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<td>Contact</td>
<td>40</td>
</tr>
</tbody>
</table>
Castings present a cost effective solution for the manufacture of complex shapes that reduce part count and improve the affordability, manufacturability and reliability of the end product.

Successful casting design requires a specialized expertise and an appreciation for the strengths and weaknesses of the foundry process.
Definition: Investment Casting is a foundry process by which a metal part is produced from a ceramic (investment) mold that has been formed by a disposable (wax or plastic) pattern.

Investment Casting is sometimes also known as Lost Wax Casting or as Precision Casting.
Investment Casting Strengths

- Complexity at Incremental Cost
  - Combine multiple pieces into one
  - Reproduce fine detail
  - Contours and rounded surfaces
  - Undercuts

- Near Net Shape
  - Minimize secondary operations
  - Minimal stock allowance

- Design Freedom
  - No draft angle
  - Internal configuration

- Low Initial Investment
  - Moderate tooling costs
The Characteristics of a Potential Investment Casting

- Alloy Machinability
  - Near Net Shape
  - Reduced Secondary Machining

- Eliminate Assembly & Fabrication
  - Reduction of Part Count

- Light Weight
  - Optimum wall .070 - .120"

- Cosmetic Appearance
  - 60 – 200 RMS

- Precision Tolerances
  - ±0.005 inch per inch

2014 – AFS / Metal Casting Design & Purchasing
“Casting of the Year” - Honorable Mention
IC Capabilities  Capabilities as compared to other casting processes

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>TOOL COST</th>
<th>UNIT COST</th>
<th>METAL OPTIONS</th>
<th>DESIGN FREEDOM</th>
<th>VOLUME CAPABIL.</th>
<th>DRAFT REQ’D</th>
<th>TOLERANCE CONTROL</th>
<th>SURFACE FINISH</th>
<th>WALL MIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLASTER MOLD</td>
<td>Low</td>
<td>High</td>
<td>Few</td>
<td>Avg.</td>
<td>Low</td>
<td>Yes</td>
<td>Avg.</td>
<td>Avg.</td>
<td>Large</td>
</tr>
<tr>
<td>RESIN SHELL MOLD</td>
<td>Avg.</td>
<td>Avg.</td>
<td>Avg.</td>
<td>Avg.</td>
<td>All</td>
<td>Yes</td>
<td>Avg.</td>
<td>Poor</td>
<td>Large</td>
</tr>
<tr>
<td>SAND CAST</td>
<td>Low</td>
<td>Avg.</td>
<td>Most</td>
<td>Avg.</td>
<td>All</td>
<td>Yes</td>
<td>Poor</td>
<td>Poor</td>
<td>Large</td>
</tr>
</tbody>
</table>
Drawing Notes
At Minimum Drawing Notes for castings must address:
- Material & Heat treatment and/or Material Specification
- Fillet Radius allowance
- Edge Radii allowance

Additional Drawing notes may be required for:
- Material Testing requirements
- In-Process (Cosmetic) Weld Repair
- Non Destructive Testing
- Part Marking
- Tolerances, Flatness, Perpendicularity
- Surface Texture
Material and/or Material Specification

- Do not include a Specification unless necessary for the application
  - Unnecessary requirements may add unintended cost
  - Specifications generally include testing & reporting requirements
    - Chemistry testing requirements
    - Mechanical testing requirements
    - Weld repair restrictions

- Select Material Specifications germane to Investment Casting
# Recommended Aluminum Alloy Specifications

## Aluminum Alloy Reference Table

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Reference Specification</th>
<th>Castability</th>
<th>Heat Treat Condition</th>
<th>Tensile Strength (psi)</th>
<th>Yield Strength (psi)</th>
<th>Elongation (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>354</td>
<td>AMS-A-21180</td>
<td>Very Good</td>
<td>T6</td>
<td>43,000</td>
<td>33,000</td>
<td>2</td>
<td>Stronger but less ductile than A356</td>
</tr>
<tr>
<td>C355</td>
<td>AMS 4215 ASTM B618</td>
<td>Very Good</td>
<td>T6</td>
<td>37,000</td>
<td>30,000</td>
<td>1.0</td>
<td>Stronger but less ductile than A356</td>
</tr>
<tr>
<td>356</td>
<td>AMS 4260 ASTM B618</td>
<td>Excellent</td>
<td>T6</td>
<td>33,000</td>
<td>22,000</td>
<td>3</td>
<td>Most commonly cast IC alloy.</td>
</tr>
<tr>
<td>A356</td>
<td>AMS 4218 ASTM B618</td>
<td>Excellent</td>
<td>T6P T6</td>
<td>33,000</td>
<td>27,000</td>
<td>3</td>
<td>Good Strength &amp; Corrosion Resistance. Excellent machining, welding, plating or anodizing</td>
</tr>
<tr>
<td>A357</td>
<td>AMS 4219</td>
<td>Very Good</td>
<td>T6P</td>
<td>41,000</td>
<td>32,000</td>
<td>3</td>
<td>Higher strength than A356. Contains Beryllium.</td>
</tr>
<tr>
<td>F357</td>
<td>AMS 4289</td>
<td>Very Good</td>
<td>T6</td>
<td>41,000</td>
<td>32,000</td>
<td>3</td>
<td>Higher strength than A356. Beryllium Free</td>
</tr>
<tr>
<td>A201</td>
<td>AMS 4229 ASTM B618</td>
<td>Poor</td>
<td>T7 T6</td>
<td>60,000</td>
<td>50,000</td>
<td>3</td>
<td>Very strong. Is difficult to cast and yields poor surface finish</td>
</tr>
<tr>
<td>D712</td>
<td>ASTM B26</td>
<td>Poor</td>
<td>T5</td>
<td>34,000</td>
<td>25,000</td>
<td>4</td>
<td>Can be brazed. Self aging alloy.</td>
</tr>
<tr>
<td>205</td>
<td>AMS 4471</td>
<td>Very Good</td>
<td>T7</td>
<td>66,000</td>
<td>59,000</td>
<td>3</td>
<td>Strongest cast alloy available</td>
</tr>
</tbody>
</table>
## Recommended Copper based Alloy Specifications

### Brass and Bronze Alloy Reference Table

<table>
<thead>
<tr>
<th>CDA Common Name</th>
<th>Reference Specification</th>
<th>Castability</th>
<th>Condition</th>
<th>Tensile (psi)</th>
<th>Yield (psi)</th>
<th>Elongation (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>C836 Red Brass</td>
<td>ASTM B584</td>
<td>Good</td>
<td>As Cast</td>
<td>30,000</td>
<td>14,000</td>
<td>20</td>
<td>Good Brazability &amp; Machinability</td>
</tr>
<tr>
<td></td>
<td>ASTM 4855</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C854 Yellow Brass</td>
<td>ASTM B584</td>
<td>Good</td>
<td>As Cast</td>
<td>30,000</td>
<td>11,000</td>
<td>20</td>
<td>Brazable, Yellow Color</td>
</tr>
<tr>
<td>C861 Manganese Bronze</td>
<td>Mil-C-22087 Composition 7</td>
<td>Good</td>
<td>As Cast</td>
<td>90,000</td>
<td>45,000</td>
<td>18</td>
<td>Weldable, Poor Machinability</td>
</tr>
<tr>
<td>C862 Manganese Bronze</td>
<td>ASTM B584</td>
<td>Good</td>
<td>As Cast</td>
<td>90,000</td>
<td>45,000</td>
<td>18</td>
<td>Weldable, Poor Machinability</td>
</tr>
<tr>
<td>C863 Manganese Bronze</td>
<td>ASTM B584</td>
<td>Good</td>
<td>As Cast</td>
<td>110,000</td>
<td>690,000</td>
<td>12</td>
<td>High Strength, Poor Machinability</td>
</tr>
<tr>
<td>C874 Silicon Brass</td>
<td>ASTM B584</td>
<td>Very Good</td>
<td>As Cast</td>
<td>50,000</td>
<td>21,000</td>
<td>18</td>
<td>Good Castability</td>
</tr>
<tr>
<td>C954 Aluminum Bronze</td>
<td>ASTM B148</td>
<td>Good</td>
<td>As Cast Heat Treated</td>
<td>70,000</td>
<td>30,000</td>
<td>12</td>
<td>Brazable, Weldable, Poor Castability</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90,000</td>
<td>45,000</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>C955 Aluminum Bronze</td>
<td>ASTM B148</td>
<td>Very Poor</td>
<td>As Cast Heat Treated</td>
<td>90,000</td>
<td>40,000</td>
<td>6</td>
<td>Brazable, Weldable, Poor Castability</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>110,000</td>
<td>60,000</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>C969 Copper Nickel Tin IC100 Toughmet®</td>
<td>AMS 4863</td>
<td>Very Good</td>
<td>Hipped and Heat Treated</td>
<td>113,000</td>
<td>96,000</td>
<td>2</td>
<td>High Strength, Low Friction, Corrosion Resistant, Excellent Machinability</td>
</tr>
</tbody>
</table>
Fillets (Inside Corners)

- Added to mitigate a stress riser in casting
- Insufficient fillet becomes a cost driver
  - Escalates frequency of “cracks”
  - Increases need of weld repair
  - Increases metal penetration of shell
- Excessive fillet can create a “hot” spot
- 060”-.120”R fillet is generally optimal
  - Fillet should be representative of wall thickness
- Express Fillet Radii with a “Max” tolerance

Note - Bubbles grow at ‘nucleation sites’. The bigger the scratch or bump is then the longer the bubble will be able to ‘hold on’; just like how a climber can hold onto an irregular surface for longer than a smooth surface.
**Edge & Corner radii** (Outside corners & edges)

- Lowers the frequency of ceramic inclusions
- Helps prevent splitting of the ceramic shell at De-Wax operation
  - Eliminates a stress riser
- **Minimum of 0.15 R corner & edge radii should always be allowed**
  - Casting will exhibit an .008 – .012 edge break when tooled sharp
- **Specify as a R-Max to provide toolmaker flexibility**
  - Cost of “Double Cutting” the parting line to root of radius (see below)
Most Material Specifications require Customer Authorization to perform In-Process Weld Repair
- A recognized, essential, routine foundry operation
  - Part yields are more predictable
  - Reduces part cost of the product
  - Improves delivery performance

In-Process welding is performed to repair minor surface discontinuities
- Pits from ceramic inclusions (AMS 2175 allows up to .05” surface pit)
- Cracks

A properly performed weld is stronger than the base metal.
- Rapid cooling of weld produces smaller grain sizes

Recommend AMS 2694 – In Process Welding of Castings
- Modifies AWS D17.1
- Written for the Investment Casting Industry

Note: See Paper presented by Authors Gerald Gagel, Daniel Hoefert, Joseph Hirvela, & Randy Oehrlein at AFS CastExpo 2013 on the “Effect of Weld Repair on Static and Dynamic Tensile Properties of E357-T6 Sand Castings” and concludes that the researchers found that “…repair welding had no detrimental effects on tensile or fatigue properties.”
AMS 2175 Classification & Inspection of Castings

- Standard reference for NDT on Investment Casting
- Successor to Mil-C-6021, Mil-Std-2175
- Established in 1958 standards for radiography of thin walled castings
- NDT Inspectors qualified & certified to NAS 410

Radiographic Inspection

- Inspection for internal defects
- Performed routinely for Foundry Process Control
- Inspection method per ASTM E1742
- Reference radiograph standards dependent upon alloy selection
  - Classifies type and acceptance limits of discontinuities

Penetrant Inspection (nonmagnetic metals)

- Inspection for nonvisual surface defects
  - Cracks, cold shuts, porosity
- Inspection method per ASTM E1417
  - Liquid penetrates small surface openings by capillary action
  - Excess liquid removed
  - Developer is applied & fluoresces
NDT inspection as directed by requirements on drawing.
- Designated as AMS 2175 Class “x” Grade “y”
- Select from four available Classes and four available Grades

Inspection Class - Determines the frequency of inspection
- **Class 1** – Failure of part would endanger lives
  - 100% X-ray and Penetrant inspection
- **Class 2** – Failure would have significant penalty
  - Sampling X-ray (Table 1) and 100% Penetrant
- **Class 3** – Margin of safety < 200%
  - Sampling X-ray (Table 2) and 100% Penetrant
- **Class 4** – Margin of Safety > 200%
  - X-ray not required and sampling (Table 1) Penetrant

Note – The frequency of inspection, or Class, has a direct impact on the cost of the casting.
Radiographic Grade – acceptance standard for discontinuities

- **Grade A** – Highest grade minimum discontinuities
  - Industry considers un-producible
  - Not attainable with predictable yields

- **Grade B** – Allows for some discontinuities
  - Producible, but difficult

- **Grade C** – High quality
  - Consistently producible

- **Grade D** – Lowest quality
  - Non critical castings

**Note:** A higher grade is more difficult to produce and so is more expensive. Hipping can sometimes be used to collapse small subsurface voids.
Inspection grade reflects but does not guarantee pressure tightness.

Pressure tightness can generally be achieved by one of two methods:

- **Impregnation** after machining
  - Penetrates and seals surface to assure pressure tightness
  - MIL-STD-276 – Impregnation of Porous Nonferrous Metal Castings
  - [http://www.impregnation.co.uk/process.htm](http://www.impregnation.co.uk/process.htm)

- **Hipping** of casting prior to heat treatment
  - Collapses sub-surface voids
  - [http://www.youtube.com/watch?v=BsnzgsEXT_A](http://www.youtube.com/watch?v=BsnzgsEXT_A)

Note: The “skin” of a casting is its densest part, so castings tend not to leak until after they have been machined (and the “skin” has been removed).
Cast Marking is Integral - permanent marking
- Letters, Numbers, Trademarks & Logos
- Part Numbers & Drawing Revision letters
- MIL-STD-130 or AS478

Cast lettering can either be “raised” or “depressed”
- Raised characters are generally the most economical

Depressed lettering should be avoided whenever possible.
- Depressed letters are “raised” on the mold so susceptible to damage
- Foundries prefer to instead cast .020” raised characters on a .030” depressed pad.
- Provides additional protection from damage during handling

The stroke width of any recessed lettering which is to be paint-filled should always be greater than the depth.
Variable Marking

- Marking that changes part to part or batch to batch
- Must be applied after final processing
  - Melt & Heat Treat Lot Identification
  - Serialization
- MIL-STD-130 or AS478
  - Ink, Vibro Peen, Electrochemical or Laser

Laser Engraving – State of the Art for variable marking

- Replaces Ink Stamp, Vibro Peen or Electrochemical
  - MIL-STD-130 Table II or AS478 15A Permanent Marking
- Neater & more legible
  - Character depth .0001 - .0003”
- Will remain legible following chromate or anodize
- Does not replace “personal” ink stamps
  - X-Ray Inspection
  - Penetrant Inspection
  - Final Inspection Stamp
Control & Production of Surface Texture

• ANSI/ASME B46.1 – Appendix B
  • Investment Casting: 60 – 200 RMS

• B1(a) Surface characteristics should not be controlled on a drawing or specification. Unnecessary restrictions may increase production costs...

• B2(a) Surface texture is a result of the processing method...

• B4(a) Surface characteristics of castings should never be considered on the same basis as machined surfaces. Castings are characterized by random distribution of nondirectional deviations from the nominal surface
Designing for Investment Casting
Castings are never perfectly flat or square

- Configuration driven distortion
  - Wax & Metal Solidification
    - Thick vs. Thin
    - Restricted vs. Un-Restricted Features
    - “Oil Canning” of surfaces

- Induced Process distortion
  - Wax
    - Removal from mold
    - Handling
  - Shell
  - Casting Cleanup
  - T4 Quench

- Presents difficulties for measurement & secondary machining
Datum Points provide an arbitrary structure for consistent measurement and a common starting point for secondary operations.

- **Primary Axis** (-A-)
  - Three points to describe a plane
- **Secondary Axis** (-B-)
  - Two parallel points to establish a perpendicular plane
- **Tertiary Axis** (-C-)
  - One point to establish a plane perpendicular to -A- & -B-

Common datum points for straightening, inspection & machining.
Datum Points — Best Practices

- Casting should balance on the Primary Datum Points without clamping

- Primary Datum Points should be spread to the extents of the casting
  - Minimize multiplying the effect of minor surface distortions

- Primary Datum Plane be adjacent to first machine cut

- Datum Points should be placed on “as-cast” surfaces not subsequently machined
  - Re-establish initial casting measurements

- Datum Points should be co-planer surfaces
  - May be necessary to incorporate a feature to act as a datum point

- Datum Points should be placed on “stable” areas
  - Rigid areas of the part that are restrained from movement
  - Avoid isolated heavy areas or thin edges.

Note: A cluster of features with location critical to each other, but not necessarily to the datum, should also be dimensioned locally to each other while the pattern location is only loosely toleranced to the datum.

Example: Connector Holes
Datum Points — Best Practices

Datum Surface Selection - External or Internal?
- External Surfaces are preferred as datums and for datum point
- Measurement requires mounting parts on datum points
- With Internal Datum Points Fixtures consume volume
- Internal Fixtures constrain ability to measure internal features

Gating will sometimes be needed on datum surfaces
- Will require gate removal and a disruption of the datum surfaces.
- Datum Points should be located away from gated area

Centralized Datums
- Standard Tolerance to accommodate the longest dimension from the 0,0,0 datum.
- Centralizing the datums shortens the longest dimension from 0,0,0
The Investment Casting Institute recommends:

**Linear Tolerances**

<table>
<thead>
<tr>
<th>DIMENSIONS</th>
<th>NORMAL</th>
<th>PREMIUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>up to 1&quot;</td>
<td>± .010&quot;</td>
<td>± .005</td>
</tr>
<tr>
<td>up to 2&quot;</td>
<td>± .013&quot;</td>
<td>± .010</td>
</tr>
<tr>
<td>up to 3&quot;</td>
<td>± .016&quot;</td>
<td>± .013</td>
</tr>
<tr>
<td>up to 4&quot;</td>
<td>± .019&quot;</td>
<td>± .015</td>
</tr>
<tr>
<td>up to 5&quot;</td>
<td>± .022&quot;</td>
<td>± .017</td>
</tr>
<tr>
<td>up to 6&quot;</td>
<td>± .025&quot;</td>
<td>± .020</td>
</tr>
<tr>
<td>up to 7&quot;</td>
<td>± .028&quot;</td>
<td>± .022</td>
</tr>
<tr>
<td>up to 8&quot;</td>
<td>± .031&quot;</td>
<td>± .024</td>
</tr>
<tr>
<td>up to 9&quot;</td>
<td>± .034&quot;</td>
<td>± .026</td>
</tr>
<tr>
<td>up to 10&quot;</td>
<td>± .037&quot;</td>
<td>± .028</td>
</tr>
</tbody>
</table>

> 10" allow ±.005" per inch

A Linear Dimension can be measured with calipers.

*Rule of Thumb: ± .005 in/in*
**Flatness:** A three-dimensional form tolerance that describes the allowable variability in the shape and appearance of a surface that lies in a plane.

Casting Tolerance: .005” Per inch of length

**Perpendicularity:** A three-dimensional orientation tolerance that describes the allowable variability in the 90 degree angular relationship between a surface and a datum.

Casting Tolerance: .005 Per inch of length

**Angular Tolerance**

Casting Tolerance: $\pm \frac{1}{2}^\circ$
This table represents what can readily be produced by the Ceramic Shell Process. Tighter proportions may be held by some foundries or with preformed ceramic rods.

**Note:** When deciding if a feature should be cast, design consideration must be made for the locational tolerance as much as the feature tolerance.
**Blind Holes**

<table>
<thead>
<tr>
<th>Dia</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; .25</td>
<td>1 D</td>
</tr>
<tr>
<td>.25 -&gt; .37</td>
<td>1.5 D</td>
</tr>
<tr>
<td>.37 -&gt; .62</td>
<td>2 D</td>
</tr>
</tbody>
</table>

**Note:** Blind Holes require fillet radius at the bottom of the cavity to prevent fracturing at the corners when metal is poured in the cavity.
Note: Like Blind Holes, Slots require fillet radius at the bottom of the cavity to prevent fracturing at the corners when metal is poured in the cavity.
### Visual Standards

- **Raised or Positive Metal**
  - Random positive metal of up to .030” of a .125 x 125 area
  - AMS 2175 allows not more than one per square inch

- **Surface Pits**
  - Random negatives up to Ø.06 x .030 deep
  - AMS 2175 allows not more than one per square inch

- **Positive or Negative metals should not interfere with the function of the casting**
  - Any discontinuity that will subsequently be removed by machining is not reason for rejection

- **Nonfill**
  - Edges may be rounded up to .015”R even though tooled sharp

- **Cleanliness**
  - Castings shall be free of scale or foreign material with a uniform appearance

- **Linear Indications**
  - Parts shall contain no linear cold shuts, visual cracks or visual shrinkage

---

Note: AMS 2175 requires a 100% Visual Inspection of castings.
Good IC Design Practices
Design for Higher Levels of Complexity

- Complexity cost is largely reflected only in tooling & at pattern injection
- Part Count Reduction - Combine multiple piece structure
- Reduce secondary operations
- Reduce assembly operations

Near-Net-Shape Design

- Machine only Critical Features

Design Freedom

- Few constraints on Configuration
- No consideration of Draft Angle
Optimum IC wall thickness 0.060” - 0.125”

- **Thinner drives cost** – can cast as thin as 0.040” wall
  - Nonfill
  - Handling issues

- **Thicker drives cost**
  - Dimensional – volumetric “sink”
  - Metallurgical – volumetric “cavity shrinkage”
  - Weight - handling

Volumetric Cavity Shrink – voids created as thick sections solidify

Dimensional Sink
Strive for uniform wall thickness and smooth transitions

- Difficult to adequately feed metal to a thick section through a thin section.
  - Foundries must gate into heavy area
- Reduce turbulence as metal fills cavity
  - Oxide formation
- Use fillet Radii & tapers to mitigate
Feathered Edges

- Avoid sharp edges from the intersection of walls at less than 90°

**Poor Design**
Casting will non-fill in sharp corner
Edge susceptible to damage

**Good Design**
Break sharp corner with “flat”
Investment Casting Handbook – The Investment Casting Institute
An excellent tool for designers, buyers and users of investment castings, as well as for employees in the investment casting foundry.

Contains chapters on the following:
1). The Investment Casting Process;
2). How to Buy Investment Castings;
3). Dimensions, Tolerances, and Surface Texture;
4). Designs and Applications of Investment Casting;
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Plus numerous case studies, examples and dozens of full-color illustrations. 1997, Investment Casting Institute, 123 pp., illus.

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