Six Parameters of Cost-Effective Metal Casting Design
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Metalcasting is simultaneously a simple process and a complicated one. From a very elementary view, metalcasters just fill a mold with molten metal and let it solidify, forming a cast component. However, each of the different metalcasting processes offer distinct advantages and benefits when matched with the proper alloy. Capitalizing on these advantages takes an understanding of the power of casting geometry and the marriage of casting process and alloy.

Designers may choose from a large number of metalcasting processes and materials to achieve the right combination for optimized success. These include green sand metalcasting, one of the most common processes, or metal molding methods, such as permanent mold, diecasting and centrifugal casting. Other techniques use ceramic slurries for molding, such as investment (lost wax) and plaster casting, or patterns made of styrofoam or no pattern at all as with rapid prototyping. Each of these processes offer unique benefits that may enhance a cast component’s design, surface finish, mechanical properties and/or dimensional tolerances. In addition, the process may allow for a reduction in machining, coating or assembly costs.

The challenge for component designers is understanding the best combination of processes and technologies for cost-effective design. Due to the extensive geometric freedom offered by the metalcasting process, designers are provided a blank palette to detail their engineered solutions. The geometric freedom of the metalcasting process allows multiple parts assembled together to become a single cast component, enhancing the finished component’s material and mechanical properties and ultimately the end product’s effectiveness and productivity.

**Six Steps to Success**

The key to success lies in a better understanding of the relationship among geometry, various casting alloys and structure. There are six parameters (based on physics) that underlie cost-effective casting design as shown in Fig. 1.

All six, applied as a system, drive the geometry of casting design. Geometry is not only the result of casting design but is also the most powerful weapon in creating successful casting design. This six-faceted system is capable of optimizing geometry for castability, structure, downstream processing (machining and assembly) and process geometry (risering, gating, venting and heat transfer patterns) in the mold. The process geometry forms the casting geometry.

Following these rules also eliminates the confusion that often results from following some of the rules of thumb that have been developed over the years for common design situations. Further, the rules help when a design engineer leaves a familiar casting design realm for an unfamiliar one. For example, good aluminum bronze geometry is different than typical ductile iron geometry, and the molding process may need to supplement the different geometry with heat transfer techniques.

Quickly sorting through possible casting and process geometries by marking up blueprints or by making engineering sketches is the way to find optimal “system” geometry. An elegant result of good sketched brainstorming can be a solid model of the casting and its process geometry, the basis of rapid prototyping and/or computerized testing.

**Applying the System**

Optimizing casting geometry using the six-parameter system is not difficult. The six casting and structural characteristics influence important variables in designing, producing and using metal castings. These variables include:

- Casting method
- Design of casting sections
- Design of junctions between casting sections
- Surface integrity
- Internal integrity
- Dimensional capability
- Cosmetic appearance

**Fig. 1. Six parameters that drive cost-effective casting design**

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<th>Structural Properties</th>
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Casting geometry is the most powerful tool available to improve castability of the alloy and mechanical stiffness of the casting. Carefully planned geometry can offset alloy problems in fluid life, solidification shrinkage, pouring temperature and slag/dross forming tendency. Section modulus, an attribute of structural geometry, has the capability to increase stiffness and/or reduce stress – a capability that can be very important when applied to alloys with lower strength and stiffness. Modulus of elasticity, an alloy’s inherent stiffness, can be combined with section modulus and section length to limit or allow deflection in a casting design.

To preview geometry’s ability to influence the four characteristics of “castability,” consider the simple steel fabrication in Fig. 2a that was converted into carbon steel and gray iron casting designs, Figs. 2b and 2c, respectively. The fabrication is a guide block to constrain low velocity/low load sliding motion, and it was welded from rectangular bar stock, subsequently milled, drilled and tapped. The geometries in 2b and 2c are considerably different as a consequence of differences among fluid life, solidification shrinkage type and amount, pouring temperature and tendency to form nonmetallic inclusions (See Junctions, Fig. 3).

Examining in more detail each of the six parameters that underlie cost-effective casting design illustrates their influence. The first four factors affect casting properties while the last two affect structural properties. Additional details on each of these parameters can be found in “Cost-Effective Casting Design,” in the 2006 AFS Casting Source Directory.

1. Fluid Life

Fluid life more accurately defines the alloy’s liquid characteristics than does the traditional term “fluidity.” Molten metal’s fluidity is a dynamic property, changing as the alloy is delivered from a pouring ladle, die casting chamber, etc. into a gating system and finally into the mold or die cavity.

Fluid life affects the design characteristics of a casting, such as the minimum section thickness that can be cast reliably, the maximum length of a thin section, the fineness of cosmetic detail (like lettering and logos) and the accuracy with which the alloy fills the mold extremities.

2. Solidification Shrinkage

There are three distinct stages of shrinkage as molten metals solidify: liquid shrinkage, liquid-to-solid shrinkage and patternmaker’s contraction.

**Liquid shrinkage** is the contraction of the liquid before solidification begins. It is not an important design consideration.

**Liquid-to-solid shrinkage** is the shrinkage of the metal mass as it transforms from the liquid’s disconnected atoms and molecules into the structured building blocks of solid metal. The amount of solidification shrinkage varies greatly from alloy to alloy. Table 1 provides a guide to the liquid-to-solid shrinkage of common alloys. As shown, shrinkage can vary from low to high shrinkage volumes.
Alloys are further classified based on their solidification type: directional, eutectic-type and equiaxed (see definitions in Table 1). The type of solidification shrinkage in a casting is just as important as the amount of shrinkage. Specific types of geometry can be chosen to control internal integrity when solidification amount or types are a problem.

**Patternmaker’s Contraction** is the contraction that occurs after the metal has completely solidified and is cooling to ambient temperature. This contraction changes the dimensions of the casting from those of liquid in the mold to those dictated by the alloy’s rate of contraction. So, as the solid casting shrinks away from the mold walls, it assumes final dimensions that must be predicted by the pattern- or die-maker. Tooling design and construction must compensate for it. The unpredictable nature of patternmaker’s contraction makes tooling adjustments inevitable.

### 3. Slag/Dross Formation

Among metalcasters, the terms slag and dross have slightly different meanings. Slag typically refers to high-temperature fluxing of refractory linings of furnaces/ladles and oxidation products from alloying. Dross typically refers to oxidation or reoxidation products in liquid metal from reaction with air during melting or pouring, and can be associated with either high or low pouring temperature alloys.

Some molten metal alloys generate more slag/dross than others and are more prone to contain small, round-shaped nonmetallic inclusions trapped in the casting. Unless a specific application is exceedingly critical, a few small rounded inclusions will not affect casting structure significantly. In most commercial applications, nonmetallic inclusions are only a problem if they are encountered during machining or appear in a functional as-cast cosmetic surface.

### 4. Pouring Temperature

The refractory characteristics and limitations of mold materials will affect the choice of the molding process and design. When pouring temperature approaches a mold material refractory limit, the heat transfer patterns of the casting geometry become important.

Sand and ceramic materials with refractory limits of 3000-33000 F (1650-1820C) are the most common mold materials. Metal molds, such as those used in diecasting and permanent molding, have temperature limitations.
Except for special thin designs, all alloys that have pouring temperatures above 2150°F (1180°C) are beyond the refractory capability of metal molds. It's also important to recognize the difference between heat and temperature; temperature is the measure of heat concentration. Lower temperature alloys also can pose problems if heat is too concentrated in a small area—better geometry choices allow heat to disperse into the mold.

**Design of Junctions**

A junction is a region in which different section shapes come together within an overall casting geometry. Simply stated, junctions are the intersection of two or more casting sections. Fig. 3 illustrates both “L” and “T” junctions among the four junction types, which also include “X” and “Y” designs.

Designing junctions is the first step to finding castable geometry via the six-faceted system for casting design. Fig. 3 illustrates that there are major differences in allowable junction geometry, depending on alloy shrinkage amount and pouring temperature. Alloy 1 allows abrupt section changes and tight geometry, while alloy 3 requires considerable adjustment of junction geometry, such as radiusing, spacing, dimpling and feeding.

![Diagram of Junctions](image)

**Fig. 3.** Junction geometry is important to alloys with considerable shrinkage and/or pouring temperature. The casting geometry at left shows “L” and “T” junctions. The illustrations at right show the consequences of junction design and geometry on increasingly difficult combinations of shrinkage amount and/or temperature. In reviewing Fig. 2, the gray iron junctions (2c) are similar to type 1 above, and steel junctions (2b) are similar to type 3.

**Considerations of Secondary Operations in Design**

System-wide thinking also must include the secondary operations, such as machining, welding and joining, heat treating, painting and plating. One aspect that affects geometry is the use of fixturing to hold the casting during machining. Frequently, the engineers who design machining fixtures for castings are not consulted by either the design engineer or the casting engineer as a new casting geometry is being developed. Failure to do so can be a significant oversight that adds machining costs.

It is best to define the casting dimensional datums as the significant installation surfaces, in order of function priority, based on how the casting is actually used. Targets for machining fixtures should be consistent with these datum principles. There is nothing more significant in successful CNC and transfer line machining of castings than the religious application of these datum fixture and targeting principles.

**Drawings and Dimensions**

The tool that has had the most dramatic positive impact on the manufacture of parts that reliably fit together is geometric dimensioning and tolerancing (GD&T), as defined by ANSI Y14.5M—1994. When compared to traditional (coordinate) methods, GD&T:

- Considers tolerances, feature-by-feature;
- Minimizes the use of the “title block” tolerances and maximizes the application of tolerances specific to the requirement of the feature and its function;
- Is a contract for inspection, rather than a recipe for manufacture. In other words, GD&T specifies the tolerances required feature-by-feature in a way that does not specify or suggest how the feature should be manufactured. This allows casting processes to be applied more creatively, often reducing costs compared to other modes of manufacture, as well as finish machining costs.
GD&T encourages the manufacturer to be creative in complying with the drawing's dimensional specifications because the issue is compliance with tolerance, not necessarily compliance with a manufacturing method. By forcing the designer to consider tolerances feature-by-feature, GD&T often results in broader tolerances in some features, which opens up consideration of lower cost manufacturing methods, like castings. Fig. 4 illustrates GD&T principles applied to a design made as a casting. Note the use of installation surfaces as datums and the use of geometric zones of tolerance.

**Factors that Control Casting Tolerances**

How a cast feature is formed in a mold has a significant effect on the feature's tolerance capability. The following six parameters control the tolerance capability of castings. In order of preference, they are:

1. Molding Process
2. Casting Weight and Longest Dimension
3. Mold Degrees of Freedom
4. Draft
5. Patternmaker’s Contraction
6. Cleaning and Heat Treating

When considering the breadth and depth of geometry’s importance in casting design, from its influence on castability, the geometry of gating/risering, structural form, cosmetic appearances and downstream fixturing, extensive brainstorming of geometry is highly recommended. The standard for “optimal” casting geometry is high, but the possibilities for geometry are limitless. Therefore, it is important to find ways of exploring geometry quickly, such as engineering sketching, before committing to a print or solid model.

**Structural Properties**

In the preceding section, it was stated that: 1) castability affects geometry, but 2) well-chosen geometry affects castability. In other words, a geometry can be chosen that offsets the metallurgical nature of the more difficult-to-cast alloys. Knowing how to choose this “proactive” geometry is the key to consistently good casting designs—in any casting alloy—that are economical to produce, machine and assemble into a final product.

The casting properties section focused on the casting engineering spectrum of geometry for the benefit of design engineers, while the structural properties section covers the design engineering spectrum of geometry for the benefit of casting engineers. Geometry found between these two spectrums offers boundless opportunity for castings.

**Structural Geometry**

Because castings can easily apply shape to structural requirements, most casting designs are used to statically or dynamically control forces. In fact, castings find their way into the most sophisticated applications because they can be so efficient in shape, properties and cost. Examples are turbine blades in jet engines, suspension components (in automobiles, trucks and railroad cars), engine blocks, airframe components, fluid power components, etc.

When designing a component structurally, a design engineer is generally interested in safely controlling forces through choice of allowable stress and deflection. Although choice of material affects allowable stress and deflection, the most significant choice in the designer’s structural arsenal is geometry. Geometry directly controls stiffness and stress in a structure.

Improved efficiency in solid modeling software has led to an interesting design dilemma. Solid models are readily applicable to Finite Element Analysis (FEA) of stress. FEA enables the engineer to quickly evaluate stress levels in...
the design, and solid models can be tweaked in shape via the software so geometry can be optimized for allowable, uniform stress. Fig. 5 depicts a meshed solid model and a stress analysis via the mesh elements.

Fig. 5. The mesh (l) shows the size of the finite elements that are used for the FEA stress analysis (r). The high-stress areas (red) could be reduced with a geometry change. Photo courtesy of General Motors

However, optimum geometry for allowable, uniform stress may not be acceptable geometry for castability. When a casting engineer quotes a design that considered structural geometry only, requests for geometry changes are likely. At this point, the geometry adjustments for castability may be more substantial than the solid model software can “tweak.” This can lead to higher-than-expected casting prices, or starting over with a new solid model.

A practical solution to this problem is to concurrently engineer geometry considering structural, casting and downstream manufacturing needs. The result can be optimal casting geometry. The most efficient technique is to make engineering sketches or marked sections and/or views on blueprints. The idea is to explore overall geometry before locking in to a solid model too quickly. Engineering sketches or mark-ups are easy and quick to change—even dramatically—in the concurrent brainstorming process; solid models are not. A solid model should be the elegant result, not the knee-jerk start.

5. Section Modulus

Playing with sketches before building a solid model requires finding another way to evaluate stress and deflection. This “other way” is the essence of efficient structural evaluation of geometry in casting design.

The equivalent of FEA for the design engineer’s structural analysis is computerized “mold filling” and “solidification analysis” for the casting engineer; the basis for both is a solid model.

The “other way” for the casting engineer is the manual calculation of gating, solidification patterns and riser sizes; these are established, relatively simple mathematical techniques used long before the advent of solid models. (See References.)

This “other way” for the design engineer is not so simple. To take full advantage of engineering sketching/print marking as a way to brainstorm geometry requires quickly evaluating stress and deflection at important cross sections in the sketches. As the design engineer well knows, the classic formulas for bending stress, torsional stress and deflection are relatively simple. Each, however, contains the same parameter, Section Modulus, which is a function of shape and difficult to compute. Therefore, a quick, simple way to compute or estimate Section Modulus (more specifically, its foundational parameter, Area Moment of Inertia) is needed so that we can move from sketch to improved sketch in our casting geometry brainstorming.

Quick Method for Estimating Area Moment of Inertia from Sketches

Although there are five kinds of stress (tension, compression, shear, bending and torsion), the interesting ones for complex structures are bending and torsion, and their equations are shown in Fig. 6. (If more than one type of
stress is involved in the same section, the Principle of Superposition allows the individual stress types to be analyzed separately and then added together; once again, the larger of the stresses to be combined are usually from bending or torsion.)

In all three cases, the relationships apply to a cross-section of the geometry. It is easy to draw a scale cross-section, whether its source is an engineering isometric sketch or a marked-up view on a blueprint.

Finding a way to quickly estimate Area Moment of Inertia allows engineers to readily estimate stresses in brainstormed sketches as well as estimate whether deflection will increase or decrease. Note that Area Moment of Inertia is in the denominator in each relationship, meaning that increased Area Moment of Inertia reduces stress and deflection.

The estimation method recommended is based on three principles. One is intuitive, and the other two are from the mathematics of engineering mechanics. The principles are:

1. **The design engineer’s sense of load magnitudes and component size/shape** — Engineers routinely use this sense to sketch sized shapes that are in the ballpark of the final design. Casting engineers can learn this “sense,” and when they do, they become effective concurrent engineering partners in their customers’ casting designs.

2. **The equation for Area Moment of Inertia (Fig. 7)** — Although the calculus for an interesting casting cross-section can be very difficult, the relationship expressed between “depth of section” (Y) and “change in cross-sectional area” (dA) is very simple. The position and shape of the two rectangles in Fig. 7 (top) clearly demonstrates this simple yet powerful relationship. The change in shape of the inside of the tube (at bottom of Fig. 7) is an even more dramatic illustration. Calculations weren’t made in either case, but the qualitative impact of \( Y^2 \Delta A \) on stiffness and stress is unmistakable.

3. **Area Moment of Inertia** — Once the engineering sense of structural size and \( Y^2 \Delta A \) have been applied qualitatively to a sketched cross-section, the Parallel Axis Theorem can be applied to simple building blocks in the cross-section to estimate Area Moment of Inertia quantitatively. A numerical value for Area Moment of Inertia is required to calculate the stress level in the sketched cross-section. The Parallel Axis Theorem is illustrated in Fig. 8 (see Appendix for example equation).

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**Fig. 6.** Shown here are the stress formulas for bending and torsion. Also shown is a proportionable (simplified) relationship for deflection.
6. Modulus of Elasticity

The measure of a material’s stiffness (without regard to material geometry) is known as the Modulus of Elasticity. In the case of metals, it is a function of metallurgy, and it is a mechanical property of the metal alloy. Modulus of Elasticity varies widely among materials, and it varies significantly among metals; that is, some metals are considerably stiffer than others. Alloy groups tend to have the same modulus value; for example, the entire family of steels (carbon, low alloy and high alloy) all have the same modulus value of 30x 10^6 lb/in.².

Modulus of Elasticity is an important parameter in structural design, and it is directly involved in the relationship between casting geometry and deflection. A larger Modulus of Elasticity means less deflection. For example, a steel casting would deflect less than an aluminum casting of identical geometry simply because steel is stiffer than aluminum.

Modulus of Elasticity is simply the elastic slope of the stress/strain diagram created when the casting facility’s metallurgical lab pulls a test bar. Fig. 9 illustrates qualitatively the results of pulled test bars for common groups of casting alloys. The steepness of the elastic slope of each graph indicates the alloy group’s stiffness.

One subtlety about Modulus of Elasticity is that it is not affected by heat treatment. However, heat treatment can affect the height of the elastic slope. This is very important because the height at which the elastic slope begins to curve is called the metal’s “yield stress.” This is the stress level at which plastic deformation begins and the metal is permanently affected. Stresses should be designed below this level so that deflections in the casting under load do not damage it. For example, consider the family of steels in Fig. 9; heat treatment can considerably raise the point at which an alloy steel yields. Although the steel is no stiffer at higher stress levels, it can withstand the additional stress without damage. The same is true for heat-treatable aluminum alloys, but the magnitude of heat treatment’s effect on yield stress is considerably less than that for steels.

Fig. 8. This relationship enables the quick estimation of Area Moment of Inertia via building blocks. The building blocks must be referenced to the centroid. The centroid can be calculated, but it is easier and quicker to use a “paper doll” of the cross-section and simply find its balance point.

Fig. 9. As shown, alloy families vary considerable in stiffness. The steepness of the elastic slope is the modulus of elasticity. Heat treatment doesn’t change the slope, but it can raise the yield points.
Summary

Fig. 10 and the Appendix illustrate a hypothetical casting design using the recommended six factors behind good geometry selection. The first four factors describe the alloy’s “castability.” The final two factors are from engineering mechanics and are Modulus of Elasticity and Section Modulus, an aspect of Area Moment of Inertia.

As a ductile iron casting design (see shrinkage characteristics in Table 1), the following example is intended to illustrate structural geometry more than geometry for castability. As noted previously, for alloys that are highly castable like ductile iron, it is convenient to focus first on geometry for structure and let the alloy’s friendly casting characteristics adapt to the structural needs.

The ductile iron casting could be made in a horizontally-parted sand mold with the center cylindrical section pointed down. One core would form the “tongue and groove” tabs, bolt holes and hollowed center of the cylinder. A second core would form the top side of the I-beam feature and the corresponding bottom side of the four-hole plate. Two risers would feed solidification shrinkage in the center section from the tab sides of the four-hole plate. A third riser would follow the side of the second core and feed the cylindrical end of the I-beam section.

This casting design is nothing more than an engineering sketch with a sense of size and proportion. Using the “quick method” of sketching cross-sectional areas, Area Moment of Inertia can be estimated with simple building blocks and minimal calculation. Once a value is known, stress can be easily calculated for the chosen cross-section. A relative measure for deflection can be easily calculated as well.

Final design would be a solid model, based on at least two or three sketched iterations of combined structural and castable geometry. Detailed structural evaluation could then be done via FEA. Any remaining stress problems could be easily solved by tweaking the solid model, which is already close to optimal geometry. Finally, the solid model could be modified to add risers and a gating system so that computer analysis of solidification and mold filling could verify the geometry chosen for castability.

References

“Basic Principles of Gating & Risering,” AFS’ Cast Metals Institute
“Risering Steel Castings (1973),” Steel Founders’ Society of America
APPENDIX: Quick-Method Stress Calculation
(Refer to Fig. 10)

TOOLBOX:
- Bending Stress Formula: p. 7
- Torsional Stress Formula: p. 7
- Parallel Axis Theorem & "Paper Doll" Centroid: Fig. 8
- Principle of Superposition: p. 7
- Sketched-To-Scale Cross-Sections: See Right
- Building Blocks of Area
  - Moment of Inertia: See Below

RECTANGLES
Area = bh
Centroid
X-Y = b/2
Y-Y = b/2
Moment of Inertia
I_x = bh^3/12
I_y = bh^3/12

ELLIPSE
Area = πab
Centroid
X-X = 0
Y-Y = 0
Moment of Inertia
I_x = πab^3/4
I_y = πa^3b/4

CIRCLE
Area = πr^2
Centroid
X-X = 0
Y-Y = 0
Moment of Inertia
I_x = r^4/4
I_y = r^4/4

HALF CIRCLE: AXIS XX
Area = 1.5708r^2
Centroid
x_Y = 0.4044r
y_Y = 0
Moment of Inertia
I_x = 0.1998r^4
I_y = 0.5327r^4

HALF ELLIPSE
Area = πab/2
Centroid
X-Y = 0
Y-Y = 0
Moment of Inertia
I_x = 0.3927ab^4
I_y = 0.1698ab

CROSS-SECTION 1 STRESS CALCULATION
Area Moment of Inertia
Top Rectangle
I = 10/12 x 10^4 in. = 8.33 x 10^4 in. = 5.98 in.^2
Middle Rectangle
I = 8.33 x 10^4 in. = 5.98 in.^2
Bottom Rectangle
I = 8.33 x 10^4 in. = 5.98 in.^2

Maximum Bending Stress in Tension:
Bending Moment x Y = 5000 lb x 10 in. = 50,000 lb-in.
Area Moment of Inertia
I = 10,000 in.^4

CROSS-SECTION 2 STRESS CALCULATION
Area Moment of Inertia
Outside Cylinder
I = πr^4/2 = π(0.05)^4/2 = 1.57 in.^4
(Inside Cylinder)
I = πr^4/4 = π(0.04)^4/4 = 0.079 in.^4

Maximum Torsional Stress:
Torque x Y_{max} = 5000 lb x 12 in. = 60,000 lb-in.
Area Moment of Inertia
I = 10,200 in.^4

CROSS-SECTION 3C STRESS CALCULATION
Area Moment of Inertia
Bottom Outside Half Circle
I = 0.1998r^4/2 (167.44 in. = 0.1998 x 0.05^4/2 = 0.2 x 0.00244 = 5.0 lbs/m)
(Bottom Inside Half Circle)
I = 0.3927ab^4 (167.44 in. = 0.3927 x 0.05 x 0.05 = 0.0194 lbs/m)

Maximum Bending Stress in Tension:
Bending Moment x Y_{max} = 3000 lb x 6 in. = 18,000 lb-in.
Area Moment of Inertia
I = 13,333 in.^4

CONCLUSION:
The ductile iron alloy choice for this casting is 65/45/12, and the design safety factor is 4; therefore, the design stress should be one-fourth of the yield stress, or about 11,000 lb/in.². Although a fairly tough alloy, the microstructure is not quite as strong in tension as it is in compression. It is easy to adjust casting geometry to reduce tensile stress as illustrated by cross-sections 3A, 3B, and 3C. By the Principle of Superposition, the stress from torsion and bending in the center cylinder is additive (shear stress has been ignored for simplicity). The combined stress at cross-section 3C would be roughly 12,500, slightly higher than the design stress. A final geometry iteration to slightly increase the diameter of the base cylinder in the region of 3C toward the base would sufficiently reduce torsion stress. This would be a tapering diameter toward the base that also would assist the solidification feed path from the plate through the cylinder to its end. Thus, geometry for costability and structure complement each other in a good casting design.