Precision Castings Division

Cost Drivers and Design Considerations for Investment Casting
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Investment Castings

Utilizing a state of the art investment casting process, Spokane Industries’ Precision Castings Division provides high quality investment castings for a wide variety of commercial, industrial and manufacturing applications. When it comes to choosing and designing for investment castings it is important to consider the cost drivers. This paper highlights the key cost drivers and ideas for how to reduce them.

Why Investment Castings?

• Near Net Shape
  Investment casting produces near net shape parts. This means the as cast part meets a majority of the finished part requirements for dimensional tolerances, surface finish and precise detail such as lettering, threads or gear teeth.

• Design Flexibility
  Virtually any shape, configuration, level of complexity or material can be accurately and reliably made as an investment casting. This allows you to design a part that is ideal for your application. Spokane Industries has experienced engineers to help you take full advantage of the flexibility provided by the investment casting process.

• Product Simplification
  Combine existing fabrications or multiple sub-assemblies into a single casting to address production problems, cost and complexity. Our design engineers will work with you to assess existing parts or production problems, and can recommend solutions that will reduce production complexity and cost, and increase reliability.

• Cost Savings
  Cost savings can be realized by optimizing designs to integrate existing fabrications and parts, improve part strength, reduce weight, reduce or eliminate finishing costs such as machining, and lower tooling costs as compared to forging and die casting processes.

• Rapid Prototyping
  Rapid prototyping is ideal for first articles, R&D and limited production runs. It also provides further reduction in lead times and tooling costs. We use both SLA (Stereolithography) and foam processes to provide quick turnaround for prototyping and limited production runs.

• Material Choices
  Investment casting offers the widest selection of alloy choices in all manufacturing fields. See “production capabilities” for a list of alloys that Spokane Industries is capable of pouring.

• Markets Served
  There are many industries that benefit from producing parts via investment casting. Spokane Industries is experienced in providing services to all of the following industries.
  • Aerospace
  • Auto industry
  • Food industry machinery
  • Gas turbines
  • Machine tools
  • Medical and dental
  • Military applications
  • Oil industries
  • Pumps and compressors
  • Weapon systems

• Improved Surface Finishes
  Investment casting can provide a higher quality surfaces finish than any other casting process. It is common to produces parts with a surface finish as low as 60 RMS without secondary finishing.
Table 1 provides a quick reference to illustrate investment casting's strengths.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Investment Casting</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Short</td>
<td>All</td>
<td>Good</td>
<td>Average</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Powdered Metal</td>
<td>Excellent</td>
<td>Fair</td>
<td>Good</td>
<td>Fair</td>
<td>Long</td>
<td>High</td>
<td>Excellent</td>
<td>Average</td>
<td>Low</td>
</tr>
<tr>
<td>Permanent Mold Casting</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Fair</td>
<td>Good</td>
<td>Long</td>
<td>High</td>
<td>Good</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Sand Casting</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Short</td>
<td>All</td>
<td>Fair</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Die Casting</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Poor</td>
<td>Good</td>
<td>Long</td>
<td>High</td>
<td>Good</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

Spokane Industries Investment Casting Production Support Capabilities:

Production Capabilities
- From a few grams up to 45 Kg
- Thousands of units per week

Alloys:
- Carbon Steels
- Low Alloy Steels
- Copper base Alloys
- Nickel base Alloys
- Cobalt base Alloys
- Precipitation Hardening Alloys
- Tool Steels
- Stainless Steels
- 300 Series
- 400 Series
- 17-4

In-House Heat Treat:
Normalizing, Quenching, Annealing
- Tilt up ovens surveyed per AMS 2750, certified to +/-25 Deg F
- <30 sec transit time from opening oven to full submersion in quench tank with full agitation

Support Services:
- Quick turnaround samples
- Prototype Runs

In-House Machine Shop
*Reliable partners for outsourcing appropriate finishing operations.*
Quality Assurance

Radiographic:
• Iridium and Cobalt sources for material thicknesses up to 8 inches
• Traditional Film Images
• Digital Images

Magnetic Particle:
• Wet continuous fluorescent AC/DC
• Dry Powder AC/DC

Mechanical Property:
• Charpy V-Notch Impact Testing (to -50°F)
• Tensile Testing

Chemical:
• ThermoScientific ARL 3460 OES
• Bruker 04 Tasman

Dimensional:
• CMM - Mitutoyo
• 12’ Faro Laser Scan Arm
• 8’ Faro Standard Arm

Hardness:
• Brinell
• Rockwell

Certifications:
• Class 1, 2 armor plate MIL-A-11356
• Welding - ASTM-A488, ASME Section IX

Engineering Support

Engineering Consulting for:
• Fabrication to Casting Conversions
• Product Enhancements
• Design for castability
• Alloy Selection

Modeling Services:
• MagmaSoft® Casting Simulation
• 3D CAD Modeling

Material Evaluation:
• On-site degreed Metallurgists
• Materials Experimentation and Analysis
• Ceramic Composite Casting Development
• Leading edge mechanical property and casting cleanliness improvement
• 10 Ceramic Composite patents granted or pending

File Capabilities:
• Preferred file types for casting, tooling and machining quotes.
• .stp
• .igs
• .dwg
• .pdf with dimensional specifications (this is critical to determine the casting and machining tolerances)
Cost Factors and Design Considerations

In general, casting costs depend on the size and weight of the part and the precise dimensional tolerances required by the blueprint and the 3D model. The cost of any part increases in direct proportion to the dimensional tolerance requirements. Tighter than standard tolerance will increase part cost.

Mold capacity is limited by both size and weight of the part thus making them critical factors in economical part design. The more pieces that can run on a single mold, the lower the part cost will be. If possible, unnecessary mass should be removed to reduce part weight.

Part geometries also impact costs. Collaboration between design and casting engineers is very important during the design process. This communication can eliminate part geometries that complicate the casting process and will help prevent added part costs. This paper provides a breakdown of specific cost drivers and design considerations.

Number of Gates

Gates are used to attach the part to the mold and are the feed mechanism for the casting. When possible, parts should be designed with a single gate to feed each part on the mold. This will yield more pieces per mold and reduce the pour weight per mold. Single gate feeding also enhances the dimensional stability of a given part by providing a directional grain structure during solidification.

Gate witness

The gate witness is the small amount of gate material left behind after removing the part from the mold. Leaving a gate witness between .010"-.030" high is the most economical for manufacturing. If necessary gates can be removed flush to the adjacent surface or ground to specific dimensions. However, this extra removal often results in a higher manufacturing cost. When possible, design parts so the gate can be put on a flat surface rather than a curved surface.

Gate witness tolerances; in order of increasing costs:
- Break-off witness - .06"-.120" maximum
- Plunge grind - .010"-.025" maximum
- Flush grind – to minus .010"
- Swivel grind - .010"-.025" maximum
- Grind to specified dimension

Normal Linear Tolerances

“Normal” tolerances are industry standard tolerances for the investment casting process. These tolerances can be expected for all casting dimensions and in many cases can be exceeded with proper design.

<table>
<thead>
<tr>
<th>ENGLISH (inches)</th>
<th>METRIC (millimeters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>Tolerance</td>
</tr>
<tr>
<td>Up to .500&quot;</td>
<td>+/- .007</td>
</tr>
<tr>
<td>Up to 1.000&quot;</td>
<td>+/- .010</td>
</tr>
<tr>
<td>Up to 2.000&quot;</td>
<td>+/- .013</td>
</tr>
<tr>
<td>Up to 3.000&quot;</td>
<td>+/- .016</td>
</tr>
<tr>
<td>Up to 4.000&quot;</td>
<td>+/- .019</td>
</tr>
<tr>
<td>Up to 5.000&quot;</td>
<td>+/- .022</td>
</tr>
<tr>
<td>Up to 6.000&quot;</td>
<td>+/- .025</td>
</tr>
<tr>
<td>Up to 7.000&quot;</td>
<td>+/- .028</td>
</tr>
<tr>
<td>Up to 8.000&quot;</td>
<td>+/- .031</td>
</tr>
<tr>
<td>Up to 9.000&quot;</td>
<td>+/- .034</td>
</tr>
<tr>
<td>Up to 10.000&quot;</td>
<td>+/- .037</td>
</tr>
</tbody>
</table>

Allow +/- .003" for each additional inch
Allow +/- 0.1mm for each additional 25mm

Meeting design tolerances is also largely dependent on part geometry. Parts with uniform wall thickness and shape will have much less distortion and deviation than non-uniform shapes.
Complex geometries will cause normal linear tolerances to vary. This variation is due to the following three factors:

1. Part Shrinkage Factors (20% of linear tolerance)
2. Tooling Tolerances (10% of linear tolerance)
3. Process Variation (70% of linear tolerance)

All three sources of variation can be reduced by:

1. Part design
2. Including the addition of tie bars, ribs, and gussets to maintain shapes.
3. Tuning of wax injection tooling after the first sample to meet nominal dimensions.
4. Straightening / coining
5. Machining

All of these options can assist in achieving tighter than normal tolerances. There may be additional costs associated with these options. Premium tolerance capability can be achieved, but must be considered on a part-by-part, dimension-by-dimension basis.

**Premium Linear Tolerances**

Premium tolerances may add secondary operations and cost to parts and may only be achieved on selected dimensions. The premium tolerance achieved will depend on the alloy used and the part geometry. It is important to designate tight tolerances only when necessary for part function and leave the rest open to normal linear tolerances. These premium tolerances and associated costs can be determined during your consultation with a Spokane Industries engineer.

**General Linear Tolerances**

“General” linear tolerances differ from “Normal” tolerances as they are used for non critical part features that require less dimensional precision. By using general tolerances for non critical features, parts can be produced more efficiently and economically. Incorporate these non critical features into the drawings and 3-D CAD file but do not dimension them for inspection purposes. The non critical features can then be tooled per design and non-value added inspections and evaluation time can be eliminated.

<table>
<thead>
<tr>
<th>ENGLISH (inches)</th>
<th>METRIC (millimeters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>Tolerance</td>
</tr>
<tr>
<td>Up to 2”</td>
<td>+/- .020</td>
</tr>
<tr>
<td>Each Additional 1.000”</td>
<td>+/- .010</td>
</tr>
</tbody>
</table>

**Tooling**

Spokane Industries utilizes a system of tooling standards to ensure uniform high quality design and fabrication of wax injection dies guaranteed for the life of the part.

Tooling types in order of least tooling expense but highest piece price:

- Manual
  - Tools in which the operator disassembles the tool and removes the pattern manually.
- Semi-Automatic
  - Slides, cores, and part ejections are operated mechanically.

Configurations that do not allow metal cores in tooling due to undercuts or complicated internal shapes must be treated in one of the following ways:

- **Collapsible Core** – With this type of tooling the core collapses to allow removal from pattern. This more complicated tooling allows for the lowest piece price but results in higher tool costs.
- **Loose Inserts** – Best for low volume parts due to the more complicated tooling.

Cores are used to provide internal spaces, cavities or features. Metal cores are the most common and cost effective but may not allow for the geometric complexity required.
• **Multi-Piece Wax Assemblies** – Only use for configurations that require less critical tolerances or are going to be heavily machined due to loss of tolerance control associated with these assemblies.

• **Soluble Cores** – Requires additional die for the soluble core and increased labor for injection and removal of the soluble pattern. Provides excellent flexibility at moderate additional cost. Use for open geometries where internal features can be effectively shelled during the standard investing process.

• **Pre-Formed Ceramic Cores** – Use ceramic cores for specialized shapes with small dimensions or where internal geometries are critical. Necessary for parts with complicated internal features that cannot be effectively shelled during the standard investing process. The additional labor and production of ceramic cores results in the highest cost of all the core options.

* There are many variables to analyze when determining the proper core for each design project. Our experienced engineers at Spokane Industries will gladly answer any questions you may have.

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**Flatness and Straightness**

Flatness and straightness are often used interchangeably but they are in fact different. Flatness is defined by two parallel planes which the part surface lies within (see Figure 1). The degree of flatness in an investment casting is almost always determined by the volumetric shrinkage of the wax pattern and cooling of the metal. This shrinkage, called sink, often occurs in the center of the part. General flatness tolerances cannot be quoted because they vary with part configuration and alloy selection. The following chart below is a rough guide for sink estimation.

<table>
<thead>
<tr>
<th>Section Thickness</th>
<th>Volume of Section</th>
<th>Possible Sink per Face of Casting</th>
</tr>
</thead>
<tbody>
<tr>
<td>In</td>
<td>In^3</td>
<td></td>
</tr>
<tr>
<td>.25</td>
<td>.5</td>
<td>Not Significant</td>
</tr>
<tr>
<td>.5</td>
<td>1</td>
<td>.005</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>.012</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>.014</td>
</tr>
<tr>
<td>Millimeters</td>
<td>mm^3</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>13</td>
<td>Not Significant</td>
</tr>
<tr>
<td>12</td>
<td>25</td>
<td>.13</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>.3</td>
</tr>
<tr>
<td>50</td>
<td>200</td>
<td>.36</td>
</tr>
</tbody>
</table>
Parts will be held flat and/or straight to .005" per inch of length. Heavy part sections may be dished, or curved, up to an additional .010".

Straightness tolerance is a tolerance zone which an axis or the considered element must lie within. To correctly measure axial straightness of a shaft, bar, or plate, the tolerance zone within which the axis or axial plane lies must also be measured. (See Figure 1)

Sometimes straightening cannot be avoided and it will add cost to the parts. Therefore, do not specify tighter flatness, straightness, roundness, etc. requirements than you actually require.

Straightening costs are dependent on the tightness of the tolerance specified.

Figures 3 and 4 demonstrate Spokane Industries ability to consistently produce casting with a high level of flatness and straightness.
**Concentricity**

Concentricity is a condition in which two or more features (cylinders, cones, spheres, hexagons, etc.) share a common axis. Any dimensional difference in the locations of centers of concentric features will be separated by no more than .005" times the difference between the diameters. If the length of the cylinder is greater than two times the diameter, add the straightness tolerance to the concentricity tolerance. Concentricity is a complicated characteristic to measure so consider changing the design to a run out or position notation. See Figure 5 below.

![Figure 5: Eccentricity and Concentricity](image)

Straightness does affect concentricity if the casting has a shaft or tube feature. In Figure 6 below, diameters “A” and “B” may be true circles but the out of “straightness” makes the features not concentric.

![Figure 6: Rod is eccentric but out of concentricity.](image)

Figures 7 and 8 show additional examples of eccentric and concentric features.

![Figure 7: Example of eccentric and concentric features.](image)

![Figure 8: Another view of multiple eccentric and concentric features.](image)
**Roundness**

Roundness specifies a tolerance zone bounded by two concentric circles within which each circular element of the surface must lie. A roundness profile or total indicator reading (TIR) can be achieved within the normal linear tolerance. Premium tolerances can easily be achieved on small diameters. See Figures 9 and 10 below.

![Figure 9: Example of roundness.](image)

![Figure 10: Example of roundness.](image)

**Angularity**

Angularity is the condition of a surface, axis, or center plane which is at a specified angle from a datum plane or axis. A good production tolerance for angularity is +/- 0.5°. It is important to note that for the angularity to be maintained the part may require mechanical straightening.

Figure 11 shows examples of angularity. Figure 11-A cannot be sized but in certain cases it can be reworked to meet tolerances. Figures 11-B & 11-C represent castings that can be reworked to +/- 1°, depending on alloy. See Figure 12 for another example of angularity.

![Figure 11: Three different examples of angularity.](image)

![Figure 12: Example of angularity.](image)
Parallelism

Parallelism is the condition of a surface equidistant at all points from a datum plane or an axis equidistant along its length to a datum axis. Parallelism is difficult to control during casting and may require a straightening operation. See figure 13 for illustrations of parallelism.

Figure 13: These drawings illustrate how parallelism is defined.

Figure 14: Casting with two long parallel walls.

Perpendicularity

Perpendicularity is precise within +/- .008” per inch of length. When specifying perpendicularity, use the longest plane for reference, establishing the datum plane with three tooling points, as shown in Figure 16.

Figure 16: Illustration of perpendicularity. Surface B will be perpendicular to surface A within .008” per 1” of length of surface B.
Draft

Draft allows parts to easily release from the die. Although draft is only required for certain part geometries it is advised to consult with investment casting engineers to determine how much draft is necessary. Some surfaces may require drafting up to $\frac{1}{2}$˚ per inch of length. See Figures 17 and 18 for examples of draft.

Figure 17: Example of a part designed with draft. This allows for easy removal of the part from the mold.

Figure 18: This part was designed with no draft. This often results in complicated removal of the part from the mold which may lead to part damage.

Surface texture

Roughness will typically be between 60 and 200 RMS for small parts weighing 0.5 pounds or less. Larger parts may be rougher than 200 RMS. If surface finish is important, secondary finishing operations can be used to meet specified surface texture. See Figure 19.

Figure 19: Visual example of industry standard surface finishes.
Radii

Large fillet and corner radii increase castability, reduce part stress, and improve final appearance. It is important to design parts with the largest fillet or radii that are practical. Design to allow a radius of at least .031” for internal or external corners when possible. Outside corners that require a zero radius may be tooled sharp but this will decrease part strength and should be avoided when possible. If a casting requires a zero radius internal corner, a recessed corner as shown in Figure 20 can be used to provide relief. See figures 21 and 22 for examples of outside and inside radii.

Figure 20: Recessed corner used as an alternative to a zero radius corner.

Figure 21: Example of outside radii.

Figure 22: Example of inside radii.
Internal Radii and Fillets

Internal radii and fillets improve the strength and integrity of the casting and reduce shrinkage and cracking verses sharp corners (see Figure 23). Internal radii can be difficult to control and can only be checked approximately by radius gages. Thus, internal radii require the widest tolerances possible.

Figure 23: Illustration of internal radii.

Holes

Roundness is affected by the volume of surrounding metal. If the surrounding metal is symmetric, holes may be cast to the following dimensions:

<table>
<thead>
<tr>
<th>Size</th>
<th>Max Depth</th>
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<tbody>
<tr>
<td>.040” - .080”</td>
<td>2 x hole diameter</td>
</tr>
<tr>
<td>.081” - .200”</td>
<td>3 x hole diameter</td>
</tr>
<tr>
<td>.201” - .400”</td>
<td>4 x hole diameter</td>
</tr>
<tr>
<td>.401” +</td>
<td>6 x hole diameter</td>
</tr>
</tbody>
</table>

If a hole is surrounded by an uneven mass of metal the hole will be pulled out of round. The longer the hole or the more mass in the section around the hole, the more pronounced the pull effect. Figure 24-A shows the effect of hole shrinkage concavity which will be somewhat present in all castings. Top and bottom openings will be designed dimensions while the center will be slightly larger in diameter. Reaming can be done for holes that are used as bearing surfaces. Figure 24-B shows how a heavy section close to the hole creates additional distortion to the shrinkage pattern.

Figure 24: Examples of shrinkage determined by surrounding part mass.

If possible it is best to incorporate countersinks and counterbores with the cast holes for improved economy.

For complicated parts that require machining, it may be more cost effective to cast the part without holes and drill the required holes during the machining process. This will be more economical and precise than reaming cast holes that are out of round.

See Figures 25 & 26 for more examples of holes.
Blind Holes

Part surfaces should be blended into cast holes by large corner radii to provide adequate core strength. In addition, bottoms of cast blind holes should be full round or radii used as much as possible. See Figures 27 and 28 for examples of blind holes. Blind holes may be cast to:

<table>
<thead>
<tr>
<th>Size</th>
<th>Max Depth</th>
<th>Blending Corner Radii</th>
</tr>
</thead>
<tbody>
<tr>
<td>.040” - .120”</td>
<td>.5 x hole diameter</td>
<td>.5 x hole diameter</td>
</tr>
<tr>
<td>.121” - .400”</td>
<td>1 x hole diameter</td>
<td>.060” - .090”</td>
</tr>
<tr>
<td>.401”+</td>
<td>2 x hole diameter</td>
<td>.091” - .180”</td>
</tr>
</tbody>
</table>

Figure 25: Example of a countersunk hole.

Figure 26: Drilled holes.

Figure 27: Blind Hold

Figure 28: Illustrations of blind holes.
Wall Thickness

It is very important to design parts with uniform wall thickness (see Figure 29). As the molten metal solidifies in the molds it cools from the outside toward the center. Any abrupt changes in wall thickness or sharp corners will inhibit the free flow of molten material throughout the mold cavity (See Figure 30). The inability of the metal to flow freely can create variation in the shrinkage pattern during cooling creating internal stresses, warpage, sink marks, or internal voids.

The minimum wall thickness that can be achieved is dependent on the material and the distance the molten metal must travel. Small investment castings, down to .5” diameters, may have walls cast as .060” in thickness. Medium to large castings, .5” to 3” diameters, require a wall thickness of .060”-.125” depending on the part geometry.

Splines/Gears/Threads

Gear and thread profiles can be produced with accuracies of +/- .004” per .5” of pitch.

Letters/Numbers/Logos

Raised letters and numbers should be designed to be depressed into a protective pad (see Figure 32). A 0.020” high character on a depressed pad yields sharp, easily cast features. Recessed characters are also less likely to interfere with the function of the part.

Figure 29: Examples of uniform wall thickness.

Figure 30: Illustration of how the flow of molten metal is affected by cooling.

Figure 31: Examples of gears

Figure 32: Depressed pad with raised numbering.
Gaging

Spokane Industries performs a full visual inspection of all finished parts. If further dimensional verification is required, a small sampling plan should be devised to avoid the added expense of gaging every part.

At Spokane Industries we are committed to quality, service, and value. By collaborating with you on design requirements, material selection, mechanical properties, and finish and inspection requirements we can ensure a cost effective product that is right for your application. Our knowledgeable staff is standing by to assist you with the design process and we look forward to developing a long term relationship along the way.

Bibliography / Sources

Figures 1,2,5,6,11,13,16,20,23,24,28: The Investment Casting Handbook, c. 1968, by The Investment Casting Institute.


