DESIGN FOR MANUFACTURE (DFM)
AND DESIGN FOR ASSEMBLY (DFA)

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OUTLINE

Economic Comments
General Comments Regarding Design
Design for Manufacturing
Design for Assembly
Lean Design and Lean Manufacturing

ECONOMIC COMMENTS

How well parts and assemblies are designed for manufacturing and assembly is literally a matter of “life or death” for a company. It is essential for engineers to have a working knowledge of how to produce a high quality product cheaper, better, and faster. Customers demand value – meaning they need a product that works well for them at a reasonable price.

The following equation use to be the norm in many industries for determining sales price:

Cost + Profit = Price

In other words, if the cost of producing a product increases, that cost can be passed on to the consumer (customer). In a highly competitive world, that is not valid. The equation that drives commerce has become:

Price (fixed) – Cost = Profit

In a competitive market, the price is fixed and will likely fall in the future. Therefore, the only way to increase profit is to decrease cost. This does not mean that the cheapest solution is the best solution – it means selecting the design that provides the best *value*. Value is what customers demand. It is a combination of both cost and quality.

There is tremendous waste in almost every corner of every company. That is the good news! There are many opportunities to reduce waste. Waste increases costs without adding value to the product. By reducing waste, costs decrease and profits increase.

The engineer's job is to determine the most economical way of producing a sufficiently high quality product. The good news is that quality and low cost are not mutually exclusive. Striving for optimal value is the challenge facing engineers.

GENERAL COMMENTS REGARDING DESIGN:

Keep it simple! Simple things are easier to produce and maintain.

Keeping it simple may be difficult (but engineers love a challenge).

Use standardized or interchangeable parts whenever possible

Use off-the-shelf items when ever possible. They are often cheaper and better quality than you can produce in-house (why?).

Take advantage of vendor expertise. Foundries know the casting business, machine shops now machining, etc. Team up with them.

Use as few of parts as possible, and where reducing total number of parts may not be possible, use common parts (identical) where possible.

Common parts and materials saves $$$. Unique parts and materials that are purchased must be:

- Purchased (a Purchase Order (PO) must be produced and processed)
- Received by someone somehow
- Inspected by someone somehow using something
- Moved to storage by someone somehow using something
- Stored (somewhere – floor space costs money, inventory costs money)
- Moved to assembly or fabrication by someone somehow using something
- Handled by the assembler or fabricator
- Installed by the assembler somehow using something
- Installation must be inspected by someone somehow using something
- Inventoried by someone somehow using something (kept track of)
- Paid for by someone somehow (book keeping expense)

Each unique part made in-house must be:

- Designed by someone somehow using something
- The engineering drawings must be maintained by someone somehow using something
- Engineering drawing must be interpreted by the mechanics and inspectors
- Parts require setup time to be produced
- Must be inspected by someone somehow using something
- Must be transported by someone somehow using something
- Must be tracked through the factory by someone somehow using something

- Must be stored by someone somehow using something
- Must be transported to assembly by someone somehow using something
- Must be installed by someone somehow using something
- Installation must be inspected by someone somehow using something

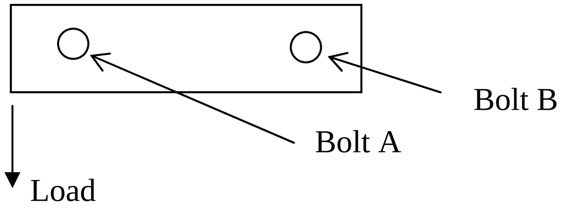
What opportunities exist to make two or more parts into a single part? Good candidates include (Corbett, et al.)

- no need for relative motion
- no need for subsequent adjustment between parts
- no need to disassemble for service or reparability
- no need for dissimilar materials

However, in the quest for combining parts into a single part, be careful NOT to:

- Create a large part that is difficult to manipulate or move
- Create a complex part that is difficult to fabricate
- Eliminate parts that provide fail-safe redundancies

Example:
While combining parts to make a single new part has advantages, the next best thing is to use common parts. As an overly simple example, consider the fasteners required to mount the plate to a support shown below. The service load is known to act only downward at the end. Bolt A has to carry significantly greater load than Bolt B, and therefore Bolt B may be smaller. Let's look at the advantages and disadvantages of selecting the bolts to be the same size or different sizes.



ADVANTAGES

Bolt B same as Bolt A	**Bolt B smaller than Bolt A**
	Having a smaller bolt at B may save bolt costs (small bolts are slightly cheaper, usually).
	Slight weight savings
Plate may be oriented in either direction (symmetric)	Would require the plate to be oriented a specific direction (may be desired, may not).
There are purchasing advantages to buying large quantities of one size rather than smaller quantities of two sizes (bulk discounts).	
Only one size of bolt must be tracked in inventory	
The mechanic only has to drill one size hole	
The mechanic needs only one size of wrench	

The mechanic needs to know only one torque specification – nothing to get confused	
The assembly area needs to only store one size of bolt, nut and washer	
Common size would make automation easier	
During servicing (maintenance) only one wrench is required to remove and reinstall the fasteners.	
The service department needs to stock only one size of fastener.	
Provides only one fastener rather than two to have problems with (such as missed delivery date from vendor, bad batch, etc.).	

While the above example might seem obvious and overly simple, it becomes more complicated when we consider larger systems; for example, an automobile. How many different sized fasteners should a single car have? How many different sized fasteners should Ford or General Motors vehicles have? The answer: as few as reasonable. Obviously, one does not want to use 12mm bolts on a instrument panel when a 2mm screw will suffice.

How can part count be reduced?

Design parts for multi-function. For example, a tube can be both a structural member as well as a fluid delivery device.

Design for multi-use. Extending the above example of fasteners and brackets to other designs within your company can reduce overall part count. For example, can similar designs use the same fasteners as you have used? What about the bracket? Is this an item your company uses frequently? If so, can a general purpose bracket be developed for most of these applications? What about the material used to produce the bracket? Will one material work for a variety of parts including basic dimensions? If so, you may need to inventory or only a few materials and stock sizes.

Think about future designs. Are there features you can add now that may extend the utility of the part to other designs?

Use modular designs. Modular designs consist of subassemblies that can be used in a variety of applications. For example, printer heads on desktop printers may be made common amongst many different models. This allows for improvements in the module to be applied quickly across the product line. It also improves serviceability of the product (service departments have lower inventory and training requirements.)

DESIGN FOR ASSEMBLY (DFA)

Why should a design engineer worry about how his or her design will be produced? The profitability of their employer, and hence their own job, may depend upon proper design for assembly and manufacturing, that's why. Before beginning detailed part design (which should involve design for fabrication), the engineer should first consider "design for assembly." This seems backwards – how do you design for assembly before designing the parts? Design needs to be iterative. If the parts are designed first, there is little that can be done to improve assembly. Concepts should be developed in order to have a good sense of what the individual parts will be, but before extensive detailed design is conducted, the concepts of "design for assembly" should be employed.

As discussed above, one aspect of DFA is to combine multiple parts into a single part – then there is less to assemble. According to Corbett et al., assembly costs can account for between 40 to 60% of total production costs, therefore, reducing part count is important. Corbett offers the following suggestions to reduce assembly costs:

Minimize part count (fewer things to assemble)
Use modularization
Orientation should be fool proof and easy
Locating parts should be made easy and fool proof
Sufficient space to allow access with tools and/or hands
Use common parts
Do not have parts that can tangle (star washers, wires, springs, etc.)
Fasteners are a pain in the … but they are sometime necessary. They may be avoided in certain circumstances where snap-together parts are adequate. Welding can be a viable alternative. Also, there are a variety of fasteners designed to minimize assembly costs. Make sure one person can install fasteners – fasteners should be able to be installed from one side
Provide lead in chamfers for parts to be inserted
Avoid visual obstructions
Parts should be assembled from one direction.

Anderson offers the following lists:

Errors of commission – installing the wrong part, installing the wrong orientation or position, damaging the part.
  Use standard parts
  Make different parts obvious
  Make sure the wrong part can NOT go into the wrong place
  Design the part so it can NOT be oriented improperly
  Revisions (changes) to the product (part) are clearly communicated to the manufacturer and implemented.

Errors of omission – leaving out parts or operations
  Design so omissions cannot happen – use geometries or special features that prevent subsequent assembly if prior parts are not installed (simple example: a belt cannot be installed until the pulley has been.)

Design so that omissions are easily noticed – use of color or geometry to make it obvious that something is missing. Shadow boards are used to identify when tools are not replaced, the same can be true of an assembly.
Eliminate process steps that rely on operator's memory – keep the assembly simple.

Sequence errors – errors consisting of sequence of events.
  Design the assembly or process so that sequence does not matter
  Design so assembly or process steps cannot happen in the wrong order
  Design so assembly sequence is obvious
  Clearly specify assembly sequence

DESIGN FOR MANUFACTURING (DFM):

The challenge is to design the part to function properly and to be produced economically.

However as always, when defining a problem, let's be careful not to suggest a solution. So far we have assumed our problem is "we need to determine the best design to be manufactured." A better problem statement might be "we need a part that performs functions *xyz*, what is the best way to obtain such a part?" That begs the question *do we need to manufacture it, or can we purchase it?* We should apply the following rule before worrying about design for manufacturing:

- Do not make what you can purchase off the shelf
    - Vendors have expertise you may not have
    - Takes advantage of high volume production (vendor sells to others)

- But there will come a time when we do need to worry about design for manufacturing. Before a part can be designed for manufacturing, the engineer must first determine what materials are viable choices. Material selection is critical. It involves performance (loads, environment (corrosion, thermal) etc.) as well as manufacturing methods. Selection of materials and processes is an iterative process. Engineers should not work in a "vacuum" – design should be done as a team. Design teams should include people with experience in manufacturing methods, materials, purchasing, sales, management, and it often should include vendors.

Three factors determine the best manufacturing process to be used for a given part: the material the part is to be made from, the geometric features of the part, and the quantity of parts to be produced. Brittle materials, for example, cannot be formed by bending or cold working.

Every part to be produced has a certain amount of "information content." Information content can be quantified as the number of dimensions required to define the geometry. When designed properly, increased information content does not have a significant effect on cast parts, but can have a very profound impact on machining costs. However, the initial capital expense required to produce foundry dies can be quite high. If only a few parts are to be produced, die casting does not make sense as the cost of the dies cannot be justified. A machined part can have relatively high piece cost (cost to produce a single part) but if only a few parts are to be fabricated, it may be more economical than casting.

The purpose of this section is to provide information regarding what sorts of processes produce what sorts of parts. The following manufacturing methods will be discussed:

- *Polymer Processing*
- *Metal Casting Processes*
- *Sheet Metal Processes*
- *Metal Shaping Processes*
- *Joining Processes*

Polymer Processing

Polymers are generally the least expensive of all engineering materials and provide highly economical finished products. They are the best choice for many designs.

While polymers may be machined, the vast majority of polymer parts are produced by molding. Thermoplastics (polymers that melt) are commonly formed with injection molding, thermoforming, extrusion, or extrusion blow molding. Thermosetting polymers (polymers that become solid due to cross-linking and do not melt) are formed by compression molding and transfer molding. In all of these processes, the polymer takes on the final shape due to direct contact with tooling (die, mold, or mandrel). Heating and cooling and/or “curing” (cross-linking) are part of all of these processes, and hence shrinkage is always an issue.

Design for molding (Eggert, El-Wakil)

Avoid designing parts with thick walls or heavy sections
Design parts without undercuts
Provide generous fillet radii
Ensure holes and similar features do not require complex tooling
Provide appropriate draft
Avoid large changes in thickness (including bosses)
Choose material for minimum tooling, processing, and material costs
Design external threads to lie on parting plane/surface
Add ribs for stiffening

Injection Molding (Poli)

Thermoplastic pellets are heated (melted) and injected into a metal cavity (mold) to produce the desired shape. A critical feature that dictates processing time is wall thickness. The part cannot be removed from the injection mold until it has sufficiently cooled. Thicker walls require longer time to cool and hence, they take longer to produce. Parts must be removed from the mold, and part features that prevent easy removal increase the cost of dies and increase process time. An example of such a feature is shown below (a cup with a hole in the side). A complex mold is required to produce the side hole.

{Discuss some "do's and do not's}

Thermoforming
While heated, thermoplastic sheets are squeezed between two dies. This process produces cup-like parts (thin walled, convex/concave parts without undercuts).

Extrusion
Thermoplastic pellets are melted and pressed through an extrusion die to create long uniform cross-section tubes, rods, sheets, etc. (remember making long "star" shapes with *play dough*?).

Extrusion blow-molding

Extrusion blow-molding starts with a hollow thin-walled thermoplastic part (typically produced by extrusion), entrapping it between two halves of a larger mold, and expanding it while hot into the final shape. This is used for making plastic drinking bottles and similar parts. This is analogous to blowing up a balloon inside a container – while under pressure, the balloon conforms to the shape of the container. If the balloon could then be "frozen" in shape it would be an example of *extrusion blow-molding*.

Compression Molding

Thermosetting polymers are often actually partially thermoplastic (copolymers). They may be solid (but soft) at room temperature and become softer upon initial heating. After extended heating, the polymer cures (cross-linking) and becomes strong. Compression molding is a forming process used with such materials.

A piece of thermosetting polymer (called a charge) is placed in a cavity and heated. The mold is closed, squeezing the charge so that it flows and fills the cavity. Heat is maintained to cure the polymer. The process takes between 20 seconds for small thin parts and up to 24 hours for very large thick parts.

Transfer Molding

Transfer molding is very similar to compression molding. The primary difference is that the charge is placed in an external cavity, and once it is soft it is forced into the mold through a sprue (similar a metal casting).

Metal Casting

Casting is well suited for parts with complex geometry, parts with internal features that are difficult to machine, and for moderate to high volume production. Casting is effective for materials that are expensive and difficult to machine as little raw material is wasted. It generally is not competitive for parts that can be made from extrusions or sheet metal, nor for very high melting point metals like tungsten.

There is much similarity between metal casting processes and polymer processes such as injection molding; therefore, the same general comments are applicable:

Design for molding (Eggert, El-Wakil)

Avoid designing parts with thick walls or heavy sections
Design parts without undercuts
Provide generous fillet radii
Ensure holes and similar features do not require complex tooling
Provide appropriate draft
Avoid large changes in thickness (including bosses)
Choose material for minimum tooling, processing, and material costs
Design external threads to lie on parting plane/surface
Add ribs for stiffening

<u>Design for Casting</u>; Poli and el-Wakil add the following comments:

Part geometry should allow for smooth flow to fill cavity evenly.
Cooling (solidification) should be quick to reduce cycle time and uniform to reduce warpage
The above two comments suggest that avoiding abrupt changes in geometry. They also suggest a balance on thickness – too thick and the part shrinks substantially and cools slowly, too thin and material may not flow sufficiently (recommended minimum is 0.25 inch walls but 0.06 inch for investment casting).
Use reinforcing ribs to provide strength and stiffness where needed in webs (or similar) rather than resorting to increasing overall part thickness.
Hot tears are caused by tensile stresses forming during cooling. These can be large if the part is self-constrained or constrained by the mold. Within the geometry of the part avoid over constraining.
If casting low ductility metals (eg. some cast irons) avoid projections that could be easily broken.
Minimize features that need to be subsequently machined
Consider cast-weld construction (welding together cast parts) to avoid complex expensive coring.

Common defects associated with castings include:

Inclusions (sand, slag, other foreign contamination)
Voids, porosity (caused by shrinkage)

Lack of fill (molten metal not filling the cavity)
Poor microstructure (due to cooling rate, and mold-quenching)
Residual stress (due to differential cooling rates, abrupt geometry changes, microstructural changes)
Hot tears (irregular crack with heavily oxidized surface created during cooling)
Cold shut (internal or surface crack likely caused where the flow of two molten streams meeting while relatively cold – hence not flowing into each other).
Shrinkage (surface sinks)
Quench cracks (created by subsequent heat treating of steel castings)
Defects may be found with X-ray, CT-scans and visual (for cracks)

Metals and alloys

Most metal alloys can be cast. But due to grain structure effects, shrink rates, high viscosity (low fluidity), etc. many are not. Specific alloys have been engineered for the sake of casting. Alloy elements to improve grain structure (grain refiners allow for more smaller equiaxed grains) and fluidity are often employed with casting alloys. In order to achieve desired properties, subsequent heat treating may be required.

There are three main casting processes:

Sand casting (*sand is formed around a pattern, the pattern is removed and molten metal is poured in its place*).
Investment casting (*a plaster (or similar) mold is formed around a wax pattern, was is melted and molten metal is poured in its place*)
Die casting (*very similar to injection molding: the molten metal is injected under pressure into a metal mold*)

Sand Casting

Sand castings are typically used for large parts. Due to the time required to pack sand, and to cut sprues, runners and risers, sand castings are typically used for low volume production.

Sand (and binder) is packed around a pattern. The pattern is typically made from wood or metal and has the same geometry as the completed part is to have. To compensate for shrinkage, the pattern is made slightly larger than the desired final part. The patterns can be a single piece (if one side of the part is flat) or two pieces (cope – top half, drag – bottom half). For hollow parts, a separate sand core is positioned inside the mold cavity.

Once the sand is packed in place, the pattern is removed. Passage ways must be cut in to the sand to allow molten metal to flow into the mold cavity. A *sprue* is a cylindrical hole cut through the cope into which the molten metal is poured. *Runners* allow metal to flow from the sprue into the mold cavity. The entrance from the runner into the cavity is referred to as the *gate*. *Risers* allow metal to flow out of the cavity and to some extent act as a reservoir providing "extra" material to help compensate for shrinkage.

Due to the low conductivity of the sand, cooling rates are relatively low. This results in large dendrite crystal formation that will affect material properties. Also, porosity (small voids) is common in sand castings. The surface finish of sand cast parts is relatively rough, and if a smooth surface is required castings must be subsequently machined.

Investment Casting
Used in relatively low volume production (less than 10,000 pieces). The process involves pouring wax into a mold, cooled, and removed. The wax is then covered in a plaster slurry (or similar). The plastic hardens and the wax is melted and removed leaving a cavity in the plaster. Molten metal is then poured into this cavity. Once it has hardened, the plaster is broken away. Very good surface finish is achievable and most parts do not need subsequent surface machining. The image at the right is an investment cast turbine blade.

Die Casting
This process is very similar to injection molding. Molten metal is injected into a metal cavity (mold). It is an economical process for high production volumes. Part shown at the right are produced from die casting.

Forging
Forging is a bulk deformation process performed on metals at elevated temperatures. Under large compressive force, the metal is forced to fill a cavity. It is a viable alternative for many castings. However, if an internal cavity is required in the part, then forging is not likely to be an option. Forging generally produces parts with higher strength and ductility and less defects than castings making the parts more robust against impact and fatigue. Castings generally are more isotropic where as forgings have direction properties due to elongated grain flow.

<u>Design for Forging</u>:

Due to high cost and limited life of tooling, forging is generally more expensive than alternatives.
Avoid large section thickness changes (as with castings)
Incorporate large fillet radii
A 5 to 10 degree draft is required (similar to castings)

Use easily formed materials such as aluminum alloys and copper alloys
Steel parts may be forged, but not as easy as aluminum. Very soft steel (spheroidized) is more easily forged, but the subsequent heat treating will remove any cold working effects.
Avoid external and internal undercuts. These features may not be possible to produce with forging.

Sheet Metal

Sheet metal forming consists of shearing, bending, and/or deep drawing. Shearing is performed to shape the outer geometry as well as to cut holes or other features within the sheet. Multiple cuts can be made simultaneously. Bending is performed to shape the part – analogous to folding paper. Deep drawing "pulls" or "stretches" the sheet to form the part in ways the bending cannot. With drawing, flat sheets can be formed into hemispherical or other such geometry.

Sheet metal forming is limited to highly ductile materials in the form of thin sheets (typically less than 0.25 inches, although thicker sheets may be fabricated). Typically, rolled sheets of metal are used – hence, even before being formed, the material will be anisotropic. Since this is a plastic deformation process, once the part is bent or drawn, elastic unloading will occur. Tight dimensional tolerances, therefore, may not be achieved.

Design for sheet metalworking
Minimize manufactured scrap
Avoid designing parts with narrow cutouts or projections
Keep side-action features to a minimum or avoid complexity
Reduce number of bend planes

Defects in Deep Drawn Parts:
Tearing
Wrinkling
Orange-peel or Luder's lines (surface "texturing")
Punch and die marks on surface

Metal Shaping

Other metal shaping processes include rolling, drawing, and extrusion. Rolling is done to reduce thickness substantially. "Drawing is the process of reducing the diameter of a wire, bar or tube by pulling it through a die of similar cross-section" (Poli). Extrusions form long parts with uniform cross section.

From Poli:

> Rolling is usually the first process used after casting an ingot. Cast ingots are rolled to form slabs (thick plates, say 40mm thick), billets (long thick rods with square, rectangular, or circular cross-sections), and blooms. Slabs are then rolled

into sheets, plates, and welded pipes, and billets are rolled and drawn into bars, rods, pipes, and wires. Blooms are roll formed into structural shapes such as I-beams and rails.

Machining

Machining processes remove material (by cutting) from a work-piece in order to produce a desired form. There are many different machining processes, but the following are basic:

Turning/Lathes –diametral features are cut into the part with a semi-stationary cutting tool while the work-piece is rotated.

Milling Machines – Slots, pockets, recesses, holes and other features are cut into the work-piece with a rotating cutting tool.

Boring and Drilling – Drilling is used to cut holes, boring can enlarge existing holes and do basic milling operations such as cutting grooves.

Design for machining, general comments

Use standard parts as much as possible.
Tight tolerances and smooth surface finish increase costs
Design the part to minimize quantity of material removal. Chips cost money to make, and the material in the chips that you have purchased is wasted.
Workpiece must have a “holding feature” – for turning operations, this would be a uniform diameter, for milling operations a flat base.
Radii in finished parts should equal cutting radii of the tool.
Thin parts can cause problems with machining. For thinner parts, beware of deflections that can be caused by cutting forces.
Use raw material available in standard forms (bars, sheets, rolls, etc.)
Employ standard features (holes, slots, chamfers, fillets, etc.)
Avoid sharp internal corners on turned parts
Allow for “run out”
For drilling, the surface should be perpendicular to the hole to be drilled.
For tapped holes, it is not possible to tap the entire length of a blind hole.
Internal features are generally more complicated to machine than external features.
The “golden rule” for designed parts to be machined is “never deviate from the primary axis” (Corbett, et al.). This means machined features should be added using one axis only (for milled parts, features should be added from one side only, for turned parts, features should be diameter only)

Joining Process

Joining is done for one of three reasons: to combine parts that were not fabricated as a single piece (due to complexity, weight, differing materials, fail safe design, etc.), to allow for adjustments and/or relative motion, and to join parts that are designed to be disassembled (for service, etc.). Some joining processes are permanent (welding, brazing, adhesives, rivets, etc.) and others are removable (threaded fasteners). For load-bearing structures, most joining processes involve a change in the nominal geometry and therefore introduce stress concentrations.

Fastening is a very important part of almost every design and the design of joints is critical. Fasteners typically transfer loads from one part into another, they must hold the two (or more) parts in fixed position, they must withstand temperature changes and vibrations which work to loosed threaded connections, and they may incorporate differing materials (which can greatly enhance corrosion problems). Although fasteners themselves are generally inexpensive (not always, some fasteners can cost thousands of dollars) fastened joints add significant expense to a part. Holes must be drilled, they may need to be de-burred or countersunk, fasteners must be inserted, wrenches applied to both the nut and bolt, and finally tightened to the proper torque. Not only do these steps add cost to the part, they introduce the possibility of defects at each step of the process.

Rivets

Riveting involves inserting a slug (cylinder) of ductile metal through holes cut/drilled/punched into the parts to be joined. The slug is plastically deformed forming a head and tail on the rivet that captivates the joint. Holes inherently are stress concentrations, however, if the rivet is "over expanded" to not only fill the hole but to expand the hole, compressive residual stresses can be produced in the hole to significantly increase fatigue life.

Threaded Fasteners

Bolts (threaded fasteners tightened with a nut) and screws (threaded fasteners inserted into threaded parts) are used for both for joints intended to be permanent as well as removable. A wide variety of designs exist for threaded fasteners – both for "bolts" and "nuts." Design problems arising from threaded fasteners include stress concentration at the hole and loosening of the joint. Methods used to prevent loosening include thread lock (adhesive) and mechanical locking (deformed threads, safety wire, cotter pins, etc.).

As with rivets, compressive residual stresses can be introduced into the hole. This can be achieved by cold-expansion of the hole prior to fastener insertion or by press-fit fasteners (specialty tight-tolerance shanks that are larger than the hole diameter) that cold-expand the hole during insertion.

Other Fasteners

There are hundreds if not thousands of different types of fasteners; each intended to help improve the performance of the joint or to reduce assembly costs.

Welding and Brazing

Welding is the process of melting the base metal and filler material (if used) to create a solid joint. Brazing is the process of melting the filler material (braze) and creating a metallic bond between the braze and base metal (base metal is not melted). Both processes require substantial heating of the base material that can alter its microstructure.

Common Welding Defects

Due to high localized heating and subsequent microstructure changes, high residual stresses, distortion and cracking are potential defects in welds. Distortion and cracking are detectable with non-destructive techniques (x-ray, ultrasound) but residual stresses remain hidden. The only way to know the effect of residual stresses is through destructive testing. Additionally, inclusions (slag) porosity, undercuts, lack of fusion, and lack of penetration can all degrade the structural quality of the weld.

Depending upon the alloy being welded, microstructure changes may include elimination of precipitation hardening, annealing (eliminating cold-worked properties), and creation of martensite, creation of dendrite crystals. To mitigate the effects of these typically undesirable consequences subsequent heat treating may need to be performed. Heat treating may be done locally around the weld, or the entire part may have to be re-heat treated. Even then, it may not be possible for the weld to have the same properties as the base metal (for example, if the base metal was coldworked).

Adhesive Joints

Adhesive bonding can be a strong inexpensive joining process. The base metal must be cleaned and in instances roughened. Depending upon the adhesive material, the joint is formed either by microscopic interlocking mechanisms (the adhesive flows in rough areas and when solidified become mechanically locked) and/or through intermolecular bonding.

Strength of an adhesive bond depends upon area of contact and the loading direction. Adhesive joints are strongest in shear, but have low tensile and pealing strength. Therefore, lap joints are generally used for these joints.

Shear Load (Good)

Tensile Load (not good)

Tensile Load
(not good – can peel)

Adhesive bonding has advantage over other joining techniques including room temperature (no thermal effects such microstructure changes and residual stress), can bond differing materials such as ceramics, and can bond dissimilar materials such as polymers to metals, metals to ceramics, et cetera. Disadvantages include difficult to inspect bond quality, lower strength than other methods (although it can be comparable strength), degradation over time, and lower service temperature limits. Additionally, cracks can form in the adhesive and propagate rapidly without detection.