NovaCast

Casting Design Considerations for Design Engineers

While there is no substitute for a close working relationship at an early stage between the design engineer and their chosen foundry, we hope that this guide will be of assistance to product design engineers. It will give an indication of the often-conflicting factors that the production team within the foundry will need to take into consideration when developing a casting solution.

When designing cast components there are several characteristics inherent in the pouring and solidification of the alloy and its interaction with the mould that define the parameters within which the designer can work. These characteristics affect the casting method chosen, the design of casting sections and junctions between sections, the surface integrity and appearance, the internal integrity of the cast alloy, and the dimensional accuracy.

Carefully planned casting geometry allows the foundry to work with the known pouring and solidification characteristics to produce high quality castings that perform to required specifications while avoiding costly and time-consuming problems. By understanding the interaction between casting geometry, the alloy (in both liquid and solid forms), and the casting process, design engineers can anticipate and avoid many iterations to their product design that could otherwise delay and frustrate the progress of a project.

The following geometry/material/process interactions dictate good casting design.

Fluid Life: Fluid Life refers to the liquid characteristics of the alloy which give it the ability to flow freely throughout the mould, along narrow sections and into fine surface detail. It is partly, therefore, fluid life that determines minimum wall thickness and how long a thin section can be. Fluid life will depend on temperature but also on the unique chemical and metallurgical properties of each alloy. So, the designer must be aware that the choice of alloy, and its associated fluid life, will dictate certain structural and aesthetic elements of the design.

Solidification Shrinkage: As the molten metal cools, shrinkage occurs in three distinct stages:

- **Liquid shrinkage** is the contraction that occurs as the alloy cools but remains in its liquid state. This is not normally significant from a casting design perspective.

- **Liquid-to-solid shrinkage** (also known as solidification shrinkage) occurs as the alloy changes from a liquid to a solid. This is significant for the designer as it gives rise to the need to keep fluid metal channels open throughout the mould during cooling as the contraction draws more metal from the risers.

- **Solid shrinkage** is the continued shrinkage that occurs as the solid metal casting cools to ambient temperature in its solid state. This is also significant from the designer's point of view. It is known as "Patternmaker's Shrinkage" and must be compensated for within the tooling or mould design to ensure that the specified final overall dimensions are achieved.

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Just as important from a casting geometry design perspective is the further classification of alloys by the type of solidification that occurs. There are three kinds as detailed below;

- **Eutectic Solidification:** These alloys remain in liquid form briefly in the mould but as soon as they start to cool solidification takes place rapidly throughout the casting. Internal shrinkage is minimal so risers are not so important as little additional alloy will be drawn into the mould. Examples or Eutectic alloys are Grey Iron, Aluminium 356, Silicon Bronze, Yellow Brass, Titanium and Zirconium.

- **Directional Solidification:** These alloys start to solidify quickly from the mould walls inwards. This makes them predictable and so good geometry design can take account of thermal gradient patterns to avoid closed pathways which could lead to internal shrinkage. Examples of Directional alloys are Carbon and Low Alloy Steel and Magnesium ZE43.

- **Equiaxed Solidification:** These alloys are somewhat unpredictable as they will start to solidify from the mould walls inwards but will also solidify in random internal islands which can block pathways. Fine, dispersed micro-porosity is typical of these alloys. Examples of Equiaxed alloys are Aluminium 356 and Aluminium Bronze.

Clearly, in order to take account of the magnitude and form that the shrinkage will take for a specific component geometry it is necessary to select the alloy to be used for the casting.

Understanding the kinds of thermal patterns and solidification processes that will take place for each alloy is vital as it allows the designer to predict how solidification should occur. There are, however, additional complications even with the most predictable directional solidification. There will be differential cooling between cooler areas, where the mould surface area to metal volume is high, and other hotter areas, perhaps where metal volume is higher. Solidification will then travel inwards from the walls and from cooler to hotter areas. It is important, therefore, that the geometry allows for a clear liquid metal pathway to the hotter areas before solidification cuts them off from the riser. This is done through tapering and effective riser placement, without which, isolated internal shrinkage can occur giving rise to voids or pores.

Whichever type of solidification occurs, Solid Shrinkage will result in an overall and relatively predictable contraction to the final size at ambient temperature. This must be allowed for in the construction of the patterns or dies or coreboxes for mould making. It is important to note, however, that contraction may not be evenly distributed throughout the component as some areas may be stiffer than others. This can lead to the introduction of residual stresses and warping of the component unless the geometry design takes account of this risk.

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Slag/Dross Formation: Some alloys are more susceptible to slag and dross formation than others so are more likely to have small, rounded, non-metallic inclusions within the casting. Quality and process control can reduce the quantity of inclusions but the designer can also help. Awareness of the likelihood of slag/dross formation for a specific alloy allows the foundry engineer to set up the running system (sprues, runners and gates) to minimise oxidation caused by turbulent flow or entrained air. Similarly, where buoyant slag/dross is likely, the designer could ensure that important surfaces or those to be machined sit low in the mould.

Pouring Temperature: Pouring temperature can have a significant effect when the molten metal approaches the mould material's refractory limit. Penetration of the metal into small sand cores can degrade as-cast surface finishes. Sand and ceramic materials with refractory limits of between 1650C and 1820C are most commonly used for moulds. This compares with upper limits of 1180C for metal moulds commonly used in die casting.

It is important to note for the designer that the concentration of heat in one area can also cause problems even with some lower temperature alloys. Better geometry design can allow heat to dissipate into the mould to alleviate these issues.

Fluid Flow: Designers should take account of the flow rate of molten metal entering the mould and the issues this can cause. A balance needs to be struck between the need to get the alloy into the mould quickly to avoid oxidisation and dross formation while avoiding the turbulence, wall erosion and core displacement that can occur at higher fluid speeds.

Although not altogether preventable in the manufacturing process, turbulence can be reduced by the design of a gating system that promotes a more laminar flow of the liquid metal. Sharp corners and abrupt changes in sections within the metal casting can be a leading cause of turbulence. Their affect can be mitigated by the employment of radii.

Poor design

Better design

The designer must also be aware that fluid flow can introduce unacceptable thermal gradients, particularly if metal flows around a core and re-joins elsewhere in the mould. Designing the casting geometry and running system at the same time can help to identify and eradicate these issues.

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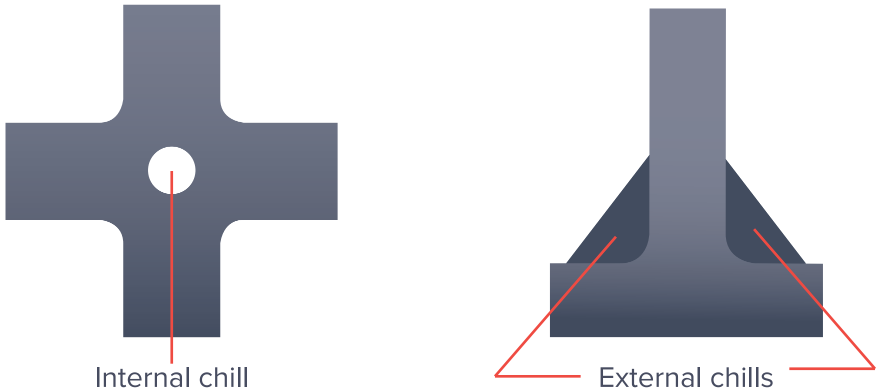
Heat Transfer Considerations: The management of heat within the mould is an important part of the geometry design. At high pouring temperatures, considerable heat must be transferred into the mould in a way that avoids the creation of localised hot spots where the heat cannot dissipate. This can occur on narrow peninsulas or tight corners where molten metal surrounds thin areas of the mould. The retained heat slows solidification in that area which can lead to hot tears or pulls – particularly if the geometry design has introduced stress build-up during Solid Shrinkage as the softer metal in the hot spot will have lower tensile strength.

As mentioned earlier directional solidification is very important to the manufacture of a part during the metal casting process, in order to ensure that no area of the casting is cut off from the flow of liquid material before it solidifies. To achieve directional solidification within the metal casting, it is important to control the flow of fluid material and the solidification rate of the different areas of the metal casting. With respect to the solidification of the metal casting's different sections, regulation of thermal gradients is the key.

Sometimes we may have an area of the metal casting that will need to solidify at a faster rate to ensure that directional solidification occurs properly. Planning the sections effectively and regulating flow rates within the mould may not be sufficient. To accelerate the solidification of a particular section it may be necessary to employ the use of chills. Chills act as heat sinks, increasing the cooling rate in the vicinity where they are placed.

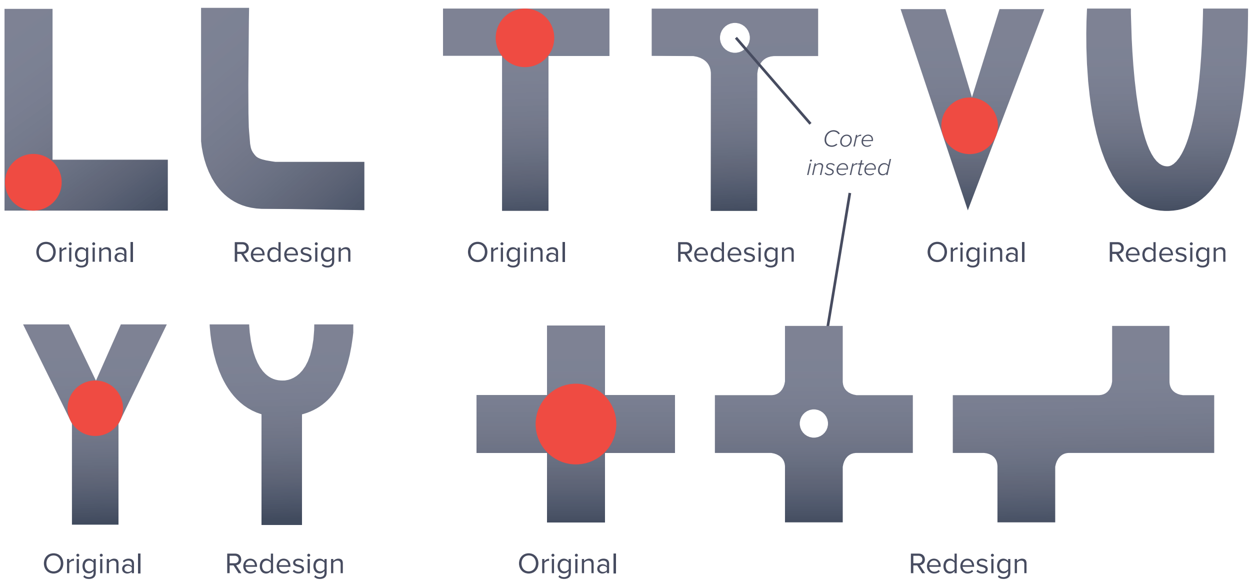
Chills are solid geometric shapes of material, manufactured for this purpose. They are placed inside the mould cavity before pouring. Chills are of two basic types. Internal chills are located inside the mould cavity and are usually made of the same material as the casting. When the metal solidifies the internal chills are fused into the metal casting itself. External chills are located just outside of the casting. External chills are made of a material that can remove heat from the metal casting faster than the surrounding mould material. Possible materials for external chills include iron, copper, and graphite. Figure 2 demonstrates the use of the two types of chills to solve a hot spot problem in + and T junctions.



Designers should remember that thermal inequalities can also occur in the opposite direction if a sharp corner is surrounded by mould material. In this case, rather than a hot spot forming, the area will cool very rapidly and can cause cold cracking and other issues.

Joint Design Considerations: L,T,V,Y and + junctions

Due to the nature of the geometry of these sections, each results in an area of metal with higher volume than the rest of the junction. Note the difference between the diameter of the circles and the general wall thickness. The larger circles represent potential hot spots. This can cause differential solidification and localised defects or weaknesses. The flow of casting material must be carefully considered when manufacturing such junctions. Design engineers can design out these potential issues by adjusting joint configuration slightly. Some possible redesign are shown.



Geometry/Alloy Interactions: Clearly, each of the characteristics detailed above has an influence on the design of the casting geometry and each will vary according to the alloy being considered. The optimum geometry will, therefore, be arrived at once these factors have been considered. The number of interactions seems to dictate that the typical geometry design process will be iterative in nature with an inevitable impact on production lead times and cost. The greater the understanding by the designer of the casting issues that will be faced, however, the closer their initial design will be to the optimum geometry and the fewer iterations will be needed.

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Design to Cast or Fabricate?

The question is posed here simply because it helps to demonstrate a couple of very important benefits that effective casting geometry design can deliver. There are very many instances where design engineers have opted to fabricate an assembly or component due to familiarity with the process or in seeking to minimise time to market. The reality is that many of these fabrications, particularly components with complex geometries, could be cheaper, lighter and stronger if they were cast in one piece.

The explanation for this lies in two unique benefits that metal casting can deliver: the ability to locate metal mass exactly where it is needed, and the ease with which complex geometries can be created. Clearly, this may not be a viable solution for a one-off application but where multiple components or assemblies are required as part of a production run, these attributes can result in lighter and considerably cheaper solutions.

In the past, the realisation of this potential called for outstanding casting geometry design expertise and experience as shape optimisation calls for complex 3-dimensional modelling. In more recent years, however, powerful 3-D modelling computer programmes and casting simulation software have allowed design engineers to quickly produce solutions featuring continuously varying section geometry that fully utilises the material strength while also satisfying stress and deflection requirements.

A real benefit of this is that many parts of an assembly can be combined into a single component. In a situation where a series of stampings or other wrought shapes are welded or bolted together, casting a single, complex shape can deliver cost, weight, performance and aesthetic benefits. Fabrication of components, assembly (including labour, quality control, interfacing information), and added complexity in the manufacturing process are all cost centres that need to be considered. Fabrication also introduces component performance issues relating to directional strength and changes in wrought metals due to welding whereas a casting can deliver uniformity in continuous sections and at junctions.

Running System Design

The running design includes the system of sprues, runners, gates, risers, and chills that channel and control the flow of liquid metal into the mould cavity. These feed the casting as it solidifies, and control the heat transfer and rate of solidification in critical regions. The running system design specifies the size, dimensions and location of all elements that comprise the system.

Running design decisions typically include selection of the following: orientation of the cast part, parting line, potential sites for chills and chill types, sprue height and location, runner types and configuration, in-gate sites, choke area (smallest cross-section area present in the flow system), riser sites and configuration, and pouring rate and temperature.

As mentioned in the introduction to this guide, the running system design is really the domain of an experienced casting engineer rather than the customer's design engineer but, as stated already, at NovaCast we encourage close co-operation between these functions at the earliest opportunity.

Conclusion

While recognising that there will always be a clear differentiation between the roles of the customer's design engineer and the casting process engineer within the foundry, our experience has proven over the years that closer co-operation at an earlier stage delivers better outcomes for all. Innovations in computer software are speeding up the process considerably and removing many of the design iterations that have often plagued complex geometry design in the past. Greater appreciation of the properties of alloys in their molten and transition stages, an understanding of the impact of thermal gradients and heat transfer within the casting, fluid life and flow rates, pouring temperature effects and the formation of slag/dross can all help design engineers to anticipate where aspects of their design are likely to result in casting defects that will require changes to their design. Addressing these issues by, for example, adjusting joint configuration in the design, can save time and cost further down the line.

Once design engineers are open to the issues surrounding the casting process they will also be better equipped to spot the possibilities for using the properties inherent in the casting process to their advantage. The replacement of fabricated components and assemblies with complex castings offers huge potential for many manufacturers to reduce manufacturing costs while incorporating components that are lighter, more aesthetically pleasing and which deliver enhanced mechanical performance.

About NovaCast

NovaCast has over 35 years of ferrous and non-ferrous metal casting experience extending into markets as diverse as transport, utilities, offshore and general engineering. The company's non-ferrous foundry, based in Melksham, England, is supported by a fully risk-managed supply chain that expends out to the Far East allowing NovaCast to provide a single source solution for precision cast and machined components. NovaCast has particular expertise in the production of pressure-tight valve and industrial pump components, complex non-ferrous castings and a wide range of precision castings for many engineering applications. Metals cast include alloys of Carbon and Stainless Steel, Copper, Aluminium, Nickel and many others with a full range of testing, machining, surface treatment and finishing options.