts, etc.) mates to another part, then this may be considered a "critical dimension." If somehow *safety* is involved, then that would place the dimension in the "critical" category of *must be inspected*.
2. Does the feature have a "special" (nonstandard) tolerance which places that dimension in the "critical" category? If so, that dimension may be considered a "critical dimension."

3. Have certain dimensions (when parts have been prototyped) been problematic in that they seem to cause the part manufacturer some problem which causes an issue to develop with that part? If so, that dimension is another candidate to be labeled a "critical dimension."

Some issues arise with this concept of "critical dimension" in that *any* feature (no matter how "insignificant," such as an internal radius), if not to tolerance, can cause an issue. It's just that many of the dimensions have a high probability on *not* causing any issue, and thus, only a small percentage can be considered "critical."

4.8.8 True Position Dimensioning

True position dimensioning, or more specifically, geometric dimensioning and tolerancing, is a means of specifying engineering design and drawing requirements with respect to actual "function" and "relationship" of part features. Furthermore, it is a technique which, when properly applied, ensures the most economical and effective production of these features. The major objective of the system is uniform interpretation among design, production, and inspection groups. I'm not going to present the details here but rather a brief overview of the basis and reasoning behind geometric dimensioning and tolerancing (GD&T). The current authoritative document governing the use of "GD&T" is shown in Ref. [15–17].

One of the basic principles of GD&T is the idea changing from a "rectangular tolerance zone" to a "circular tolerance zone." Normal positional tolerances in a rectangular coordinate system permit a "square" tolerance zone, while the tolerance zone changes to a circle with true positioning (with the area of the circle being larger than the square by 57%).

The manufacturing industry is turning to geometric tolerancing primarily because it increases productivity and reduces cost. The advantages include:

- Increased productivity by specifying maximum but workable tolerances, in many cases permitting manufacturing variation beyond the tolerances specified by dimensional tolerancing (the older system of tolerancing)
- Interchangeability of mating parts by specifically stating design requirements in relation to the function of the part and making possible the use of time saving functional gages
- Uniformity in drawings and in their interpretation, ensuring effective communication between engineering, manufacturing, and quality control

If a pattern of four holes is located from part edges and a distance is given between holes (including the tolerance on the four dimensions), it increases the chances of mating parts that won't fit together. Instead, if the pattern of four holes is located from part edges and *basic* (exact, theoretical, untoleranced) *dimensions* are used for X and Y between holes, along with the addition of a "*true position*" dimension, there will be no ambiguity as to the pattern's potential positions.

If a single hole location with +/−0.005 inch tolerances given with dimensional tolerancing is replaced with a positional tolerance zone of 0.014 inch *diameter*, the tolerance "area" grows from a rectangular (0.010 × 0.010) area to a circular $\pi/4$ $(0.014)^2$ area, with a resulting 57% increase of area. This can equate to "real-world" rejection rates going from four parts per 100, being reduced to two parts per 100. Thus, there are more acceptable parts just by changing from dimensional tolerancing to positional tolerancing.

Complete true position dimensioning consists of:

1. Basic locating dimensions (where tolerances do not apply)
2. An expression (notation) such as located at true position within.XXX DIA (or located within.XXX R of true position) added to the feature to be located
3. Datum references

To prevent misunderstanding, true position should always be established with respect to a datum.

Actually, the "circular tolerance zone" is equal to the positional tolerance and the axis of the feature (usually a hole) must be within the cylinder. The center line of the hole may coincide with the center line of the cylindrical tolerance zone, it may be parallel to it but displaced so as to remain within the tolerance cylinder, or it may be inclined while remaining within the tolerance cylinder. Thus, the axis of the holes are not only defined in 2D but rather in 3D, which is a much more powerful description of acceptability for a hole pattern. This is illustrated in Fig. 4.4.

Methods of indicating geometric tolerances, by means of GD&T, define conditions of straightness, flatness, parallelism, perpendicularity, angularity, symmetry, concentricity, and roundness. For example, a note attached to a cylinder that states "*straight within* 0.010 *total*" is a "shorthand" for the statement:

Regardless of the actual size of the feature, any longitudinal element of the surface must lie between two parallel lines (0.010 apart) where the two lines and the nominal axis of the feature share a common plane.

Thus, a "standardized" note conveys very clear meaning universally understood by the designer, the fabricator, and the inspection departments.

Datum features are powerful tools in GD&T. They should be selected based on their ability to be:

- Functional
- Mating surfaces
- Readily accessible
- Repeatable

Some other facts about datums:

- A datum is a theoretically exact geometric reference.
- Primary datums provide feature orientation.
- Datums are assumed to exist on the part itself.
- Datums are established from tooling points or surfaces.
- Surface plates and V-blocks are simulated datums.

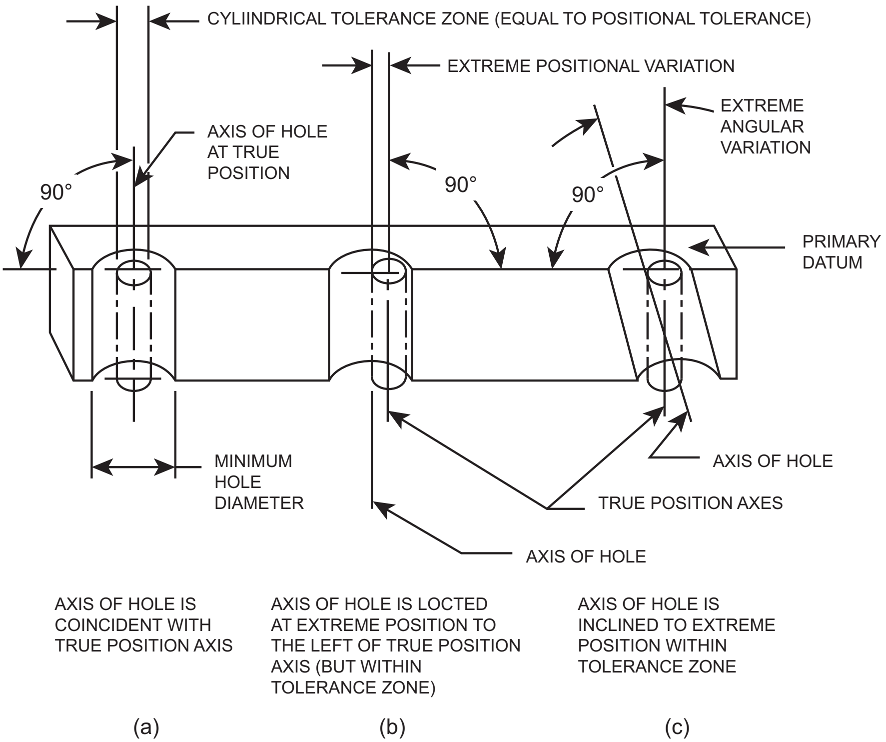


Fig. 4.4 Positional tolerance controls perpendicularity

- Datum features (which are actual features of a part mated to simulated datum surfaces) contain inaccuracies.
- A datum reference frame consists of three mutually perpendicular planes.

GD&T also has the concept of “modifiers.” Modifiers are used in conjunction with feature control symbols to identify how the geometric tolerance zone is affected by the size tolerance. The modifiers that are used most commonly are maximum material condition (MMC) or regardless of feature size (RFS).

MMC is shown on a drawing as a “circled M,” while RFS is shown on a drawing as a “circled S.”

MMC indicates the most material possible in an object and is used in a feature control symbol. It means that the geometric tolerance will only affect the size of the part at MMC. (The true position symbol “circle with cross hair” implies MMC).

RFS means that the geometric tolerance will affect any produced size of any object. Most geometric characteristics (straightness, flatness, etc.) imply RFS.

Let’s look at how the use of modifiers affects a geometric tolerance zone. We’ll look at three examples:

- Conventional (non GD&T)
- MMC
- RFS

A bar with the dimensions 0.25 +/− 0.02 will all be produced in a range of acceptable sizes from 0.27 to 0.23.

With conventional tolerances, there is *no control* on the *straightness*.

With GD&T, a straightness symbol, and MMC (or RFS), the maximum out of straightness varies as the produced size varies:

Size	Max. out of straightness	Max. out of straightness
	MMC	RFS
0.27	0.03	0.03
0.26	0.04	0.03
0.25	0.05	0.03
0.24	0.06	0.03
0.23	0.07	0.03

Again, geometric tolerancing is a powerful technique to help the designer think about what are the "control features" of the part design and how the part will actually be inspected to determine whether the features are in compliance with the drawing (design). Additional references are listed.

4.9 Off-the-Shelf Components

The designer of electronic enclosures must always start the design with a search of what has already been designed that could be utilized in the new design. The search should include inside (within the designer's own company) sources or OEMs external to the company.

Examples that are already available to the designer are:

- Fasteners, washers, standoffs, threaded inserts, pins, springs
- Heat sinks, insulators
- Cabinets, racks, slides
- Rubber grommets, bumpers, shock isolators, gaskets, O-rings
- LEDs, display products, switches, pushbuttons
- Cables, connectors
- Labels, nameplates

Sometimes the off-the-shelf part is not quite what is needed. The decision to either make the new part (exactly what is wanted), contact the OEM to see whether the slightly different version can be attained, or adapt the design to the existing part needs to be analyzed. The decision should converge on the normal constraints of cost, time, and conformance to specification. Also, the catalogs of the OEM suppliers usually contain relevant design information that can be used to design similar parts to those within the catalogs.

Consideration should be given to the reuse of parts from another design. For example, if a new slimmer enclosure is needed, can the upper part of the present enclosure be reused?

4.10 Prototyping

I've tried to write this book so that it will be relevant to designers going forward in time, that is, to not put technical material in the text that quickly would become obsolete. This section on prototyping is "at risk" in that I've witnessed that the techniques used for prototyping have undergone the biggest changes in my 30+ years of design engineering, and I can see them continuing to change at a rapid pace, making a lot of what I now say about the particular processes obsolete (perhaps before publication). However, one thing that will not become obsolete is the *need* for prototyping.

Prototyping is essential to the efficient design of any engineering product. Producing a quick, relatively realistic representation of the "final idea", gives everyone on the team a sense in what direction the project is moving. The prototype will either move the project forward or cause a reassessment of the present thinking. The prototype can be of any portion of the entire project, from just a small portion of the product to the entire finished product.

I've seen many instances of (very) crude prototypes providing amazingly quick information to the design team. Paper, cardboard, and scissors can quickly illustrate some aspects of a design – again, the speed of prototype production cannot be overemphasized.

Drawings, by themselves, do not give everyone on the design team an idea of what the design "will be." Even three-dimensional representations will not completely convey the design. There are some design engineers who can just look at drawings and see that the final design will achieve the objectives; however, there are some people who do not have the ability to interpret those "lines and numbers" into something they can imagine and that they need to touch and feel an object to determine whether it "will work." *size* is one aspect that seems to be more easily conveyed by a physical prototype (than on a drawing). Certainly, any design feature that has human "interaction" will need to be actually picked up and used by the design team to understand the design feature's ability to achieve the design's objectives. Just about anything that the customer's hand will touch needs to be modeled to see how that "mind-hand interaction" will work. An entire discipline, ergonomics, is dedicated to determine those best decisions. For example, if a door is to occur on a product, some common questions occur (where a prototype will help answer the questions):

- What mechanism will open the door (and close it)?
- How is the door repaired once broken (under abnormal use)?
- Will the door open side to side or up and down?
- How well does the door need to seal (once it is shut)?
- How much force is needed to open the door (and close it)?
- Does the door need to stay open (without holding it open)?
- Does the door need to be locked?
- Does the door slide, hinge, roll, or otherwise move to open?
- What (on the door) serves to open and close the door?

Speed is a key factor in the production of a prototype. The prototype is purposed to provide “quick information” on the design itself, so finding out whether to pursue a design direction, or whether to change direction, is paramount to the process. Also, a determination on how well the prototype will portray the design intent must be made. That the prototype is so “crude” that it allows a design direction to continue just because it didn’t accurately mimic the final design enough will not help the overall process. A balance must be made in determining “accuracy” vs. timeliness in the prototype process. Once “speed” is determined to be the *key* factor, cost must then be secondary. That is, costly prototype production that saves overall product delivery parameters (time and conformance to specification) is a solid investment.

In-house prototyping capability vs. subcontracting out the prototyping is always a question to be answered (by the project management team). Some companies feature having the prototyping capability in-house, as this has the advantages of:

- Scheduling of the prototype (against competing needs) is better controlled (should result in quicker prototypes being produced).
- Profit in the prototyping process itself is kept in-house.

Having the prototyping process being subcontracted out may be better due to:

- Latest processes are more available (usually) out of house. This is due to the rapid pace of change in prototyping processes and the capital cost of equipment needed for these prototyping processes.
- No maintenance or instruction is required on prototyping equipment.

The decision (in-house or contracted prototyping) must be analyzed as time moves forward. For example, the cost of 3D printing (of plastic parts) in-house was generally prohibited as capital cost, size of machine, training required, and pace of technology change were all too high before the year 2000. But, by 2005, having a 3D printer right there in the office became quite common.

Getting sheet metal or metal parts prototyped can also be done by various 3D printing methods but, at present, continue to be in the domain of “quick-turn” prototyping facilities (utilizing the standard metal fabrication methods of drilling/machining/punching).

Another consideration of the prototyping process is whether the prototypes are fabricated at either:

A. The same vendor that will manufacture the production parts
B. Vendor that is independent of the future production part location choice

An advantage of utilizing the “same vendor” is that some of the issues are worked out with the prototype parts that will “smooth the flow” of production parts. However, sometimes the speed gained by using a vendor that is independent of the future production parts will get the prototype parts in hand sooner. Again, no one answer will fit all unique situations.

Appendix

This appendix is provided to the EPE designer to make them aware of some common sheet metal punching and forming methods. Also, there is some information on the "best practices" of dimensioning sheet metal designs. The EPE designer will be designing quite a few parts that are made out of sheet metal as sheet metal provides the strength that many individual parts of enclosures will need. Common metals used will include aluminum and stainless steel.

Much of the material shown here has been commonly shown in corporation design guides and the EPE designer will hopefully find useful information. As usual, the designer should also consult with sheet metal fabricators to see if this information is consistent with their fabrication process.

Dimensioning of Sheet Metal on Drawings

Dimensions should be placed to prevent having to add or subtract material thicknesses and tolerances, and should be supplied according to the *function* of the part. This is illustrated in Fig. 4.5 for a base and base cover. Note here that normally, all dimensions should apply to the outside of the part. When inside dimensions must be utilized to assure fit of mating parts, the word "inside" can be added to the dimension to emphasize the idea that the part's dimension "mates" with another part (and is therefore critical). The most important aspect of this is that the dimension is on the item that is the most critical, and that is that the cover will, indeed, fit on the base.

Dimensioning Bends

The dimensioning of bends in sheet metal parts should be applied from a tangent or extension point and not to the radius center as shown in Fig. 4.6. Tangent or extension points are better because these points can be *measured*, and this is the

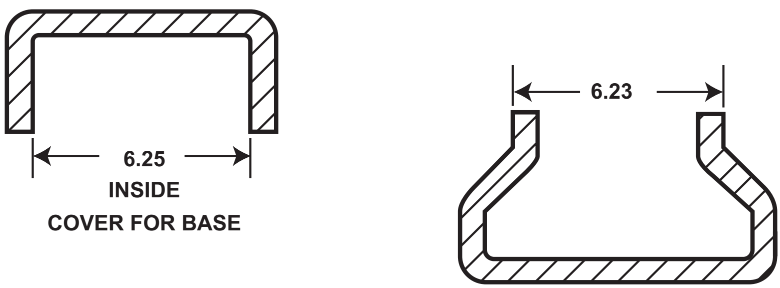


Fig. 4.5 Feature control

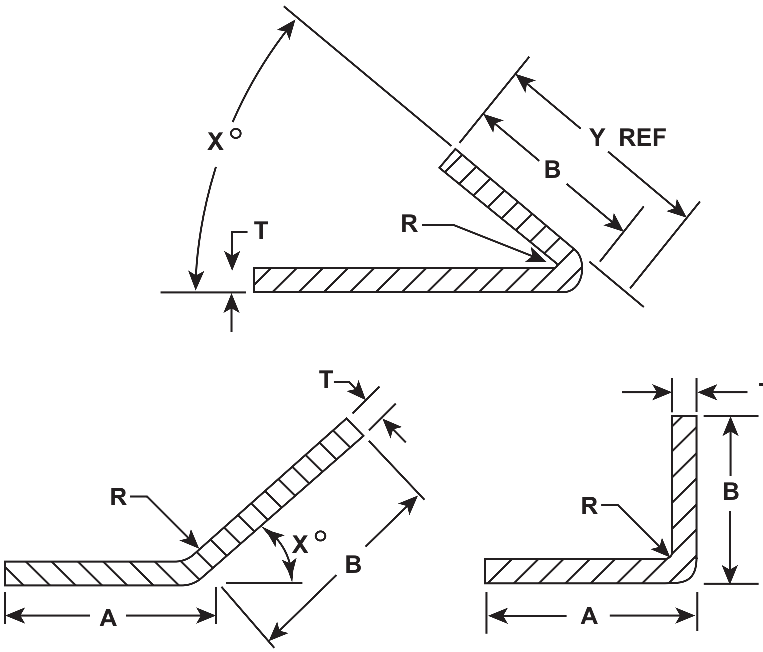


Fig. 4.6 Dimensioning bends

important goal. Anytime a dimension is given to a point which cannot be measured (easily), ambiguity can result. Another point to be made is that, usually, the center of a radius is not what actually needs to be located in the design, but the part edge is the more critical. A more simple "rule-of-thumb" may be that if the center of the radius is not required to construct the part, then the dimension to the center of the radius is probably not required.

Note also in Fig. 4.6 that the dimension "B" in the acute and obtuse angles could be replaced by a dimension from the base to the upper height of the angle (as the right angle is dimensioned). This dimension would be even more valuable as it is easily arrived at (inspected) with a height gage.

Minimum Flange Height

In order to provide sufficient material for the proper forming of bends, the minimum flange height should be as shown in Fig. 4.7. If the design calls out a dimension less than the minimum 2.5T + R in Fig. 4.7, shock will have to be added for bending and then cut off, requiring an additional operation at added cost.

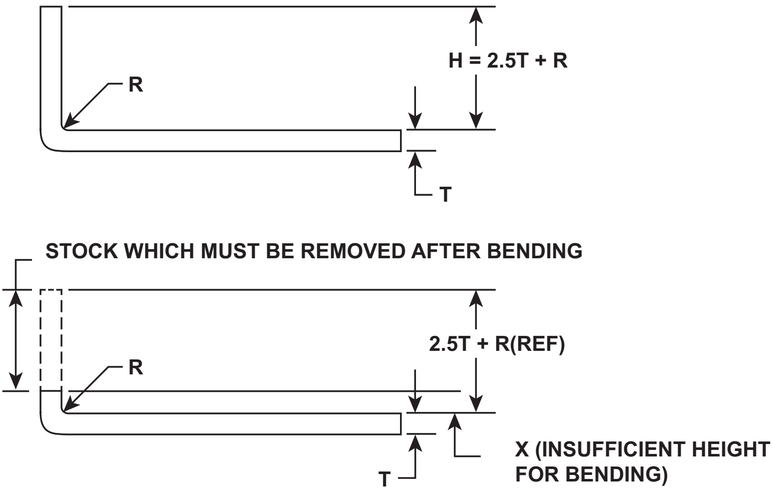


Fig. 4.7 Minimum flange height

Minimum Distance Between Bends

Parts having "Z" bends similar to those shown in Fig. 4.8 should have the minimum distance between bends no less than the values shown. Also, there is a minimum aspect ratio between bends in a "U" shaped piece. As shown, a forming tool cannot be made small enough to avoid interfering with metal on a bend already created. It is a good practice to imagine (with a sketch on a drawing) the forming tool *itself* on a relatively high depth-to-width ratio part to see if the forming tool is practical in size.

Location of Holes Adjacent to Bends

In order to prevent distortion of a hole pierced or punched before bending, the minimum distance between the edge of the hole and the edge of the bend should be as shown in Fig. 4.9. This distortion takes the form of an elliptical hole with an increase in material thickness which would be unacceptable in most design efforts. Note, calculate "X" dimension so that "Y" is not less than 1.5T + R.

For slots which lie parallel to the bend as shown in the figure, the following minimum distances shall apply:

When L = up to 1 inch,	"A" = 2T + R
When L = 1 to 2 inches,	"A" = 2.5 T + R
When L = 2 inch or greater,	"A" = 3T + R

MATERIAL THICKNESS	LENGTH "A"
.000 - .040	.188
.041 - .080	.500
.081 - .125	1.250

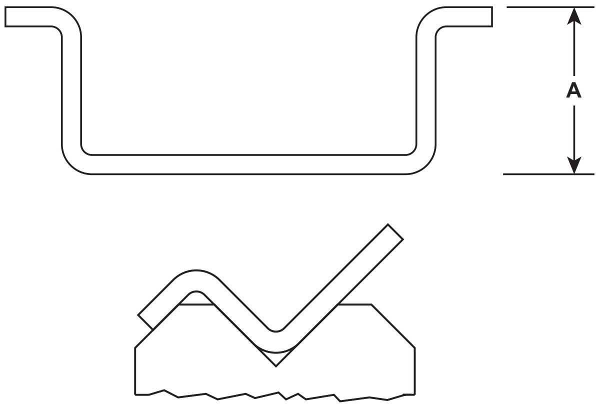


Fig. 4.8 Minimum distance between bends

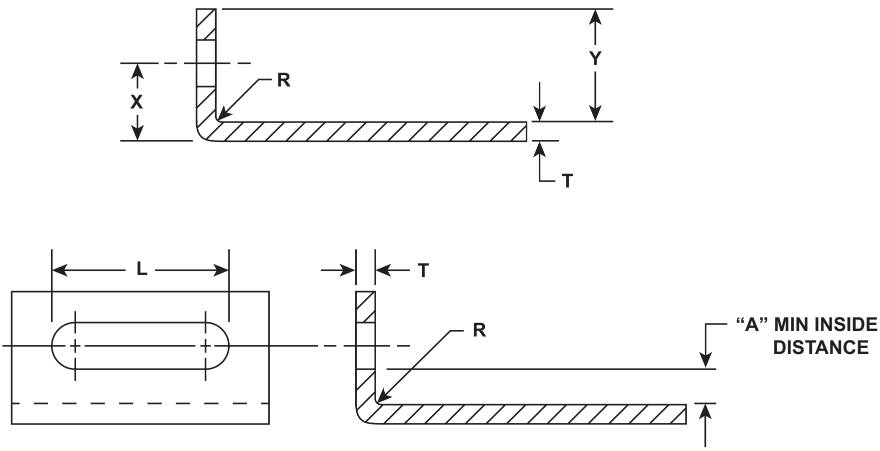


Fig. 4.9 Location of holes adjacent to bends

Location of Holes to Prevent Distortion

To prevent distortion of the edge of a part or of the material between holes, minimum distance calculation for punched holes must consider:

A. Material used, its thickness, and physical properties
B. Hole shape and size
C. Hole application

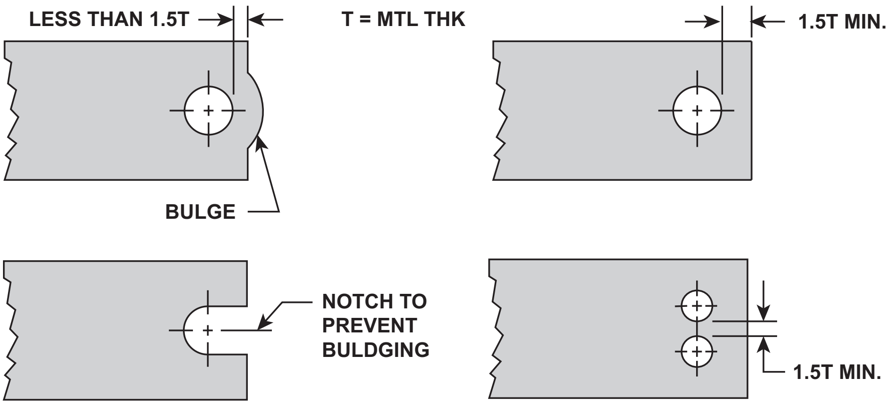


Fig. 4.10 Location of holes to prevent distortion

Nominal minimum distances are shown in Fig. 4.10. The variables listed above should be used to determine special requirements. For example, edge distortion may be avoided by notching, as shown in the figure.

Punching Holes

Round holes may be economically punched in sheet metal parts provided the diameter of the hole is larger than the thickness of the material. If the hole diameter is less than the material thickness or less than 0.032 inch, the hole will have to be drilled.

Normal punching tolerances are +/−0.010 inch from edges and +/−0.005 between holes. These would be considered normal for numerical controlled (NC) machines such as those made by Strippet and Amada. More on this in Sect. 4.8 on tolerances.

Figure 4.11 illustrates two methods used to dimension holes. Only one datum in each direction should be used. Use the lower left or upper left corner of the part for datum unless there is a good reason to do else wise.

For a “cut” corner (flat panels, plates, etc.), use the corner as datum references. For folded corners, the first hole should be the datum reference (tolerance +/−0.03 preferred).

Typical punched slot dimensioning is shown also in Fig. 4.11. The drawing would specify basic sizes, detail dimensions, and tolerances required. In this case, a +/−0.010 tolerance was entered in the drawing title block.

Standard punches exist at most sheet metal vendors. They should be able to provide you a listing of the standard punches they have, so that you can avoid a “custom-sized” punch.

Punches include variations of round, square, rectangular, and oblong punch sizes for use on aluminum and mild steel sheet. Inside and outside corner radius punches are also available in most common radii. Special punches such as standard connector cutouts may also be stocked at some vendors. Standard sizes and standard toler-

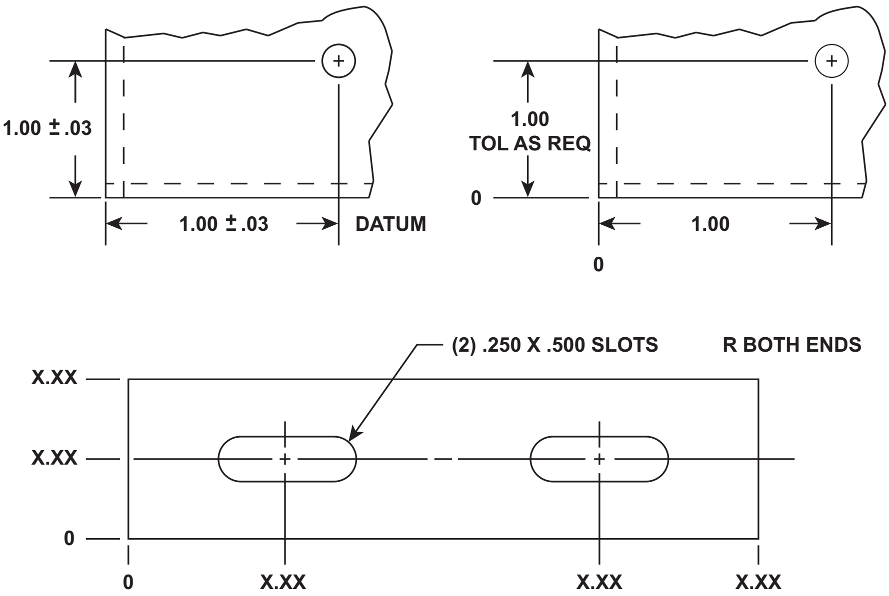


Fig. 4.11 Punching holes

ances should be used whenever possible, but in some cases, a special tool may be justified. In fact, even complete dies that blank entire parts are justified if the quantities of parts are high enough.

Bend Relief

The three designs illustrated in Fig. 4.12 are not desirable for quality or economy. In these examples, the metal at the base of the tab will tear in forming resulting in stress risers which could cause ultimate failure of the part.

Adding a cutout, which provides relief at the bends, is also shown. These examples represent good designs with relief for the bends to prevent tearing and to minimize fatigue under stress. The relief, which can have a radius to it (as shown) or can be "squared-off," is basically deep enough to be at the tangency point of the radius.

The relief is approximately a material thickness wide, but is generally not any narrower than 0.03 inch due to limitations on punch width. In general, this relief would not be dimensioned on the drawing; rather, it would be called-out as "Use Minimum Bend Reliefs" with the general drawing notes.

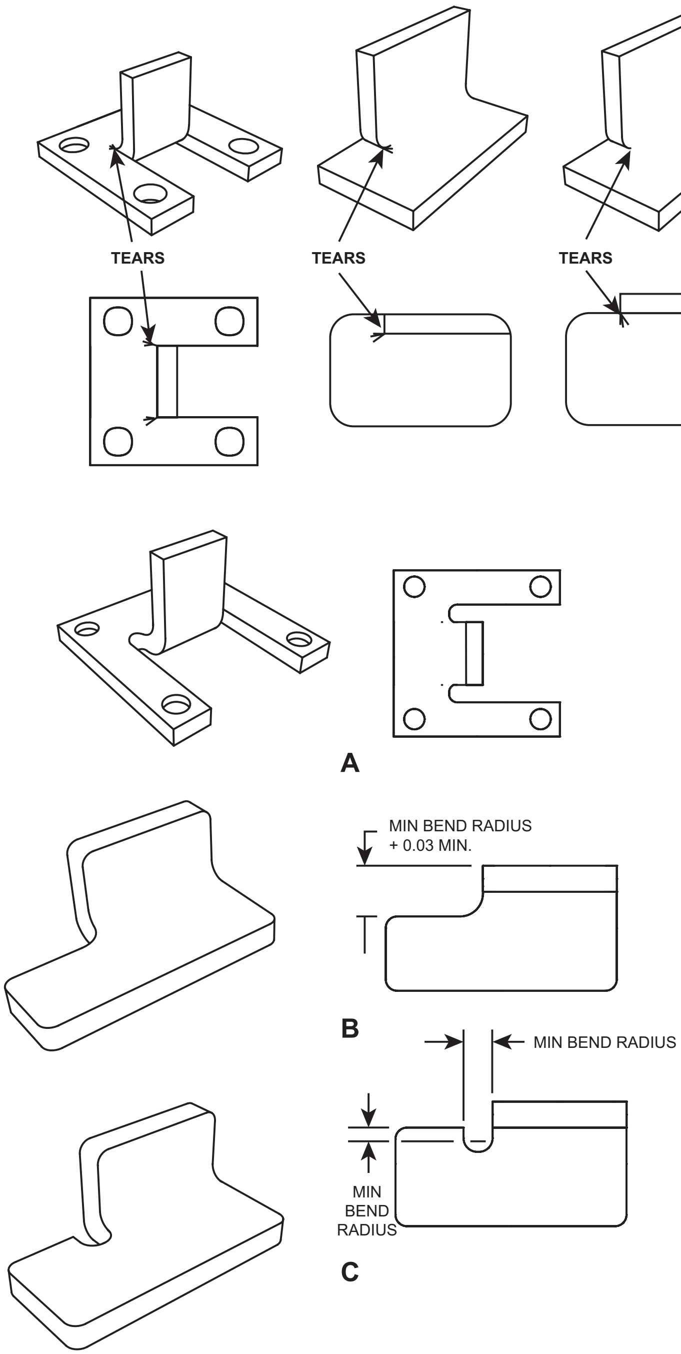


Fig. 4.12 Bend relief

Corner Construction

On all formed parts which involve adjacent flanges, relief cuts or notches should be incorporated to prevent tearing or wrinkling of the metal during the forming operation. The minimum allowances that must be made are illustrated by the examples shown in Fig. 4.13. Again, note that bend lines are at radius intersection with the flat surface.

An important note is to be made about corner construction. In some cases, extra strength may be required in a design that warrants the extension of both connecting flanges at the corners as illustrated by the closed corner construction of example "C' in Fig. 4.13. This corner would be welded (either inside or outside) to join the two perpendicular flanges to each other and greatly increase the strength of the member.

Beads and Gussets

To avoid the cost of additional parts or thicker metal with additional weight, formed beads (ribs) and gussets are recommended. Examples of such practice are on large areas of side panels, small brackets required to support heavy loads, on chassis, and cabinets.

Various types are illustrated in Fig. 4.14. "A" shows an open end center bead, which may be used for reinforcing large panels. "B" shows a straight closed end bead. This type of bead is used where greater rigidity is required and the additional cost of die construction is warranted. The radius at the intersection of the beads should be two times total bead width minimum. "C" shows the use of flanges for stiffening purposes. However, this method often produces "oil-canning" which may be eliminated by depressing an area as shown.

Bead corner designs are also shown in Fig. 4.14. The sharp corners shown in the bead at "A" are likely to tear the surrounding metal. The bead corner shown at "B" is a better design provided the beads intersect with liberal radii. The nonintersecting beads shown at "C" are generally as strong as those shown at "B" and are much cheaper to produce.

The stretching of metal may cause some wrinkling at the ends of the beads. To avoid distortion of the edge of the metal, distance "X" of Fig. 4.14 should be 40T minimum and the distance "Y" should be 25T minimum (where T is the material thickness). If the edges are flanged, the "X" and "Y" distances may be reduced to 30–35T and 15T, respectively.

Where beads and flanges are combined, both should project on the same side of the part for most economical die design as shown.

Minimum Bend Radii

There are recommended minimum bend radii for various materials and tempers that can be formed parallel to the grain of the material without cracking. Going below the recommended bend radius for a minimum bend should not be resorted to unless

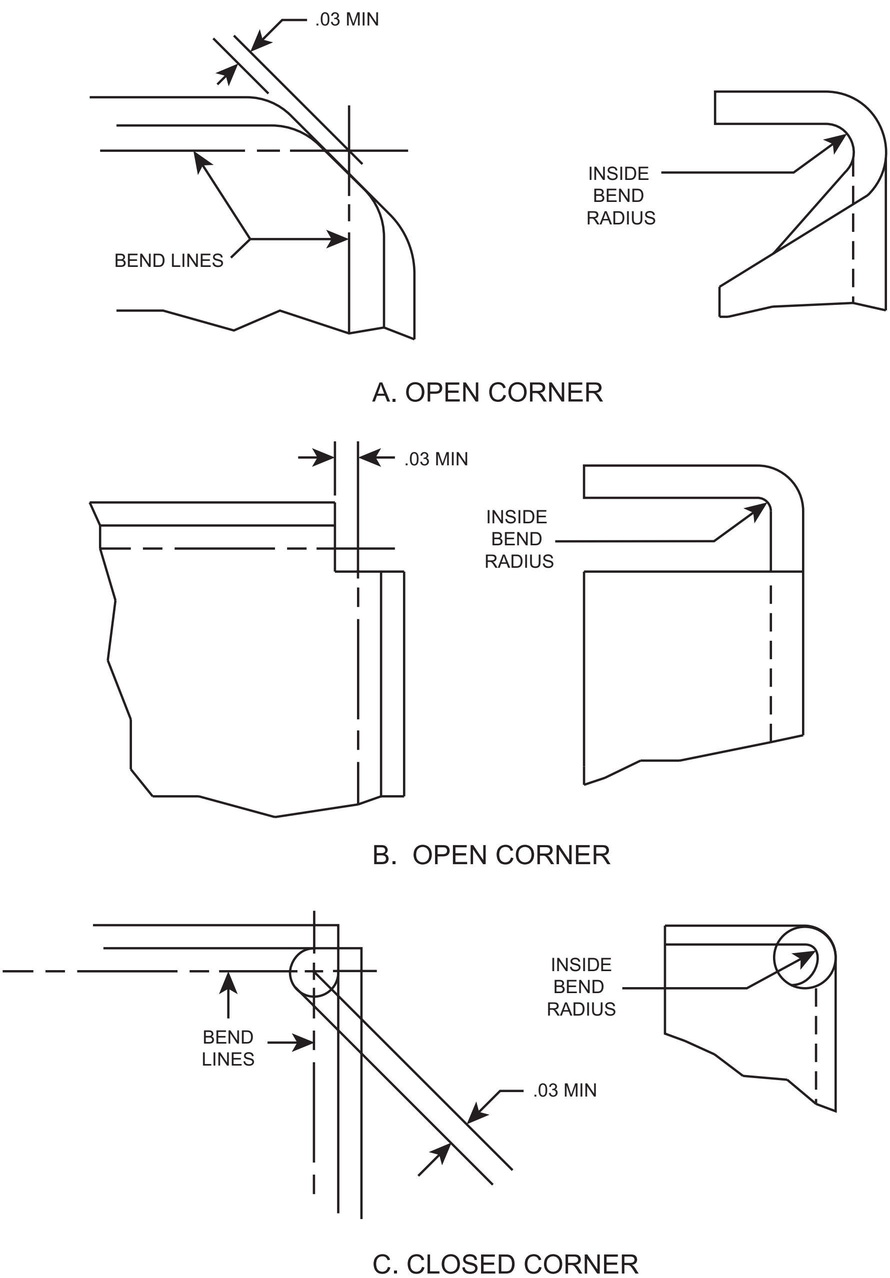


Fig. 4.13 Corner construction

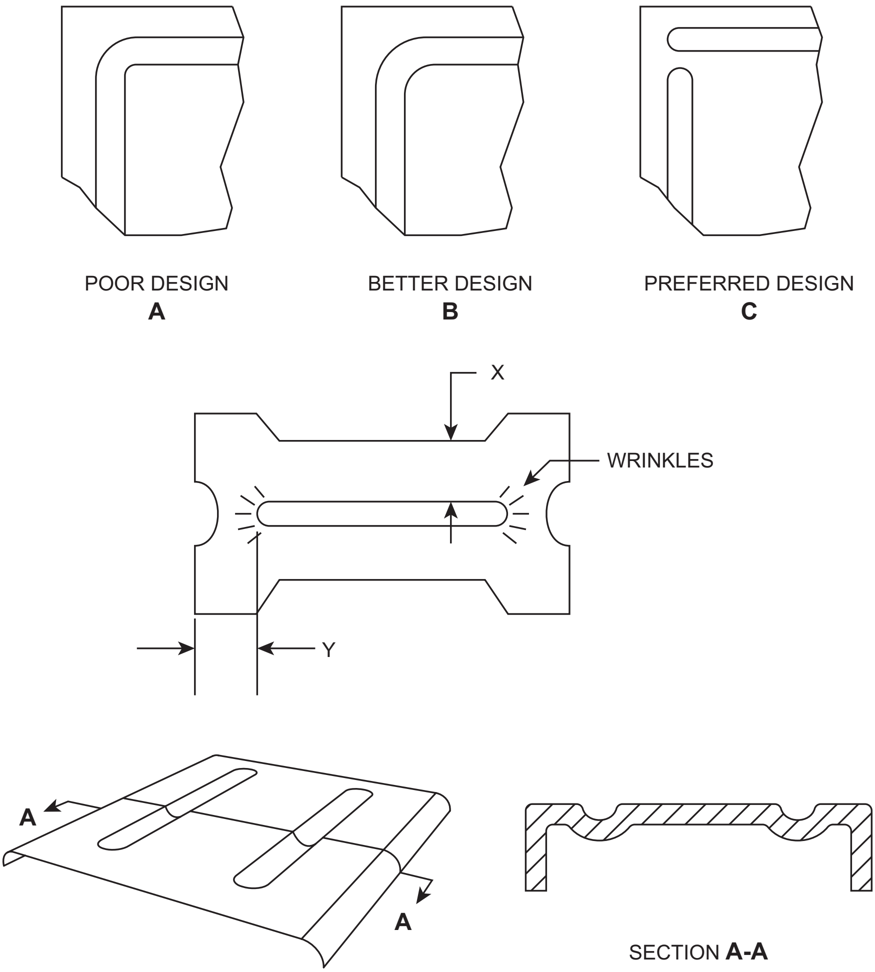


Fig. 4.14 Bead designs

absolutely necessary. These minimum bend radii can be attained from various references and may look like:

For 90° cold bending of Alloy 7075 Aluminum, Temper –T6,

Thickness 0.016	Min. Radius = 0.03–0.06
Thickness 0.032	Min. Radius = 0.09–0.16
Thickness 0.062	Min. Radius = 0.25–0.37

Normally, a note in the general note area of a drawing states: "Use Minimum Bend Radius (Unless Otherwise Specified)" which means to the sheet metal vendor

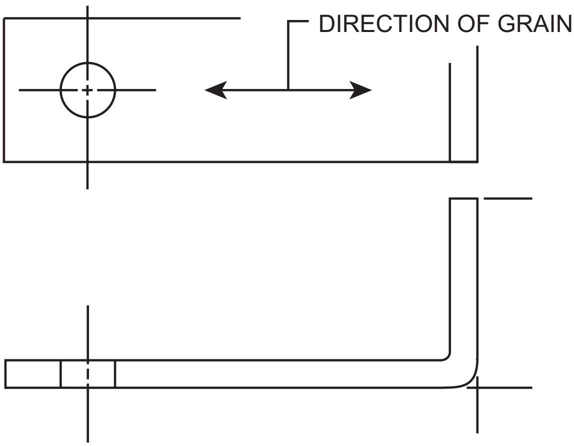


Fig. 4.15 Grain direction

that minimum recommended bend radii are to be used. Otherwise, a radius is called out on the drawing as preferred. Important to note is that bends should be as *generous as practical* to increase the overall strength of a part but are generally on the order of a material thickness.

Grain Direction

The grain direction of the material should not be specified on the drawing unless a bend radius is required that is smaller than the recommended minimum. In which case, the bend should be specified *across the grain*. This is illustrated in Fig. 4.15 showing that the bend direction is 90° to the direction of the material grain. Grain direction may be specified for minimum bend radii in hard or spring temper sheet or to show direction for a decorative (for example, silk-screened) part.

Temper

Harder tempers should be considered first since they often permit the use of thinner, stronger, and lighter material. Stiffer materials, however, require larger bend radii.

Recommended Slot Widths

All of the below slot widths are considered standard:

Screw size	Slot width
#2	0.093
#4	0.125
#6	0.156
#8	0.171
#10	0.218
¼	0.281

Folding

Folds are used on materials which can be bent back on themselves as shown in Fig. 4.16. To prevent cracking, especially on the flattened type, the folds are normally placed across the grain of the material (see section "Grain Direction"). The grain direction is, thus, usually specified.

Curling

Curling may be used for edges of sheet metal parts where rigidity requirements are greater than can be met by ordinary folding. The sizes of these edge curls should be in accordance with Fig. 4.17.

Crimping

The edges of large sheets may be crimped for extra rigidity and to prevent "oil canning." A typical crimp is shown in Fig. 4.18.

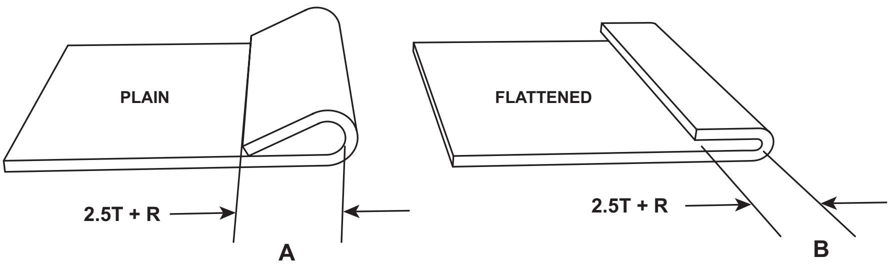
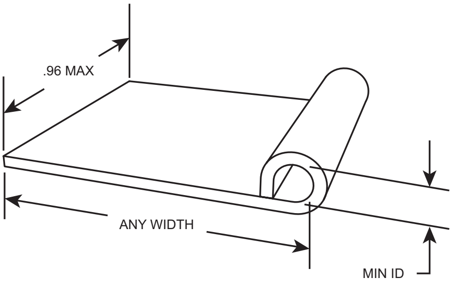


Fig. 4.16 Folding



MINIMUM CURL DIAMETER	
THICKNESS	MIN ID
.001 thru .032	.12
.033 thru .040	.19
.041 thru .063	.25

Fig. 4.17 Curling

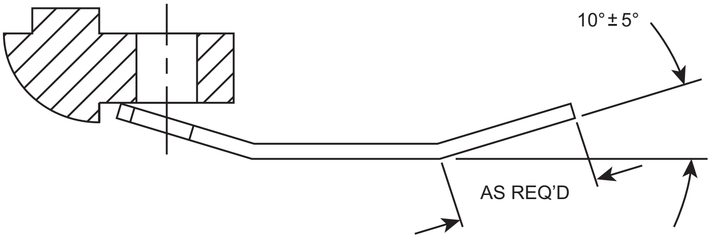


Fig. 4.18 Crimping

Joggles

Joggles are used to provide a step in sheet metal parts for lapping joints, etc. The width of the web or joggle allowance, dimension "L," should be a minimum of 3 times dimension "D," the depth of the offset. For brittle materials such as heat treated aluminum alloys, a minimum joggle allowance of 6 times the offset depth is recommended. Where the design requires that the offset depth exceed the material thickness, the 45° joggle should be used. See Fig. 4.19.

Dimpling

The most common application for dimpling is for countersunk head screws or rivets, see Fig. 4.20. Soft materials can be dimpled easily. Aluminum alloys such as 2024, 7075, and the harder tempers of stainless steels may edge-crack unless they are "hot-dimpled." Dimensional data for dimpling is given.

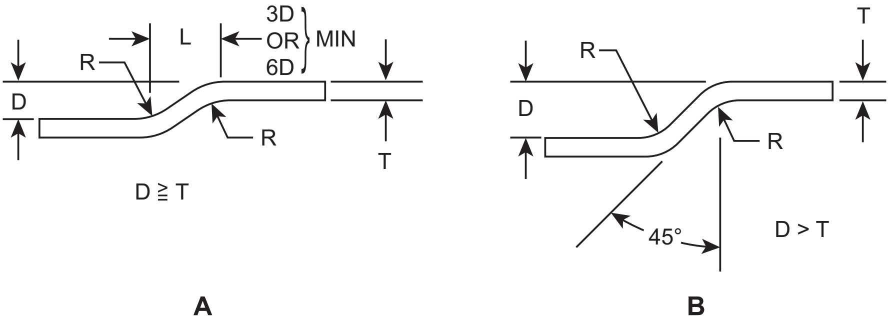


Fig. 4.19 Joggles

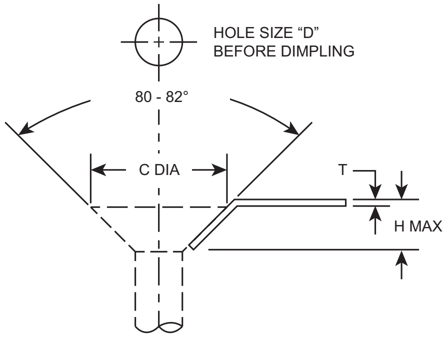
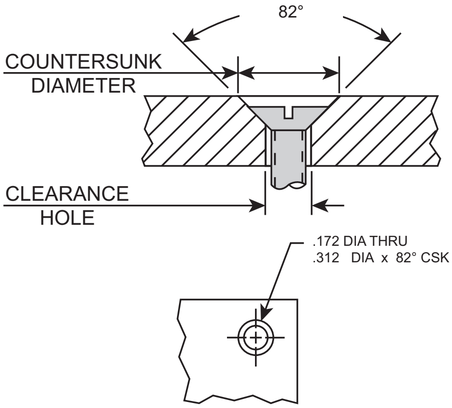


TABLE 1 - DIMPLING DIMENSIONS														
	HOLE SIZE (D) BEFORE DIMPLING												C DIA +.010 -.000	H MAX
	THK (T)	.016	.020	.025	.032	.040	.050	.063	.080	.090	.100	.125		
SCREW SIZE	2 - 56	.047	.055	.060	.063	.067								
	4 - 40		.055	.060	.063	.067	.070	.073						
	6 - 32			.070	.076	.078	.082	.086	.094					
	8 - 32				.089	.096	.102	.110	.113	.125				
	10 - 32					.096	.102	.110	.113	.125	.140		.392	.195
	1/4 - 20						.125	.144	.156	.166	.173	.185	.516	.250

Fig. 4.20 Dimpling

Countersinking

Where thicker material precludes punching or dimpling, drilling and countersinking may be employed to accommodate flat heat screws. See Fig. 4.21. This figure illustrates the dimensions involved with countersinking for an 82° included angle flat head screw (100° is also a commonly used flat head type). Note the "sample



SIZE OF SCREW	MAX HEAD DIA	MAX SHANK DIA	NORMAL		PRECISION		ALL
			COUNTERSINK DIAMETER TOLERANCE ± .010	LEAST MATERIAL CONDITION	COUNTERSINK DIAMETER TOLERANCE ± .005	LEAST MATERIAL CONDITION	CLEARANCE HOLE ± .005
#2	.172	.086	.202	.085	.192	.075	.106
#4	.225	.112	.270	.102	.260	.092	.141
#6	.279	.138	.322	.118	.312	.108	.172
#8	.332	.164	.375	.147	.365	.137	.188
#10	.385	.190	.426	.162	.416	.152	.219
1/4	.507	.250	.545	.188	.535	.178	.281

Fig. 4.21 Countersinking

call-out" given for a #6 flat head screw ("precision" design). The call-out gives the (clearance) *hole diameter* and *countersunk diameter* (not the actual shank diameter and screw head diameter). Also note that the thickness of the material is normally at least the depth of the screw head.

Distortion from Bending

Figure 4.22 illustrates the distortion condition that occurs with forming operation. It is a particularly noticeable distortion when heavy material is bent with a sharper inside bend radius. It is "hardly noticeable" on material thicknesses less than 1/16 inch or when the inside forming radius is large in comparison to the material thickness.

The material on the inside of the bend is under compression, which results in this bulge condition on the edges. In addition, the edges on the outside of the bend are under tension and tend to pull in. This bulge or distorted condition is usually of no

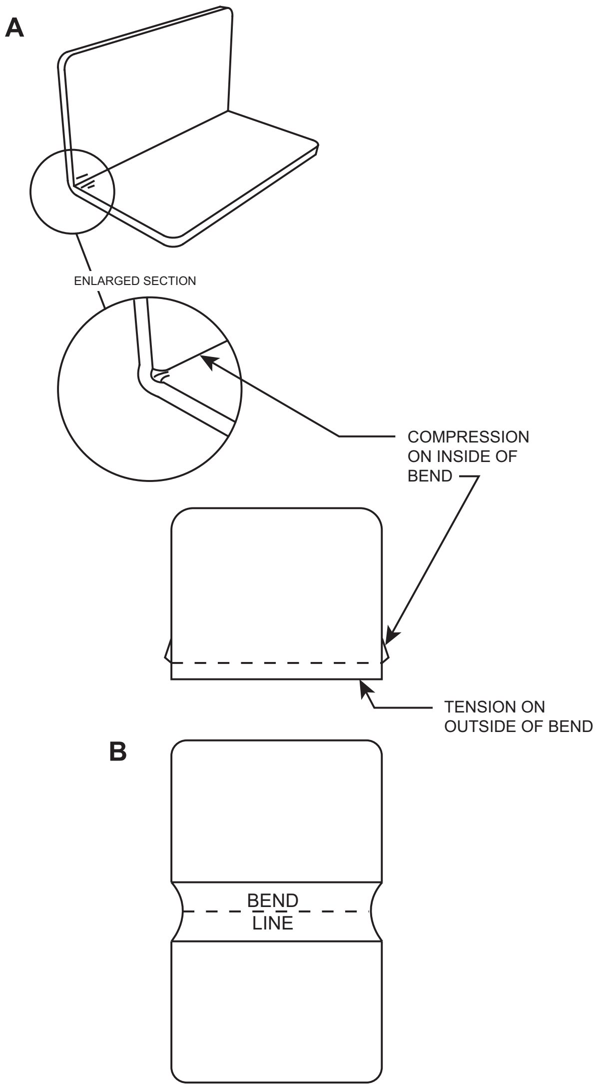


Fig. 4.22 Distortion from bending

concern and is accepted as standard practice. But, if this bulging will cause any interference with a mating part, then this should be referred to on the part drawing so a secondary operation can be considered to remove this interference. This extra operation may not require tooling but it will add to the cost of production.

Also shown in the figure is a blank developed to prevent interference resulting from bulge (without the extra production cost).

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