

INTRODUCTION

Gravity die casting or Permanent die casting is a widely used method of producing casting by pouring liquid metal into a die cavity; gravitational force then assists the feeding process during solidification. In designs where sand cores are required the process is often called semi – permanent mould casting. The choice between the various methods of producing castings depends largely upon the technical and economical requirements. Sand casting would be chosen for up to a total of thousand components; above this figure the lower price for gravity die casting begins to offset the initial tooling charge. When quantities amounting to 10,000 or more are involved pressure die casting becomes a more economic proposition, due to the lower piece price, provided that the design is suitable.

Even for very large quantities Gravity die casting is used when under cuts in the casting shape requires either expandable sand cores or multi piece steel cores, or where a particular alloy which is not easily pressure die cast is required, for example an alloy that must be heat treated.

From its French origin shortly before the First World War, Gravity die casting provided a major step forward from established sand casting practice. Nowadays its degree of mechanization depends on the required output per man hour. Greater foundry skill is required in Gravity die casting than in the pressure die casting. It is, however, considerably slower in production, though more versatile. It is nevertheless a significant production method and the tonnage is comparable with that produced by die casting, but the trend continues to be in favour of die casting.

In past component designers have paid insufficient heed to the eventual production method of the casting they designed. Fortunately it is now becoming appreciated that the valuable savings are possible in this area and great efforts are being made by designers to co-operate with foundry engineers in arriving at the most economical component.

GRAVITY DIE CASTING

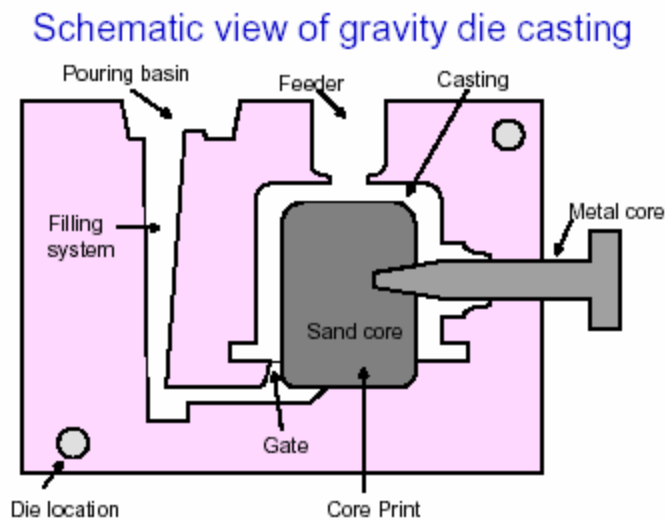
The permanent mold casting process is the production of castings by pouring molten metal into permanent metal molds under gravity pressure. Castings produced in permanent molds have finer grain structure and better strength properties than those cast from similar alloys in sand casting and die casting. Major savings through reduced machining costs are often obtainable because the castings have better dimensional uniformity, machining allowances are smaller, and holes may be accurately located and dimensioned with metal cores. In addition, a smooth surface finish is achieved right out of the mold, therefore, eliminating some secondary polishing operations. The permanent mold process is frequently chosen because it can reduce secondary operations. Permanent metal molds have a production life up to 120,000 or more castings. Casting sizes range from a few ounces up to 50 pounds.

PROCESS

The permanent mold casting process is the production of castings by pouring molten metal into permanent metal molds using gravity or tilt pouring. The process involves the following steps:

- 1) A refractory wash or mold coating is brushed or sprayed onto those surfaces of the preheated mold (usually 250-500F or 121-260C) that will be in direct contact with the molten metal alloy. The proper operating temperature for each casting is set.
- 2) Cores, if applicable, are inserted, and the mold is closed either manually or mechanically.

- 3) The alloy, heated above its melting temperature, is poured into the mold through the gating system.
- 4) After the casting has been allowed to solidify, cores and other loose mold members are withdrawn, the mold is opened, and the casting is removed.
- 5) The usual foundry practice is followed for trimming gates and risers from the castings.



The basic difference between sand casting and permanent mold casting is the metal (or permanent) mold used in the p.m. process. Permanent mold castings usually have better mechanical properties than sand castings because solidification is more rapid and fill is more laminar. The basic difference between permanent mold and die-casting is that permanent mold is a gravity feed process versus injection yielding a denser casting. Metal dies usually are made of high – alloy iron and steel and have a production life of upto 120,000 or more castings. It is desirable and generally more

economical to use permanent steel cores to form cavities in a permanent mold casting. When the casting has re-entrant surfaces or cavities from which one-piece permanent metal cores cannot be withdrawn, destructive cores made of sand, shell, plaster and other materials are used. This variation is called the semi permanent mold method. Sectional steel cores are used in some instances. Due to the chilling nature of a solid steel permanent mold tool, the castings are sounder than sand castings. For pressure-tight and nonporous castings, the permanent mold process is excellent. Permanent mold castings can be stronger than die and sand castings and less porous than die – castings. Permanent mold aluminum castings generally range from a few ounces to more than 100 lbs. Aluminum castings weighing several hundred pounds have been produced commercially by the permanent mold process. Permanent mold castings usually need less finish machining and polished than sand castings. If the parting lines on the outside of a casting can be held to a minimum, high quality as-cast finishes approaching 100 rms. can be achieved and many aluminum castings with these good as-cast finishes are used without subsequent finishing for cooking utensils, hardware items, automotive parts, highway bridge railings and ornamental work.

Advantages

Because of the various factors that must be considered when choosing a process, the decision to use permanent molding should be based on thorough engineering and production cost studies for each casting. Castings produced in permanent molds have finer dendrite arm spacing (DAS) and grain structure and better strength properties than those cast from a similar alloy in sand do. Therefore, the casting often can be designed with

thinner walls and lower weight. In addition, the cast surfaces are generally smoother than sand castings and closer dimensional tolerances can be maintained.

When properly produced, permanent mold castings can be subject to less shrinkage and gas porosity than sand castings. They do not ordinarily contain entrapped gas (such as in die-castings); thus, they are superior to die-castings in soundness and pressure tightness. For these reasons, permanent molding is sometimes chosen for better quality.

CASTING PROPERTIES

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. Heat transfer reduces the metal's temperature, and oxide films form on the metal front as this occurs. Fluidity decreases most rapidly with temperature loss, and it can decrease significantly from the surface tension of oxide films.

The absolute value of temperature is not the test of fluidity at a given moment. For example, some aluminum alloys at 1200-1400F (650-750C) have excellent fluid life. However, some molten steels at 3000F (1650C) have much shorter fluid life. In other words, a molten alloy's fluid life also depends on chemical, metallurgical and surface tension factors.

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.

It is essential to understand that moderate or even poor fluid life does not limit the cost-effectiveness of design. Knowing that an alloy has limited fluid life tells the designer that the part should feature:

- softer shapes and larger lettering;
- finer detail in the bottom portion of the mold, where metal arrives first, fastest and generally hottest;
- coarser detail in the upper portions of the mold where the metal is slower to arrive and more affected by oxide films and solidification "skin" formation. Even an alloy with good fluidity, when overexposed to oxygen, may form a high surface tension oxide film that makes the fluidity die, "rounding off" of the leading metal front as it flows.
- more taper toward thin sections.
- Some alloys, like 356 aluminum, have been specifically designed metallurgically to enhance fluid life. In the case of 356, the high heat capacity of silicon atoms "revive" aluminum atoms as their fluid life begins to wane.

2. SOLIDIFICATION SHRINKAGE

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

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

2. *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.

Table 1. Four Casting Characteristics of Common Foundry Alloys

Solidification Shrinkage					
Alloy Group	Fluid Life	Type	Amount	Pour Temp.	Slag/Dross
FERROUS:					
Gray Iron	Excellent	Eutectic-Type	Very Small	2500-2600F (1371-1427C)	Little
Ductile Iron	Good	Eutectic/ Directional	Small	2500-2600F (1371-1427C)	Some
Carbon & Low-Alloy Steel	Poor	Directional	Large	2850-3000F (1566-1649C)	Moderate
High Alloy Steels	Fair	Various	Various	Various	Moderate
NONFERROUS:					
Aluminum 356	Excellent	² Eutectic-Type	² Little	1300-1400F (704-760C)	Moderate
Aluminum 206	Fair/Good	Equiaxed	Moderate/ Large	1300-1400F (704-760C)	Moderate/ Large
Aluminum Bronze	Fair	Equiaxed	Moderate/ Large	2000-2150F (1093-1177C)	Large
Silicon Bronze	Fair	Eutectic-Type	Little	1900-2050F (1038-1121C)	Large
Magnesium ZE43	Excellent	Directional	Moderate	1300-1400F (704-760C)	Little/ Moderate
Yellow Brass	Poor/Fair	Eutectic-Type	Moderate	1800-1950F (982-1066C)	Large
Titanium	Very Good	Eutectic-Type	Little	3200-3300F (1760-1816C)	Very Large
Zirconium	Fair	Eutectic-Type	Little	3300-3400F (1816-1871C)	Very Large

¹ Among martensitic, partly austenitic and fully austenitic grades, solidification shrinkage encompasses all three types. Shrinkage amount and pouring temperature vary also.

² For premium structural castings, solidification is more complex. Depending on alloy modifications, section sizes and specifics of liquid-to-solid transformation, directional and/or equiaxed shrinkage may be involved.

Definitions:

Eutectic-Type Solidification: Eutectic alloys or behaving like them. These alloys remain liquid in the mold for a brief period, cool and then solidify very quickly all over. This phenomenon minimizes internal shrinkage and the need for risers.

Directional Solidification: These alloys begin solidifying quickly, perpendicular to molds walls. Solidification "direction" and pathways are predictable from casting geometry and thermal patterns in the mold walls. Without proper pathway geometry, isolated internal shrinkage can result.

Equiaxed Solidification: These alloys not only begin solidifying perpendicular to mold walls, but also solidify in the midst of the liquid, forming equiaxed islands of solid. Solidification pathways are interrupted by the equiaxed islands, making these alloys difficult to feed. Fine, dispersed microporosity is typical.

Figures 3-5 illustrate what is implied by the three solidification shrinkage types defined in Table 1. In each case, a simple plate casting is shown with attached risering (a "riser" is a reservoir of liquid metal attached to a casting section to feed solidification shrinkage). Cross sections of the plate and riser(s) show conceptually how solidification takes place; metallurgical reality is similar, but microscopic.

Figure 3 shows solidification on and perpendicular to the casting surfaces, known as "progressive" solidification. At the same time, solidification moves at a faster rate from the ends of the section(s) toward the source of feed metal (risers)—this is known as directional solidification. Directional solidification moves faster from the ends of the sections because of the greater amount of surface area through which the solidifying metal can lose its heat. The objective is for directional solidification to beat out progressive solidification before it can "close the door" to the source of the feed metal. As shown, directionally solidifying alloys require extensive risering and tapering, but they also have the capability for excellent internal soundness when solidification patterns are designed properly.

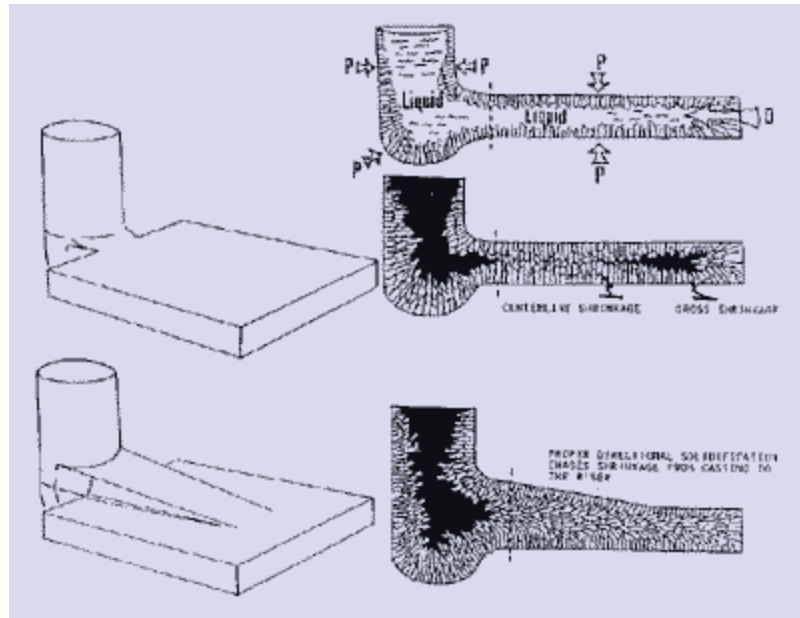


Fig. 3. Directional solidification on a plate casting is illustrated here. Extensive risering and tapering (bottom) allows for excellent internal casting soundness.

Figure 4 illustrates the eutectic-type alloy, the most forgiving of the three. Such alloys typically have less solidification shrinkage volume. Risers are much smaller, and in special cases can be eliminated by strategically placed gates. The key feature with these alloys is the extended time that the metal feed avenue stays open. The plate solidifies more uniformly all over and all at once, similar to eutectic solidification. Eutectic-type alloys are less sensitive to shrinkage problems from abrupt geometry changes

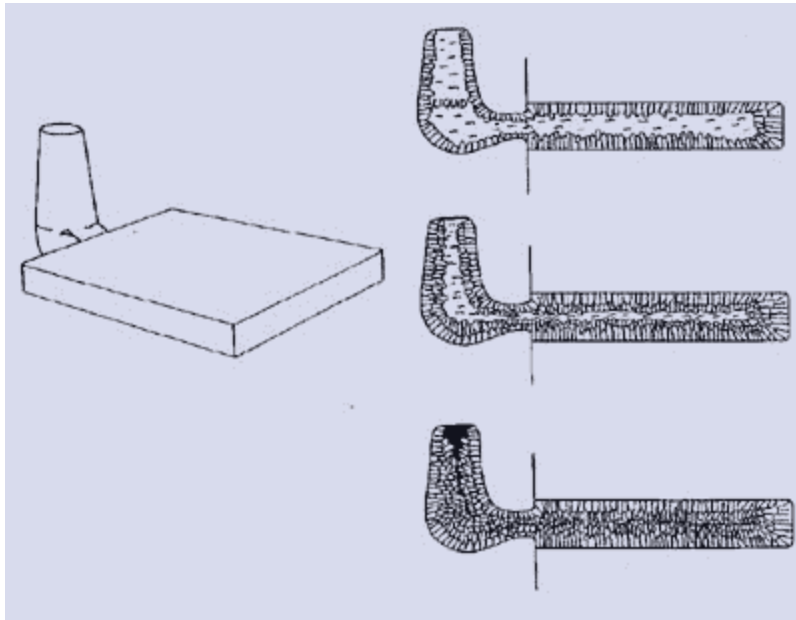


Fig. 4. Eutectic-type solidification is the most forgiving of the alloy shrinkage types. Risers may be much smaller with these alloys, as the avenue of liquid feed metal remains open through solidification.

Alloys that exhibit equiaxed solidification respond the most dramatically to differences in geometry (Fig. 5). Shrinkage in these alloys tends to be widely distributed as micropores, typically along the center plane of a casting section. The reason is that solidification occurs not only progressively from casting surfaces inward and directionally from high surface area extremities toward lower surface area sections, but also equiaxially via "islands" in the middle of the liquid. These islands of solidification interrupt the liquid pathway of directional solidification. Gradually, the pathways freeze off, leaving micropores of shrinkage around and behind the islands that grew in the middle of the pathway. Larger risers, thicker sections and tapering (shown at center of Fig. 5) are counterproductive, causing micropores to coalesce into larger pores across more of the casting cross section. As

illustrated at the bottom of Fig. 5, microporosity is kept small and confined to a narrow mid-plane in the casting section by more "thermally neutral" geometry with smaller, further-spaced risers.

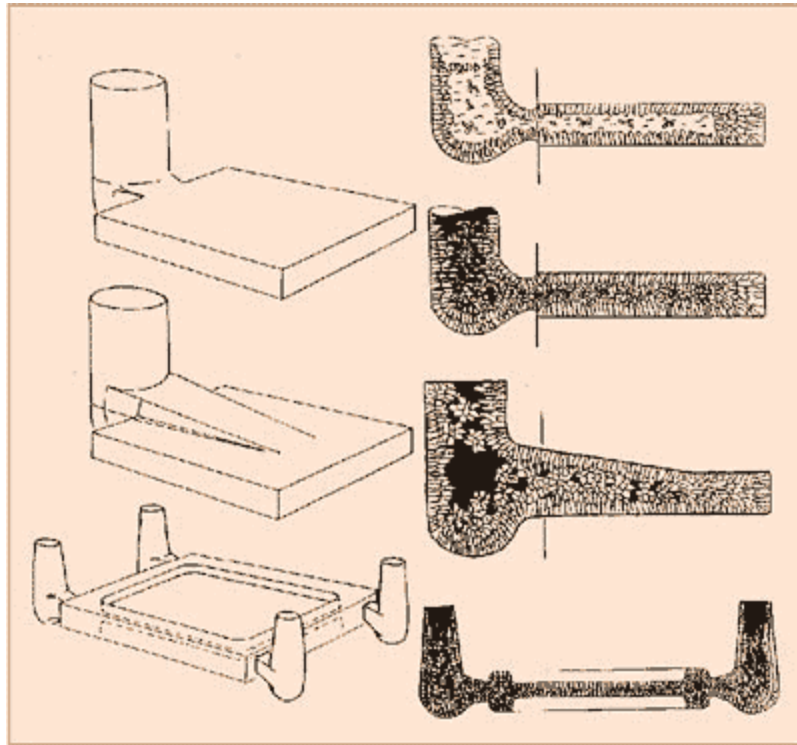


Fig. 5. Designs for equiaxed solidifying alloys are shown here. The large riser design (second from bottom) illustrates how not to feed a section. While such a taper and large riser worked with directional solidification, using this approach here adds more heat to an area that needs to cool more uniformly, and results in larger, coalesced shrinkage. The proper casting and process geometry (smaller risers and a thermally neutral shape) is illustrated at bottom.

As illustrated in Fig. 3-5, there is a significant bilateral and reciprocal relationship between solidification shrinkage and geometry. Most simply,

eutectic-type solidification is tolerant of a wide variety of geometries; the least reciprocity is required. Most complex, equiaxed solidification requires the most engineering foresight in the choice of geometry and may require supplemental heat transfer techniques in the mold process. In the middle lies directional solidification, while capable of the worst shrinkage cavities, it is the most capable of very high internal integrity when the geometry is properly designed. Well-planned geometry in a directionally solidifying alloy can eliminate not only shrinkage but the need for any supplemental heat transfer techniques in the mold.

In fact, the real mechanism behind the bilateral and reciprocal relationship between solidification shrinkage and geometry is heat transfer. All three modes of heat transfer, radiation, conduction and convection are involved in solidification of castings, and all three depend on geometry for transfer efficiency. Convection and conduction, are very important in casting solidification, and transfer rates are highly affected by geometry.

3. *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 diemaker. This variability of contraction is another important casting design consideration, and it is critical to dimensional accuracy. Tooling design and construction must compensate for it.

Achieving dimensions that are "just like the blueprint" require the foundry's pattern- and/or diemaker to be included. The unpredictable nature of patternmaker's contraction makes tooling adjustments inevitable. For example, a highly recommended practice for critical dimensions and tolerances is to build the patterns/dies/coreboxes with extra material on critical surfaces so that the dimensions can be fine-tuned by removing small amounts of tooling stock after capability castings have been made and measured.

3. SLAG OR DROSS FORMATION

Among foundry men, 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. The best defense against nonmetallic inclusions is to inhibit their formation through good melting, ladling, pouring and gating practices. Ceramic filters, which can be used with alloys that have good fluid life, have

advanced the foundry's ability to eliminate nonmetallics. Vacuum melting and pouring are applied in extremely dross-prone alloys, like titanium.

4. POURING TEMPERATURE

Even though molds must withstand extremely high temperatures of liquid metals, interestingly, there are not many choices of materials with refractory characteristics. 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 3000-3300F (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 2150F (1180C) 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. Figure 6 illustrates both "L" and "T" junctions among the four junction types, which also include "X" and "Y" designs.

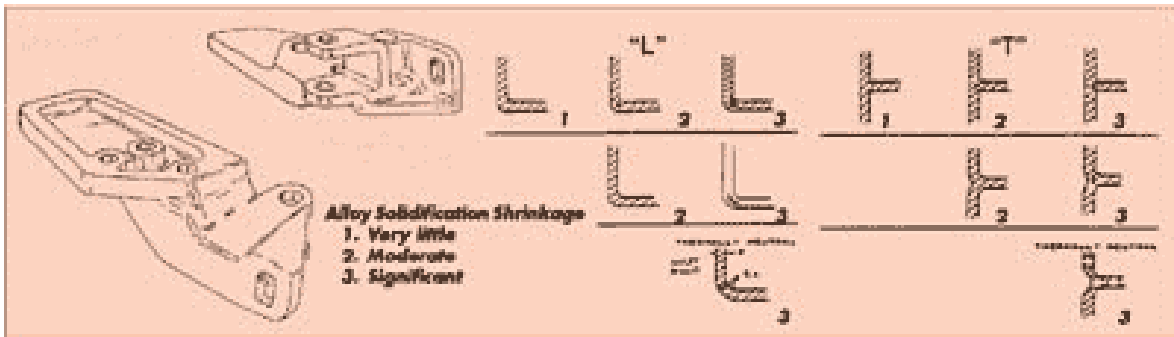


Fig. 6. Junction geometry is important to alloys with considerable shrinkage and/or pouring temperature. The casting geometry at left shows "L" and "T" junctions. The illustrations at right show the consequences of junction design and geometry increasingly difficult combinations of shrinkage amount and/or temperature. In reviewing Fig. 2, the gray iron junctions (2c) are similar to type 1 above, and steel (2b) are similar to type 3.

Designing junctions is the first step to finding castable geometry via the six-faceted system for casting design. Figure 6 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. Figure 7 illustrates a very high form of the foregoing principles in a critical automotive application.

CONSIDERATION 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 foundry engineer as a new casting geometry is being developed. Failure to do so can be a significant oversight that adds machining costs. If the casting geometry has been based on the four casting characteristics of the alloy, then the designer knows the likely surfaces for riser contacts and may have some idea of likely parting lines and core match lines. These surfaces and lines will be irregularities on the casting geometry and will cause problems if they contact fixturing targets.

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.

DRAWING 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. Figure 8 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:

Molding Process—The type of molding process (such as green sand, shell, investment, etc.) has the greatest single influence on tolerance capability.

How a given molding process is mechanized and the sophistication of its pattern or die equipment can refine or coarsen its base tolerance capability.

Casting Weight and Longest Dimension—Logically, heavier castings with longer overall dimensions require more tolerance. These two parameters have been defined statistically in tolerance tables for some alloy families.

Mold Degrees of Freedom—This parameter is least understood. Just as some molding processes have more mold components (mold halves, cores, loose pieces, chills, etc.) than others, some casting designs require more mold components. Each mold component has its own tolerances, and tolerances are stacked as the mold is assembled. More mold components mean more degrees of freedom; hence more tolerance. Good design for tolerance capability minimizes degrees of freedom in the mold for features with critical dimensions.

Draft—It is common for casting designs to ignore the certainty of draft, including mold draft, draft on wax and/or styrofoam patterns made from dies, and core draft. Since 1° of draft angle generates 0.017 in. of offset per in. of draw (about 0.5 mm/30 mm), draft can quickly use up all of a tolerance zone and more.

Patternmaker's Contraction—The uncertainty of patternmaker's contraction is why foundrymen normally recommend producing first article and production process verification castings (sometimes called "sample" or "capability" castings) to establish what the dimensions really will be before going into production. A common consequence of patternmaker's contraction uncertainty is a casting dimension that is out of tolerance, not

because it varies too much, but because its average value is too far from nominal. In other words, the dimension contracted more or less than was expected.

Cleaning and Heat Treating—Many casting dimensions are touched by downstream processing. At the least, most castings are touched by abrasive cutting wheels and grinding—even precision castings. Many castings are heat-treated, which can affect straightness and flatness.

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. 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 foundry alloy—that are economical to produce, machine and assemble into a final product.

While the casting properties section was the foundry engineering spectrum of geometry for the benefit of design engineers; the structural properties section is the design engineering spectrum of geometry for the benefit of

foundry 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. As we will see, geometry directly controls stiffness and stress in a structure.

The casting processes are limitless in their combined ability to allow variations in shape. Not many years ago, efficient structural geometry was limited by the designer's ability to visualize in 3-D. Now, computer generated solid models and rapid prototypes are greatly enhancing the designer's ability to visualize structural shapes. This technology often leads to casting designs.

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. Figure 9 depicts a meshed solid model and a stress analysis via the mesh elements

However, optimum geometry for allowable, uniform stress may not be acceptable geometry for castability. When a foundry 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." The result can be no-quotes, 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, foundry 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.

The Objective

Our objective is to explore geometry possibilities, looking for an ideal shape that is both castable in the chosen foundry alloy and allowable in stress and deflection for that alloy. As noted, there is great variety in the four metallurgical characteristics that govern alloy castability. Similarly, great

variety exists among metals in their allowable stress and deflection. Therefore, an ideal casting shape for all six of the casting design factors in Fig. 1 is not necessarily a trivial exercise. For alloys that have good castability, choosing geometry for allowable stress and deflection is the best place to start. For alloys with less than the best castability, it is better to first find geometry that assists castability, and then modify it for allowable stress and deflection.

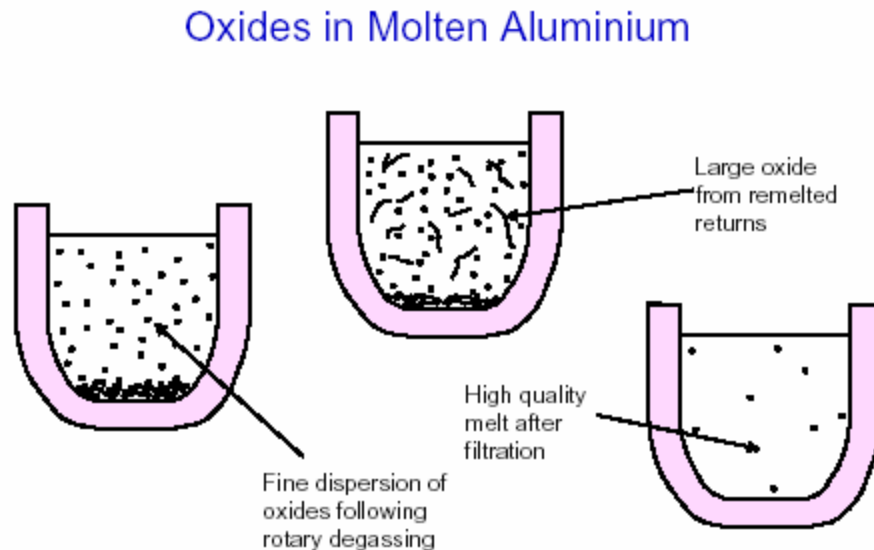
Not all alloys are like ductile iron, which is both highly castable and relatively resistant to stress, and moderately resilient against deflection. For ductile iron, many geometries may be equally acceptable. Martensitic high-alloy steel has fair-to-poor castability, but can have amazing resistance to stress and can tolerate very large deflections without structural harm. Therefore, structural geometry is easy to develop, but a coincidental castable shape is more difficult to design. Premium A356 aluminum has good castability, but rather weak resistance to stress and low tolerance for deflection. Carefully chosen structural geometry, however, combined with solidification enhancements in the molding process, has resulted in extremely weight-effective A356 structural components for aircraft, cars and trucks.

THE LIQUID METAL

Types of Impurities

Oxide pollution

When molten, and with its surface cleared of oxide, liquid aluminium looks like quicksilver. It is with regret, however, that we have to come to terms with the fact that the quality of the liquid underlying the silvery surface is likely to be anything but pure or clean metal (Figure 3202.00.01).



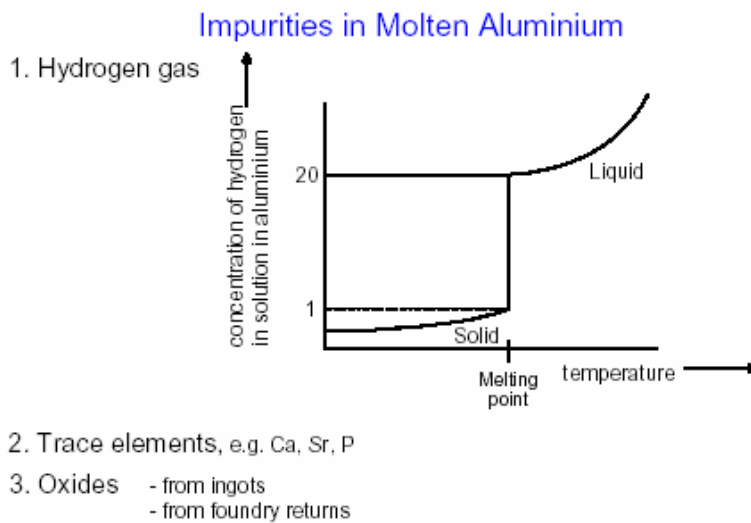
In fact, it is necessary to develop a view of the liquid as a slurry of sundry solid debris in suspension. It is only the size and quantity of solid debris which is changed from melt to melt and from one melting practice to another. In particular, we will see how the large oxide films which may be present from remelted returns can be substantially reduced by rotary degassing and filtration.

Hydrogen pollution

Other undesirable impurities may also be present in solution (**Figure 3202.00.02**). Perhaps the most important of these is hydrogen. Hydrogen is especially unwelcome in aluminium alloys because it is highly soluble in the liquid, but hardly soluble at all in the solid. In fact, as the aluminium solidifies, only one twentieth of the hydrogen is retained in solution under equilibrium conditions. The other nineteen twentieths will be rejected and will form gas pores, providing nuclei are present. (If nuclei are not present, then the gas will be unable to precipitate as porosity in the casting, but will remain as a supersaturated solid solution. We shall consider this phenomenon in more detail later in this lecture).

Other pollutants

Other impurities may seriously affect certain alloys. For instance, the presence of traces of Ca, Sr or P in Al-Si alloys will lead to changes in the modification of the eutectic silicon. (This will be discussed in a later lecture). However, in this lecture we shall concern ourselves only with the solid materials in suspension and hydrogen in solution in the melt.

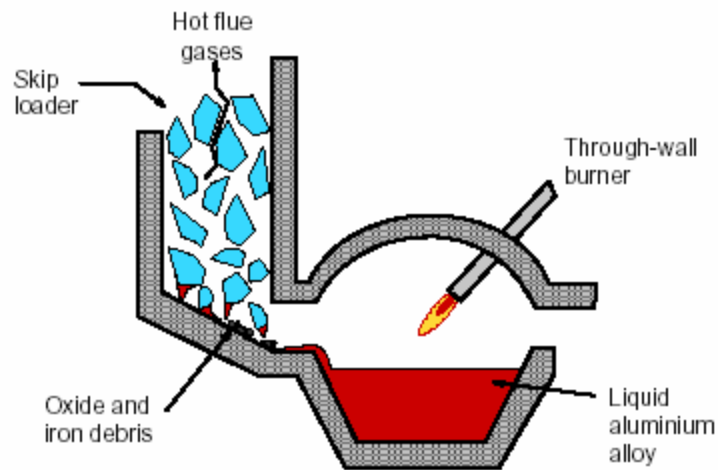


Origins of oxide inclusions

The solid materials arrive in the melt right from the start of melting. They arrive as oxide skins on the surface of the material to be melted. In the case of ingots (bars cast into cast iron pig moulds) the cooling rate of the ingots is rapid, and although carried out in air, the oxide skin which develops on the ingot during cooling is not especially thick. Thus when remelted in a crucible furnace, or other type of bath of molten metal, the oxide floats free and becomes dispersed in the melt. In the case of a sand foundry remelting foundry returns, the oxide skin is especially thick and can remain intact during remelting and float into the area where metal is being ladled or pumped from the furnace. Such films can finish up as complete, massive, filmlike or dross-like inclusions in finished castings.

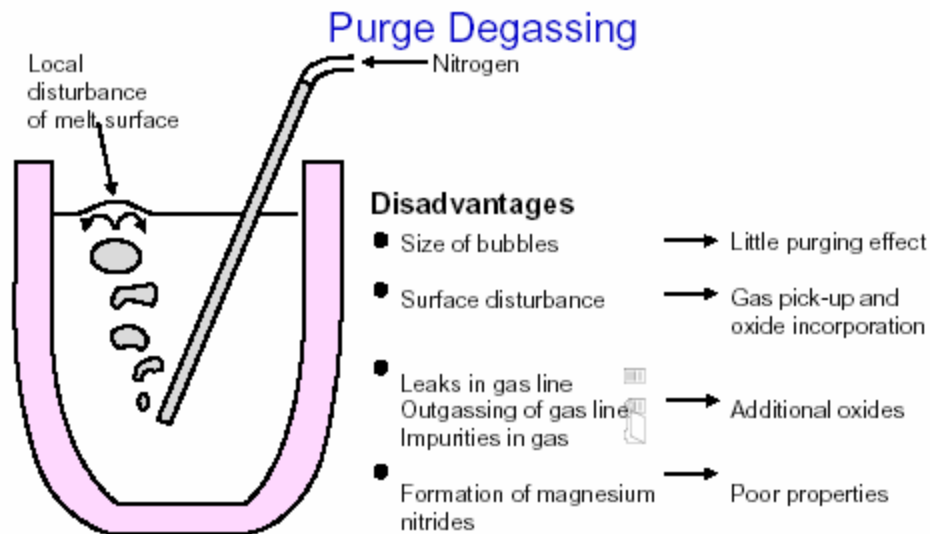
This direct recycling of the oxide skins occurs in those situations where the material to be remelted is introduced directly into the melting bath. These include common types of melting furnace, such as crucible furnaces or reverberatory furnaces. Whatever is added to these kinds of furnace is automatically submerged and redistributed in suspension in the melt. The action of the tower, or vertical shaft, type melting furnaces is quite different (Figure 3202.00.03). The material to be melted is loaded into the vertical shaft where it is preheated with the flue gases from the melting and holding region of the furnace. The shaft is offset from the bath so that unmelted debris does not enter the liquid metal directly - metal enters the bath by first melting and then running over a supporting platform, and so joining the bulk of the melt. The oxide skins are left behind at the base of the shaft, together with other unwanted debris such as iron inserts in scrapped castings. The sloping hearth of the furnace can be scraped clean of such accumulations from time to time as melting progresses.

Vertical Shaft Melting Furnace



Having started with a reasonable quality of liquid metal, it is necessary to try to keep it in good condition. However, it is again with regret that it has to be reported that most aluminium foundries do not achieve this. (It is achieved in casting houses designed for the continuous casting of wrought quality aluminium alloy, especially that to be used for such discriminating applications as foil or can stock.) Various treatments are notorious for the introduction of much additional oxide debris into the melt.

Effect of Purge degassing



One such treatment is degassing (see **Figure 3202.00.04**). This is often carried out badly, using an open-ended lance to introduce a purge gas into the melt. The size of bubbles from such a lance and the disturbance of the melt surface ensure that:

1. little gas is purged from the liquid, and
2. that the melt comes into equilibrium with the surrounding environment because the freshly presented surface is ideal for re-introducing fresh hydrogen into the melt. In addition, the rolling action of the surface creates extra oxide and may stir this into the melt. Furthermore, the impurities in the purge gas will generate additional oxide in the liquid. These impurities arise from leaks in the gas line, or the out-gassing of the gas line, especially if it contains long lengths of rubber or plastic. The extended time for such low efficiency degassing methods means that much additional oxide is introduced.

Where degassing with nitrogen is carried out continuously, as in some large holding furnaces, and where the alloy contains some Mg (which is most often the case), there is an additional danger from the build-up of nitrides in the liquid. This can become so prolific that the melt takes on the appearance of a slurry such as porridge or cement. The mechanical properties of the resulting castings are lamentably low because of the embrittling effect of the large concentration of nitrides. The only way to avoid such disasters when attempting to degas continuously is to use a truly inert gas such as argon. In addition, of course, the gas lines should be soundly plumbed in metal throughout.

Effect of flux degassing

A treatment which purports to clean the melt and simultaneously degas is flux degassing (**Figure 3202.00.05**). This process blows in a powdered chloride and/or fluoride flux into the melt on a carrier gas, usually nitrogen.

Flux Degassing

- ❑ Powdered chloride and/or fluoride flux introduced using nitrogen carrier gas.
- ❑ However ... oxides and gas are not totally eliminated.
- ❑ Environmental disposal problems.

For example:

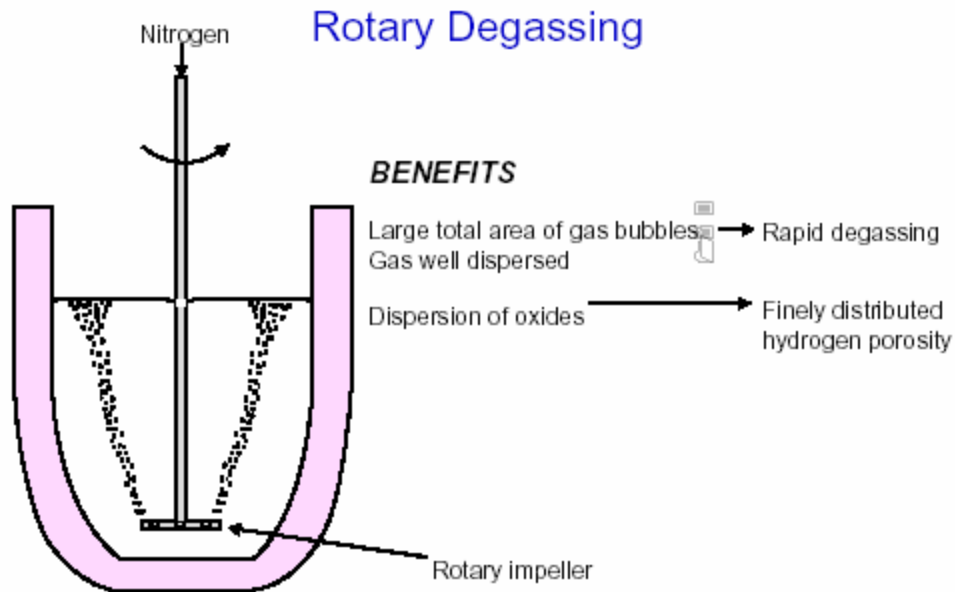
If oxide content reduced by 95%
and if gas content reduced by 75%

- ▷ 25% of remaining gas precipitates on 5% of remaining nucleation sites
- ▷ General porosity in the casting is reduced, but is 5x worse in more scattered areas

By this means both the oxide content and gas content of the melt are reduced. However, the oxide content and gas content are not, of course, eliminated. A problem arises, therefore, that if the oxide content is reduced by perhaps 95 % and the gas content reduced by 75 %, then we have the situation where 25 % of the gas now tends to precipitate on only 5 % nucleation sites. Thus the porosity in these more widely scattered regions is now 5 times worse than before. Whereas in the original material, the porosity might have been acceptable in a finely dispersed form (which might actually have been invisible on a radiograph), the casting is now rejected for occasional concentrated severe pores.

Effect of rotary degassing

An alternative degassing treatment is rotary degassing (**Figure 3202.00.06**). In this treatment a central hollow rotor introduces a purge gas (usually nitrogen) into the centre of a melt, where the emerging bubbles are fragmented and dispersed by the rapid rotation of the rotor. The large total area of the bubbles and their wide dispersion throughout the melt give a rapid degassing action. Whereas the hollow lance might give only poor degassing in an hour or so, the rotary technique typically reduces hydrogen to very low levels in only 10 minutes.



Because rotary degassing is a relatively new technique, little investigative work has been carried out on it so far. There seems to be evidence that the system causes large oxide films to float out, and maintains them at the surface so that they can be skimmed clear after degassing. In addition, however, it may be that the system actually introduces a new dispersion of fine oxides, possibly by fragmenting the large films which were originally in suspension, or possibly by reaction with the oxide or moisture contamination of the purge gas, which can arise either from trace impurities in the original gas or impurities introduced from sources in the local plumbing. An additional dispersion of nitrides is to be expected if nitrogen is used for degassing melts which contain some Mg. This fine dispersion of solids may have some benefits to melts intended for the production of shaped castings (provided that very high mechanical properties are not required). The low hydrogen content, together with the high density of nuclei on which the hydrogen can precipitate, will probably ensure that the residual hydrogen

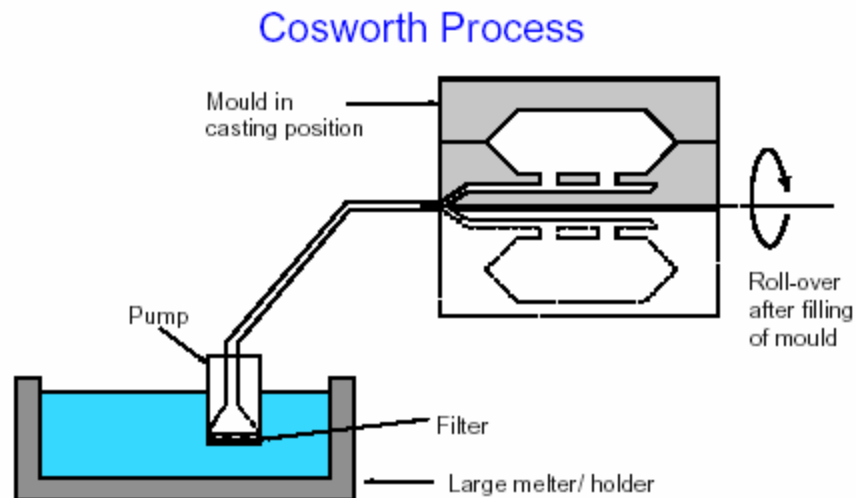
porosity, if present at all, is extremely fine and well dispersed. Thus the quality of the melt will be expected to be quite different from that produced by flux degassing. So far the melt has sat in its furnace, but has had to suffer a number of treatments, most of which will have increased its oxide content. Measurements of oxide contents of liquid aluminium in a major low pressure die casting plant have shown that the quality of alloy sitting in the well is good at the beginning of the Monday morning shift. However, as the shift progresses, the slopping of the metal up and down the riser tube, and the consequent disturbance of the sediment on the furnace bottom, results in a considerable increase in oxide level. A further major increase occurs when the furnace is topped up. The churning and surging of the melt and the thorough mixing-in of floor sediments greatly impair the melt quality further. During the day, the melt continues to deteriorate, finally becoming unrecognisably bad by the last shift on a Friday.

Low inclusions casting processes

Cosworth Casting Process

Such degrading of melt quality by turbulent transfer operations and by the general dipping and slopping which accompanies the casting operation itself is typical of many casting operations. This underlines the importance of those processes which are designed to handle the melt without unnecessary disturbance, such as the well-established Cosworth Casting Process (**Figure 3202.00.07**). In this process, the metal is melted and held in a large furnace. The furnace holds enough metal for several hours production so that there is some time for oxide films to sink or float. It can be noted that there is only a small density difference between molten aluminium and its oxide, and air is often entrained in folds of the film. Thus the separation takes place only slowly, and may be downwards or upwards. A significant proportion of films

have, by chance, almost neutral buoyancy and so never sink. It is essential, therefore, to ensure the removal of residual films by filtration.



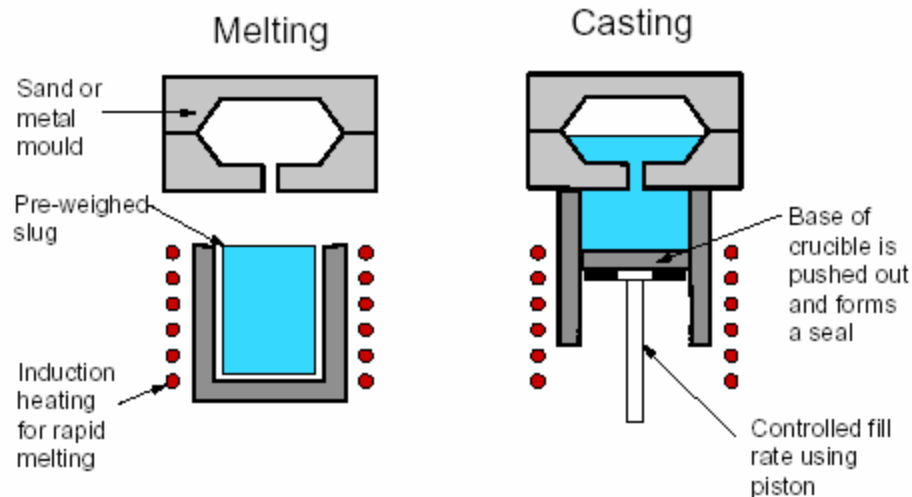
An electromagnetic pump is used to remove the molten metal which is taken from middepth in the furnace to minimise the risk of transferring oxides. Furthermore, a filter, integral with the base of the pump, is used to trap any oxides. Thereafter, the molten metal travels only uphill. The metal is pumped at a controlled rate through vertical gates into the casting. This approach ensures that the metal rises through the system in a nonturbulent manner, thereby minimising the formation of excessive oxide films and their incorporation into the casting. In its original form, the Cosworth Process had two main disadvantages. Firstly, the mould had to remain attached to the pump until the casting had solidified, which resulted in a slow production rate. Secondly, this method of mould filling resulted in the coldest metal being at the top of the casting which (as we will see in **TALAT Lecture**

3206) is not conducive to producing sound castings (i.e. free from shrinkage). Both of these problems can be overcome by the latest variant of the process in which the mould is filled from the side and is rolled over after casting. This means that the mould can be removed from the filling station (and replaced by an empty mould), increasing the production rate from about 1 casting every 4 minutes to better than 1 casting per minute. Furthermore, after inverting the mould the hottest metal is at the top of the casting and, in effect, the preheated runner bar now acts as the feeder.

Lost Crucible Process

Alcan have recently invented another means of preventing poor transfer of metal, known as the *Lost Crucible Process* (**Figure 3202.00.08**). In this, a pre-weighed slug of material is rapidly melted in an induction furnace. However, instead of the normal refractory crucible, a disposable fibre-ceramic crucible is used. Once the charge is molten and at the required temperature, the base of the crucible is pushed out by a vertically moving piston. As the piston continues to move upwards, the base of the crucible acts as a seal and the molten metal is introduced through the bottom of the mould at a controlled rate. This new Alcan Lost Crucible Process, if fully developed for production in due course, will conserve the quality of the alloy as produced by the primary producer.

Lost Crucible Method



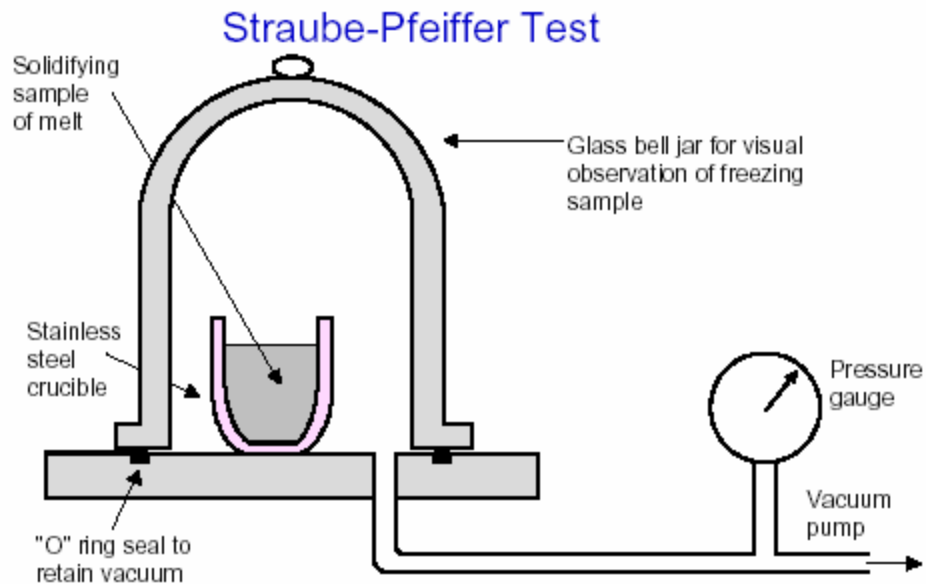
However, for all other processes, where the metal has to be melted in a furnace and then transferred for casting, the problem exists of how to test the quality of the metal.

Melt quality Assessment

Reduced Pressure Test

One of the simplest and oldest tests is the Straube-Pfeiffer Test, or Reduced Pressure Test (**Figure 3202.00.09**). This test simply comprises taking a small spoon sample from the melt, pouring this carefully into a small stainless steel crucible of the size of an eggcup, and placing this under a bell jar from which the air is evacuated by a vacuum pump, reducing the air pressure to typically one tenth (or possibly as low as one thirtieth) of one atmosphere while the sample solidifies. The observation of the sample during this time is important. The emergence of many bubbles indicates the presence of gas. Similarly, the final density of the sample may be low (although this is not an unambiguous result, since the precipitating gas may

have entirely escaped from the free surface of the sample; hence the need to observe it during freezing).



The reason for carrying out the test under reduced pressure is simply for the convenience of the magnification of the volume of gas by a factor of ten (or more if carried out at lower pressure; a factor of 30 is rarely exceeded). The pores are much more easily seen as they emerge at the surface, and are easily visible when the sample is cut up for subsequent examination.

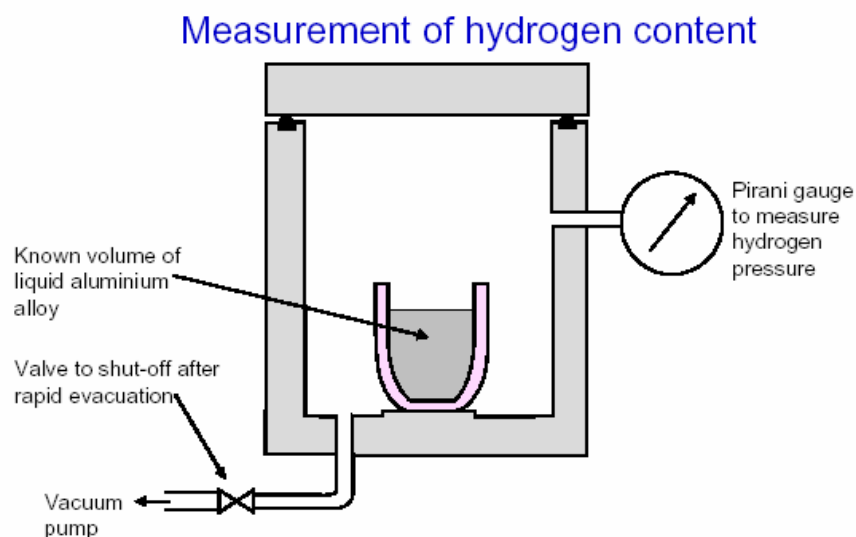
However, the test is interesting, since if no bubbles are observed one cannot conclude that the sample contained no hydrogen in solution. In fact, the hydrogen level may have been high, but the sample has retained its gas in supersaturated solution. This is because the gas cannot precipitate without the presence of nuclei which are usually non-wetted interfaces such as oxides. (It should be noted that TiAl_3 , TiB_2 , Al solid, and other interfaces on which the solid is thought to nucleate are well-wetted and thus probably

good nuclei for solid aluminium, but of no use as nuclei for pores. Nuclei for pores will require to be non-wetted, such as oxide films.)

The reduced pressure test is therefore a good test for the combined effects of hydrogen and nuclei. As such, it is really a "pore forming potential" test, in other words, a porosity test (i.e. it is definitely not a gas test, as is commonly supposed, and unjustly criticized when the test fails to agree with other fundamental techniques for the measurement of gas content). It is therefore a good test for the practical foundryman since it will reflect the likely quality of the castings.

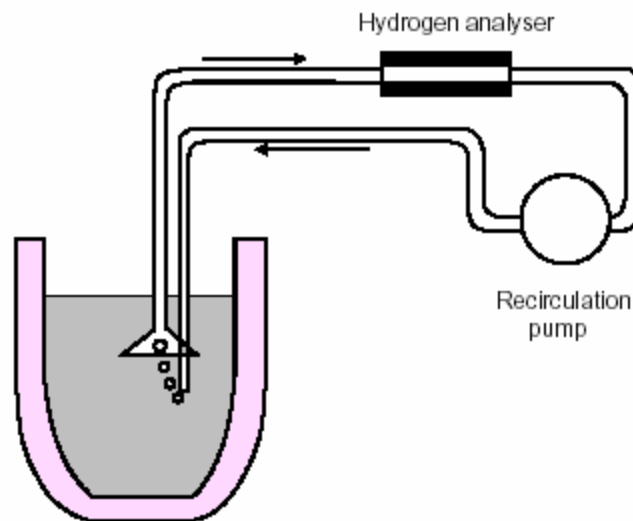
Gas Content Measurement

Other tests for hydrogen content in the melt are based on sampling, and measuring the volume of hydrogen gas that emerges under vacuum during the freezing of the sample (**Figure 3202.00.10**). Clearly this test relies on most of the hydrogen escaping, and will thus probably give an underestimation of the hydrogen content of the metal where the metal is particularly clean.

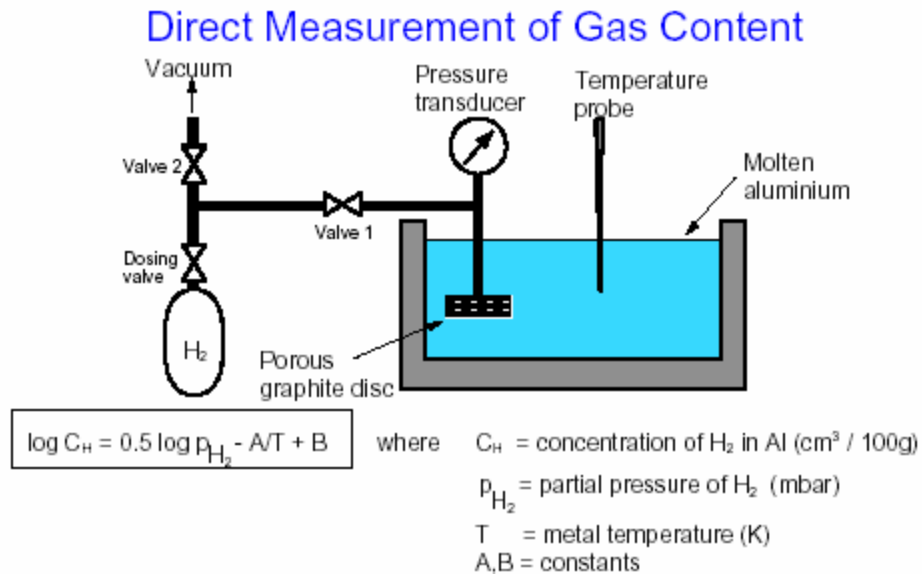


Other tests attempt to assess the gas content in situ in the melt, and have the advantage of the possibility of continuous operation. Such devices include the Telegas type instruments originally invented by Ransley (**Figure 3202.00.11**). These devices, now much improved by further sophistication from Alcoa and Alcan, repeatedly cycle a small amount (about 3 ml) of an inert gas such as argon (or nitrogen) through the melt, where it picks up hydrogen. The hydrogen content of the carrier gas gradually increases, reaching a condition of equilibration between the hydrogen gas in solution in the melt and the partial pressure of hydrogen gas in the carrier gas. This takes about 5 minutes. The hydrogen in the carrier gas is measured by a catherometer, an instrument for comparing the temperature of a hot wire in the flowing gas with the temperature of a similar hot wire in a stream of pure argon gas. The probe can then be left in place indefinitely, continuing to sample on a continuous basis. Modern probes appear to last for many hours, if not days, when used continuously or semi-continuously.

Principle of the telegas probe



A recent variation of the Ransley test is the CHAPEL test (Continuous Hydrogen Analysis by Pressure Evaluation in Liquids), see **Figure 3202.00.12**.



In this, a porous graphite probe connected to a pressure transducer is dipped into the melt and quickly evacuated. Hydrogen in the melt diffuses into the disc until the pressure in the probe and the hydrogen partial pressure in the melt have equalised. (About 30 - 60 minutes is required to establish equilibrium but this can be reduced by dosing the probe with hydrogen using the valve arrangement shown here.) Since hydrogen is the only gas which dissolves in molten aluminium, the total pressure measured in the probe is equal to the hydrogen partial pressure. By simultaneously measuring the temperature, Sievert's Law then allows the hydrogen concentration C_H to be derived from the hydrogen partial pressure p_{H_2} .

$$\log C_H = 0.5 \log P_{H_2} - A/T + B$$

where A and B are Sievert's constants (dependent on alloy composition) and T is metal temperature (K).

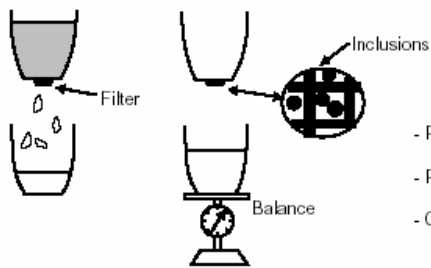
This elegantly direct and simple approach has yet to be developed for regular industrial use. Some attempts have been made to develop hydrogen sensors based on solid electrolyte cells immersed in the melt. However, these are at an early stage of development, and their lifetime and cost have yet to be established. Clearly, an independent measurement of hydrogen content, especially if carried out by a fundamental technique such as a Telegas type probe or direct reading pressure probe, when combined with the results of the Reduced Pressure Test would give an indication of both the gas and inclusion contents of the liquid metal.

Inclusion content measurements

Independent measurements of the inclusion contents of melts is rarely carried out outside of continuous casting operations. However, this would undoubtedly be of considerable advantage to foundries attempting to produce very high quality parts. A standard technique is the passing of a known volume of melt through a fine filter (see **Figure 3202.00.13**). The inclusions are caught on the filter and are subsequently identified and counted on a polished cross section under the optical microscope. This sampling method is of course rather laborious, but has been used to calibrate the continuous measurement techniques which I will now describe.

Inclusion Counts

Standard Techniques



- Pass known weight through filter
- Prepare metallographic sample
- Count inclusions
 - optical microscope, or
 - image analyser

Continuous Techniques

- Ultrasonic reflection from particles
- Conductivity measurement

Two main types of continuous devices are currently used:

1. An inspection of the melt by ultrasonic. An ultrasonic beam directed into the liquid metal, and is reflected from floating particles. The density and intensity of reflections is monitored electronically and processed to give information on the quality of the melt.
2. A conductivity probe measures the electrical current flowing through a small hole through which a sample of the melt is continuously being passed. As inclusions pass through the hole the electrical resistivity of the current path changes in proportion to the size of the inclusion. Again, the signals are processed electronically to monitor the size and number of inclusions.

FILLING OF CASTINGS

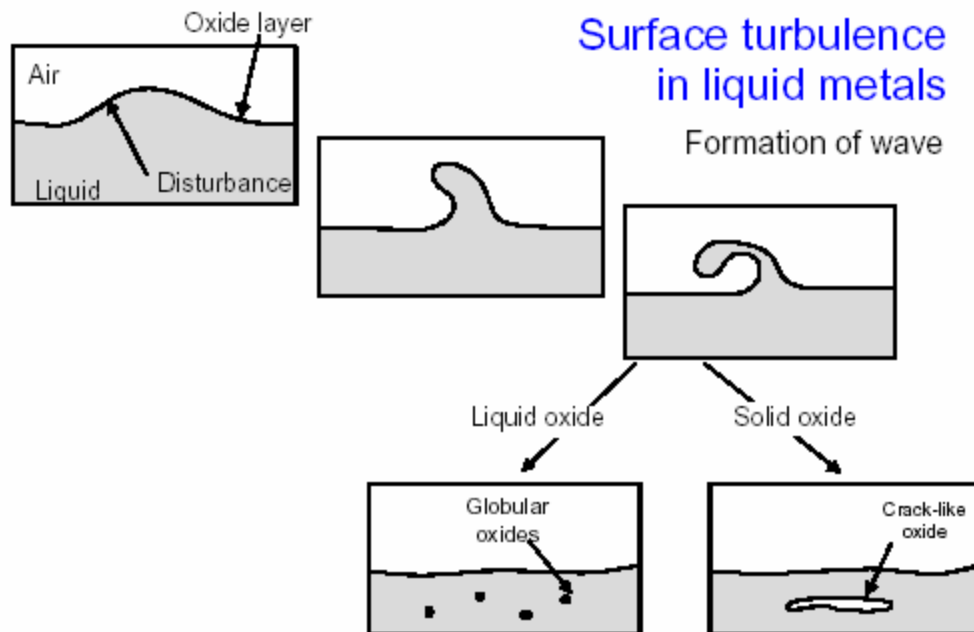
This chapter is concerned with filling the mould cavity with molten metal. Although this is one of the most important steps in producing a good quality casting, it is often the one which is the least understood and, as a result, it is often overlooked. It is all too common to see poor quality running systems in use in foundries, with consequential damaging effects on the quality of the castings produced.

The feeding system, which is used to compensate for the shrinkage of the casting as it solidifies, is in two parts. One feeder can be seen on the top of the casting and another on the right hand side. It can be clearly seen that the filling and feeding systems are separate, which is appropriate since they perform completely different functions in the production of a casting. It should be noted that the filling and feeding systems can sometimes be combined (although it is usually much more difficult to design a combined system which accomplishes both functions equally well). The difference between the very different functions of filling and feeding systems is emphasised when it is realised that, in the case of a typical casting, it might take ~ 10 seconds to fill the mould, whereas the feeding system would typically be operating for ~10 minutes as the casting solidifies. The present lecture will concentrate on the *filling* of castings, whereas a later one will concentrate on the *feeding* of castings. In this example of an aluminium casting, it should be appreciated that the metal has been carefully introduced into the cavity through gates in the bottom of the casting. This is in contrast to many iron castings in which the metal is poured directly into the top of the casting cavity with very little thought being given to providing a proper

illing system. In spite of this apparently rather crude approach to the filling of grey iron castings, they are nevertheless normally of quite a good quality. It is instructive to consider why this might be so.

Oxide Formation

All molten metals oxidise when in contact with the air, but the nature of the oxidation products varies considerably. For example, grey irons oxidise to form a liquid silicate skin, whereas aluminium and some other metals form a dry oxide skin. Molten aluminium is an extremely efficient 'getter' for oxygen and calculations show that a vacuum of less than 10-40 atmospheres would be required to prevent oxide film formation. (This is somewhat better than the vacuum found in outer space!!)



When a metal is poured rapidly into a mould, it enters in a turbulent manner, and it is inevitable that the oxide film folds over itself so that oxide-to-oxide contact occurs (see **Figure 3203.00.02**). Furthermore, as the metal tumbles over and churns about, the oxide film is continually being stretched and ruptured and also re-growing. In the case of grey cast irons, this is not too serious since the liquid silicate films can meet and fuse together, agglomerating to form droplets which generally float out of the molten iron. Even if they remain in the iron, they normally have a shape which does not have a detrimental effect on properties.

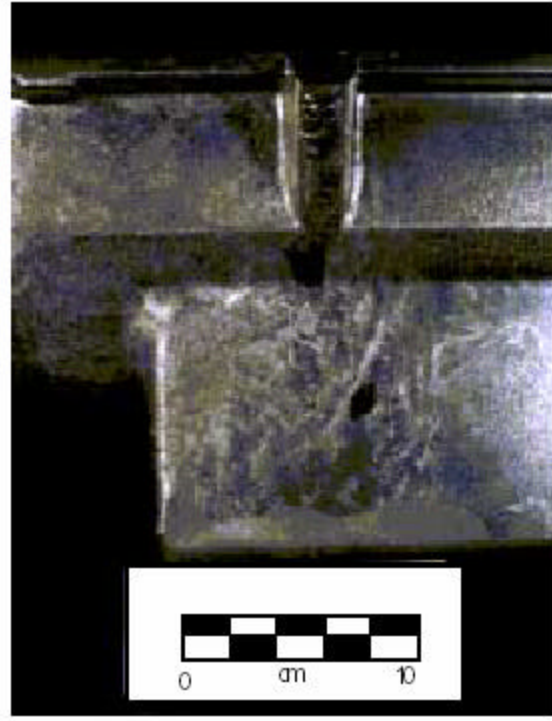
In contrast, when the solid alumina (Al_2O_3) films on molten aluminium meet, they do not 'knit' together, but instead form crack-like defects which remain in the casting as it solidifies. These introduce a mechanical weakness into the casting which will probably result in it being less reliable in service. Such crack-like defects also often result in leakage problems in castings which are required to contain a liquid or a gas. Unfortunately, aluminium castings have an unenviable reputation for being prone to leakage defects as a result of poor filling practice.

Casting Defects

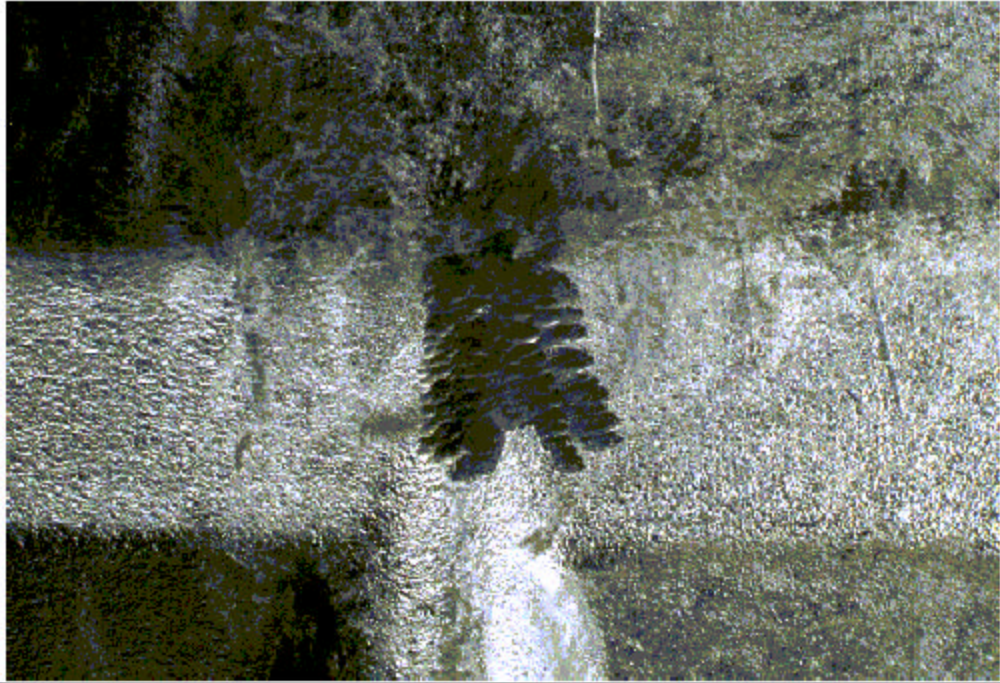
Figure 3203.00.03 shows a considerably larger casting and is in fact a sump for a diesel engine. It weighs ~ 6 kg and has an average wall thickness of 6 mm. Although the casting is complete and apparently satisfactory, the trained eye can see from quite a distance away that in fact it contains defects.



Figure 3203.00.04 is a close-up of the same casting and shows a dull matt area which is the oxide film formed as the metal entered the mould. The casting was produced with several feeders (to compensate for the solidification shrinkage) and the metal was introduced into the mould through one of these. As it was poured into the mould, turbulence led to the formation of layers of oxide which got trapped in the metal, hanging in place like curtains and creating extensive planes of mechanical weakness. In some cases, castings with defects such as these can crack spontaneously at any time after solidification. If these cracks are found, the castings would often be stressed to remove the cracks and then welded, but the thermal cycle resulting from this can lead to further cracks which then have to be removed and weld-repaired. Unfortunately, it is an all-too-common foundry experience that cracks can be 'chased round' a casting!



The fact that these oxide film defects often cause castings to fail leak tests clearly implies that the defects are continuous from one side of the casting to the other. Castings are normally tested by pressurising them with air whilst they are submerged under water so that the defects are revealed by a stream of bubbles. The operator then attempts to seal the porosity by peening over the surface, leaving these tell-tale marks on the casting surface (**Figure 3203.00.05**).

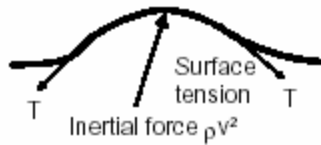


The lesson to be learnt from this is that castings in metals such as aluminium should not be top-poured. The remainder of this lecture is concerned with how to fill a casting without creating this mess of entangled oxide films.

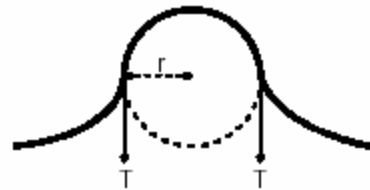
Critical Velocity

We will firstly consider a simplified approach to the formation of surface turbulence in a liquid metal. The top half of **Figure 3203.00.06** shows a slice through a liquid metal which is subjected to some vertically rising disturbance, such that a wave starts to form under an inertial pressure having an approximate value of $\rho \cdot V^2$, where ρ is the molten metal density and V is the velocity of the disturbance. The ultimate shape of the disturbance would be a droplet of radius r , but its formation is restrained by the surface tension T .

Turbulent Flow in Metals



Limiting condition is when a drop is about to form



$$\rho V^2 = \frac{2T}{r}$$

Therefore $V_{crit} = \sqrt{\frac{2 \cdot T}{r \cdot \rho}}$

The limiting condition can be seen to be when the inertial force is balanced by the surface tension force, i.e. when

$$\rho V^2 = 2 \cdot T / r$$

so that the critical velocity, V_{crit} , can be defined as

$$V_{crit} = \sqrt{2 \cdot T / (r \cdot \rho)}$$

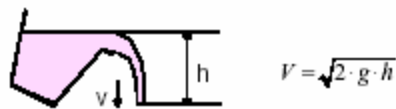
We shall now consider what this means when applied to aluminum.

Critical Velocity

$$V_{crit} = \sqrt{\frac{2 \cdot T}{r \cdot \rho}}$$

For aluminium	$T \sim 1\text{N/m}$
	$\rho \sim 2500\text{kg/m}^3$
Assume	$r \sim 5\text{mm} = 0.005\text{m}$
$\Rightarrow V_{crit} = 0.4\text{m/s}$	

Generally find that $v_{crit} \sim 0.5\text{m/s}$ for most metals



The critical velocity is reached after a drop of:

$$h_{crit} = \frac{V_{crit}^2}{2 \cdot g} = 12.7\text{mm}$$

Typical values for liquid aluminium are (see also **Figure 3203.00.07**)

$$T = 1 \text{ N m}^{-1}$$

$$\rho = 2500 \text{ kg m}^{-3}$$

$$r = 5 \text{ mm} = 0.005 \text{ m (assumed radius of aluminium droplet)}$$

and so

$$V_{crit} = 0.4 \text{ m s}^{-1}$$

Slightly more accurate values for these parameters give a value of V_{crit} of about 0.5m s^{-1} for aluminium and it is found that most other liquid metals tend to give similar values within a factor of 2. This is because T tends to increase as ρ increases, so keeping the ratio T/ρ roughly the same from one metal to another. The above values of V_{crit} therefore provide an indication of the critical velocity of molten metal in a mould. Once these values are exceeded, the surface of the metal will behave in a turbulent fashion, i.e. there is a real risk that the surface will break up into waves and droplets, causing the oxide film defects seen earlier. It is instructive to obtain a feeling

of how readily this critical velocity is reached. It can be shown from a simple energy balance (of potential and kinetic energies) that when a stream of metal has fallen a height of h , its velocity V has become $V = \sqrt{2gh}$ (2) where g is the acceleration due to gravity. Combination of equations (1) and (2) shows that the critical drop height, h_{crit} , before the critical velocity is reached is given by $h_{crit} = V_{crit}^2 / 2g = 12.7 \text{ mm}$

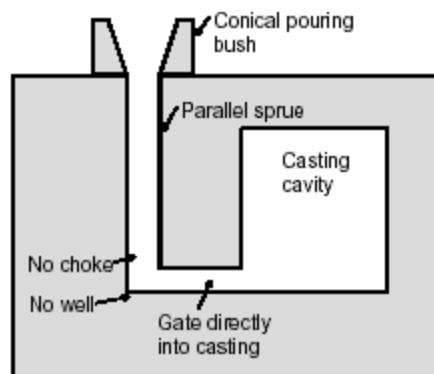
when $V_{crit} = 0.5 \text{ m sec}^{-1}$

This shows that once the metal has fallen by *only* 12.7 mm, it is already at a critical velocity, i.e. it has sufficient energy to break its surface in a turbulent manner, and is therefore likely to cause defects. This implies that it is *never* possible to fill a casting from the top and therefore the only solution is to fill it from the bottom.

Casting Design Assessment

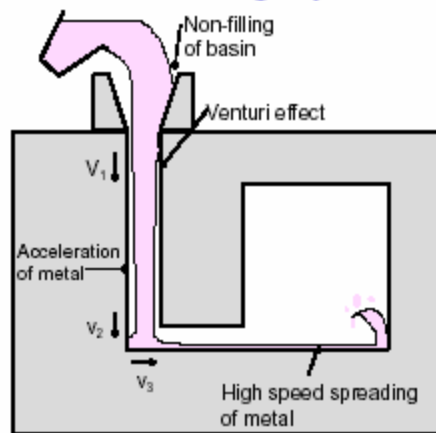
I would now like to consider the various elements of the running system and will start by examining what constitutes a deliberately bad running system (**Figure 3203.00.08**). Unfortunately, it is one that is seen all too often in foundries.

Deliberately Bad Running System



This a section through a mould and shows four deliberate mistakes, namely a conical pouring bush, a parallel sprue, no choke and no runner bar, so that the metal enters directly into the casting. We will now consider the effect of these bad design features. As the metal is poured directly from the ladle into the conical pouring bush, it is already moving quite quickly as it enters the top of the sprue. Its velocity V_1 will be determined through the height through which it has fallen. Thus, this basin design is bad because it has no decelerating effect on the metal. As the metal runs down the sprue, it accelerates due to gravity and so the stream gets thinner, reaching a velocity V_2 at the bottom. Since there is no 'choke' at the bottom of the sprue, neither it nor the pouring basin ever fill up completely. As a result, there is a Venturi effect with air being sucked into the metal stream through both the sand walls of the sprue and the incompletely filled pouring basin, thereby creating conditions to form oxides (**Figure 3203.00.09**)

Problems Resulting from Deliberately Bad Running System



The metal stream then hits the bottom of the sprue. One might intuitively expect that it would then form a splash but slow-motion video photography has shown that, contrary to expectation, the stream spreads out in a relatively thin film along the horizontal surface of the gate with a velocity of V_3 which can be significantly greater than V_2 . It therefore enters the casting at speed, hitting the far wall where it rebounds in an uncontrolled manner, forming a splash and creating conditions for further oxidation.

Top versus Bottom Gating

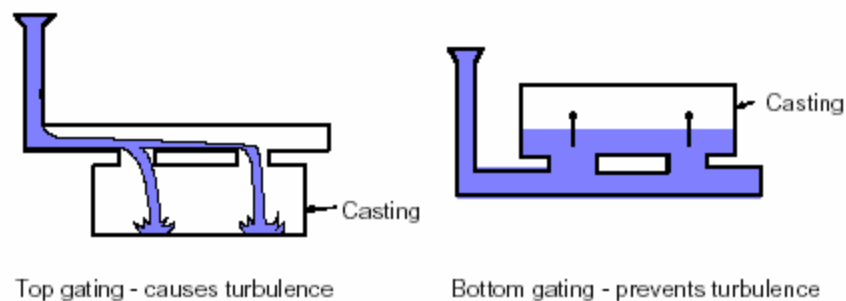
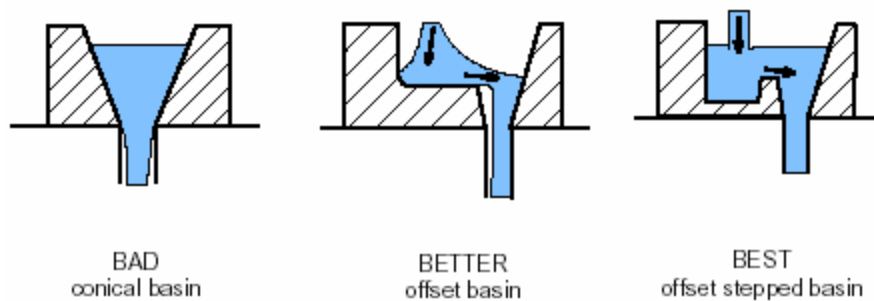


Figure 3203.00.10 shows another common mistake, in which the metal is introduced into the top of the casting cavity, i.e. by top gating. The critical velocity is readily exceeded and the resulting turbulence and splashing cause oxidation of the molten metal. The preferred technique is to use bottom gating, i.e. to introduce the metal uphill into the casting although, as we will see, it is still important to limit the velocity with which the metal enters the mould. Having considered ways in which a casting should NOT be produced, we will now look at the proper way to design a running system, starting from the pouring basin and working our way through in order.

Pouring Basin As we have already seen, it is important to avoid the use of a conical pouring basin since this does not decelerate the metal and also acts as a venturi and causes air ingress. One improvement would be to use an offset pouring basin which helps to decelerate the metal stream before it enters the sprue. However, a jet of metal still travels at high velocity across the top of the sprue, hitting the far side, and there is a tendency for the metal to flow down only one side of the sprue (**Figure 3203.00.11**).

Good Design 1: Pouring Basin



The best design is to introduce a step into the basin to give an *offset stepped basin*. The step acts to stop the rapid motion of the metal over the top of the sprue and helps to ensure that the latter is completely filled.

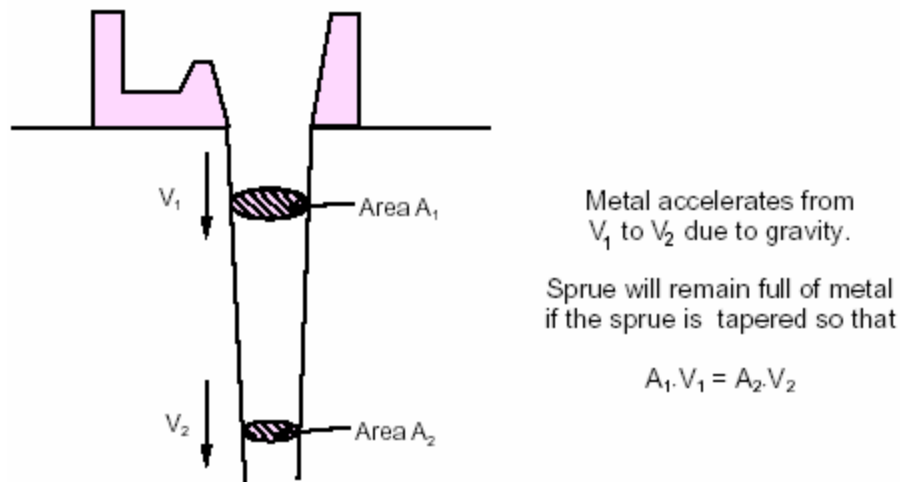
Tapered Sprue

The next point is to ensure that a tapered sprue is used (see **Figure 3203.00.12**). The stream of metal will accelerate from a velocity V_1 at the top of the sprue to a velocity V_2 at the base of the sprue and the conservation of matter requires that its cross-sectional area will decrease from A_1 to A_2 . It can therefore be seen that the sprue will remain full if the following criterion is satisfied:

$$A_1 \cdot V_1 = A_2 \cdot V_2$$

A tapered sprue can be readily moulded into vertically-parted moulds, but is more difficult to produce in horizontally-parted moulds because the sprue pattern has to be withdrawn from the top of the mould. (If the sprue pattern is fixed to the pattern plate then, of course, the sprue automatically has an incorrect, negative taper, with much consequent damage to the liquid metal entering the mould.).

Good Design 2: Tapered Sprue



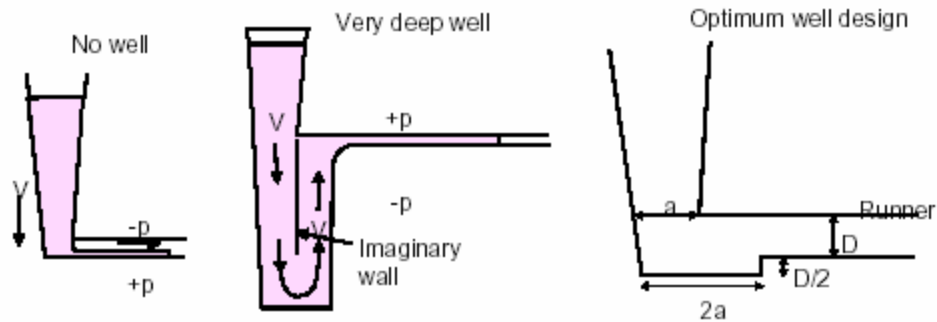
Sprue Well

The next stage is to transfer the metal from the sprue into the runner bar via a sprue well (also called a sprue base). This has three important functions:

- (i) it helps to decelerate the metal, (ii) it constrains the first metal as it exits from the sprue and prevents splashing, (iii) it helps to ensure that the runner bar is filled.

Good Design 3: Sprue Well

The sprue well helps to: (i) Decelerate metal
(ii) Stop first splash
(iii) Fill runner

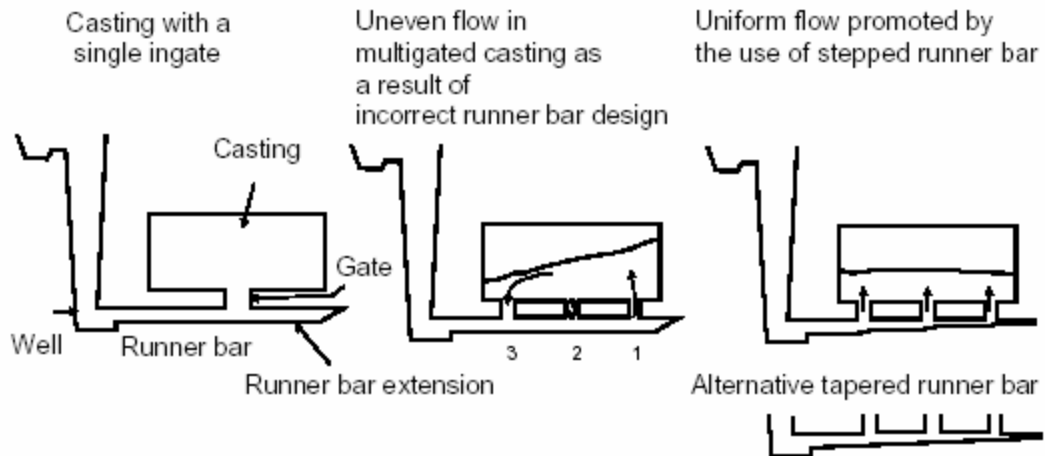


If there is no well, the falling metal stream hits the bottom surface of the runner bar at a velocity V and spreads along the bottom surface of the runner (see **Figure 3203.00.13**). In doing so, it creates a pressure, $+p$, which is balanced by a negative pressure, $-p$, on the top surface of the runner bar. This tends to draw in air through the permeable sand mould, leading to oxidation of the metal. We shall now consider a hypothetical case of a very deep well designed such that the falling metal stream reaches the bottom of one side of the well and then returns up the other side without meeting the falling metal. If we assume that there are no energy losses due to friction, then as the metal is about to exit from the well into the runner, its velocity will again be V , the same as when it entered. This time, however, the metal hits the top surface of the runner bar and spreads along it. In doing so, it creates a pressure $+p$ on the top surface and a corresponding pressure $-p$ on the bottom surface. It can therefore be seen that a very deep well completely reverses the metal distribution and pressures that are produced when there is

no well. This purely hypothetical reasoning (a kind of thought experiment) indicates that some intermediate well design will be 'neutral', i.e. metal will tend to fill the cross-section of the runner and to create equal pressures on the top and bottom surfaces of the runner bar. Rather surprisingly, there has been little detailed research on well design. However, recent experiments suggest that the optimum well design has a base with a depth in the range D to $D/2$, where D is the depth of the runner bar. The well should have a width of $2a$, where a is the diameter of the bottom of the sprue.

Good Design 4: Runner Bar and Gates

- AIMS: (i) to distribute metal to lowest point(s) on a casting
(ii) to reduce metal velocity.



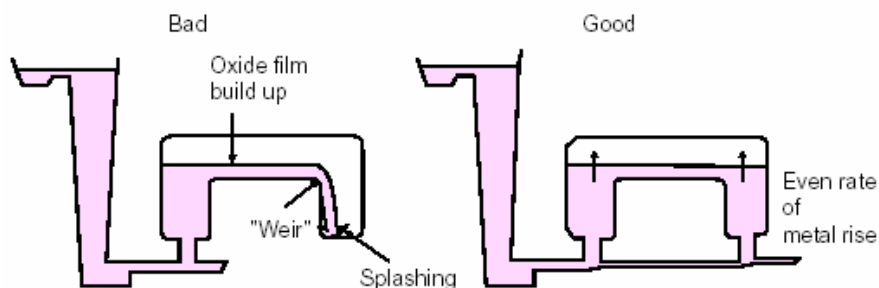
The well should be the lowest point of the casting and filling system and the metal should always progress uphill thereafter (**Figure 3203.00.14**). In doing so, it firstly passes through the runner bar which distributes it through gates to the lowest point or points on the casting. Careful thought has to be given to how the metal will flow through the runner and casting, bearing in mind the need to keep the speed low in order to avoid surface turbulence.

In some castings, only one gate will be required. In such cases, the runner bar will be a simple parallel sided channel, arranged so that the metal rises uphill from the sprue base, through the runner and gate and into the casting. It is good practice to have a runner bar extension which can be used to receive the first metal poured into the mould and which often contains air bubbles and slag particles. In other castings, it may be necessary to use two or more gates, in which case the runner bar must be stepped to promote equal flow through both gates. If this is not done, in the case of three gates for instance, the furthest gate (gate1) tends to fill first and so becomes super-heated, whereas metal tends to flow out of gate 3 and the latter becomes cold. Gate 2 takes on a neutral character. Uneven flow leads to an uneven temperature distribution and an increased risk of turbulence-induced defects. The runner bar should therefore have a gentle tapered step at each gate to promote even metal flow. In extreme cases, where there are many gates or a single gate along the length of the casting, the runner bar can be tapered along its length.

Good Design 4 (Continued): Runner Bar and Gates

Waterfall effects must be avoided so that:

- (a) splashing is prevented
- (b) the critical velocity is not exceeded
- (b) the metal meniscus is never stationary

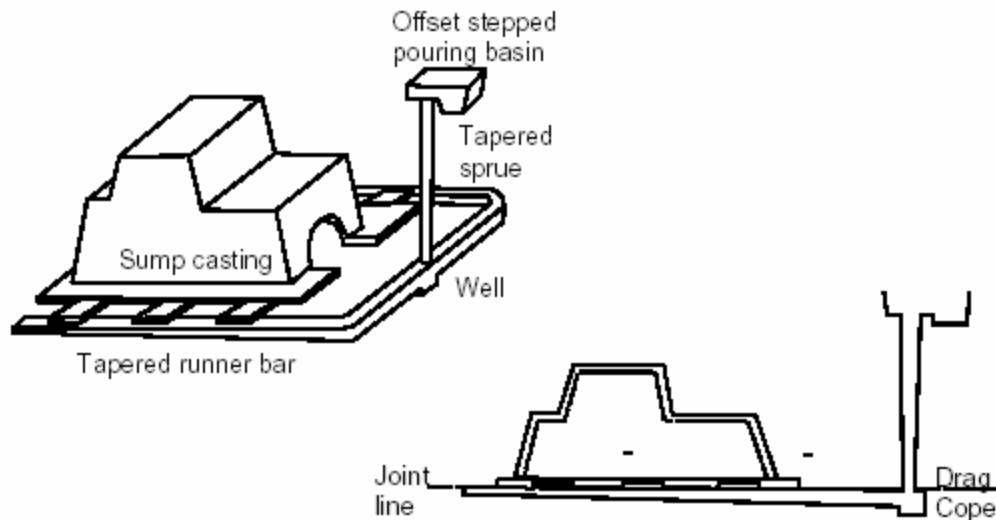


Another important feature is that the gating arrangement must avoid waterfall effects (see **Figure 3203.00.15**). In the first example shown here, metal is introduced into only one leg of an inverted 'U' casting. As one leg fills up, the point is reached where the metal splashes over the 'weir'. The splashing leads to unwanted oxidation of the metal and is of course particularly bad if the fall exceeds the critical height defined earlier (12.5 mm in aluminium) since the critical velocity condition will then be reached. At the same time, whilst the metal is filling the non-gated leg, the top meniscus is static. As a result, its oxide surface layer will be rapidly growing in thickness and will become increasingly difficult to move once the waterfall effect has finished. The molten metal will then tend to flow over the top of the thick oxide skin, leading to an entrapped defect which is known as an **oxide lap**. The solution is to use more than one gate, so that metal rises in both legs at the same time. This avoids both the waterfall effect and the development of thick oxide films. For castings with multiple isolated low points, a separate ingate is required for each low point.

Good Designing Example

Figure 3203.00.16: Some of these aspects of good design will now be examined in a little more detail by reference to the sump casting that we saw at the beginning of the lecture. You will recall that this contained extensive oxide defects which led to leakage problems. This was originally top poured, i.e. the casting was the other way up to that shown here and the metal was poured in through the flanged area.

Diesel Engine Sump



This shows a much better way of making the casting. Firstly, the casting is inverted. The metal is poured into an offset stepped pouring basin to reduce the velocity at the top of the sprue. The sprue is tapered so that aspiration of air is prevented as the metal accelerates and the stream reduces in area. The metal passes through a well which acts to control the metal as it enters the horseshoe shaped runner bar. This design is used to distribute the metal to both sides of the casting. (If the metal were delivered only to one side, then a waterfall effect would occur over the semi-circular cut-outs in the end walls.) Gates are taken off the top of the runner and into the bottom edge of the casting, thus fulfilling the requirement to fill from the bottom up. Calculation showed that 3 ingates were required per side to ensure that the critical velocity of 0.5 m s^{-1} was not exceeded through the ingates. It would have been possible to use a stepped runner bar, but in this case it was considered simpler to mould a tapered runner bar.

Nomogram for Running System

I would like to finish this lecture by briefly considering how running systems are designed by using this sump casting as an example. Their dimensions can be calculated from first principles but, in practice, it is easier to use nomograms designed for the purpose.

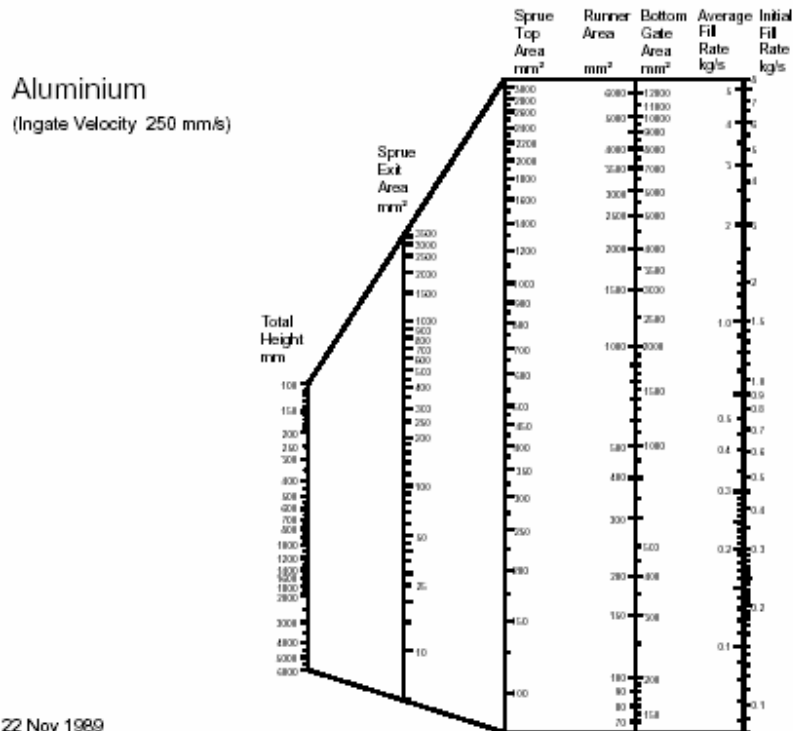
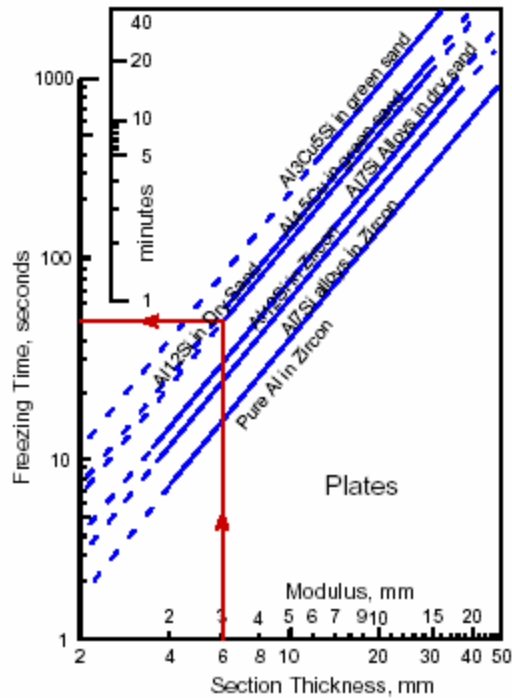


Figure 3203.00.17 is a nomogram for the design of running systems for aluminium castings and will ensure that the maximum ingate velocity does not exceed 250 mm s⁻¹. This is half the critical velocity and will therefore provide a certain safety margin. We start on the right-hand side of the nomogram and move to the left. The first thing we need to calculate is the average filling rate. The weight of the casting is easy enough – it weighs 6 kg. We also need to know the weight of the running system which is of course unknown until it has been designed! However, as a first estimate, we

can use previous experience to guess a weight of 4 kg, therefore giving a total weight of 10 kg. We next need to select the time it will take to fill the mould. Again, this is not easy and is based on experience and basically a question of trying to imagine how the metal will flow through and fill the mould on the foundry floor. In this case, we could imagine that it might take 10 seconds for the metal to fill the mould, giving an average filling rate of 1 kg s⁻¹.

Solidification Time Assessment

Another way of approaching this is to predict the solidification time for the thinnest section of the casting, using information such as shown here (**Figure 3203.00.18**), and then to use this as a guide to selecting the filling time. This graph shows that our 6 mm thick casting produced in an Al-7Si alloy in a dry sand mould would solidify in about 50 seconds. Clearly, it is important that the casting is poured in less than that!! A filling time of 10 seconds would appear to be appropriate.



Source: JC 17 Nov. 89

Gates

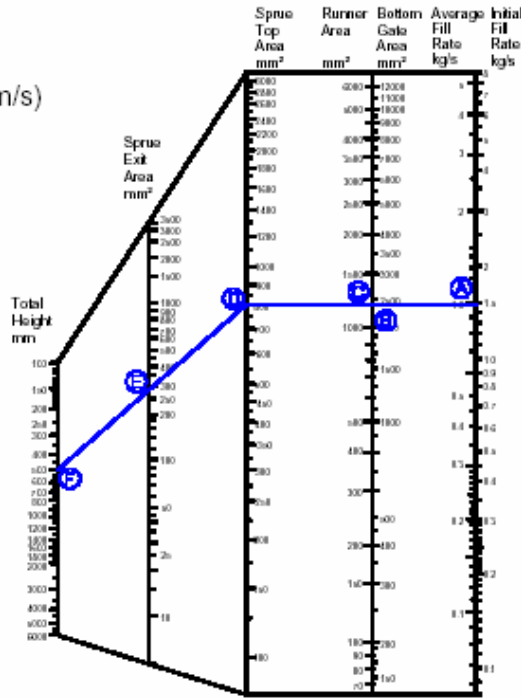
Returning to the nomogram, we can now place the average filling time of 1 kg s⁻¹ on the right hand axis (point A in **Figure 3203.00.19**). A horizontal line is then drawn to intersect the next two vertical axes. The intersection at point B gives the required gate area of 2400 mm². We then have the freedom to select how we wish to use that available gate area - whether we want one gate of 2400 mm² or whether we want a multiplicity of gates having a total area of 2400 mm². In this case, it is wished to run the metal into both sides of the casting and it is felt appropriate to use three gates on each side. We therefore now have 6 gates, each having an area of 400 mm², and again it is our responsibility to choose the actual dimensions. To ease cut-off, it might be best to use thin gates, so one possible choice would be

gates of 4 mm thick x 100 mm long. In choosing the gate thickness, consideration must be given to the resulting junction between the gate and the casting: this is considered in greater detail in **Talat Lecture 3206**.

Also on the same vertical axis, we see that the runner area should be 1200 mm² (point

C). Since it is a horseshoe runner, each leg should have an area of 600 mm² at the start. Again, it is the Methods Engineer's responsibility to choose the actual dimensions, one choice being an approximately square runner of 24 x 25 mm. This would then be tapered down at each ingate, as we have previously seen. Moving to the intersection with the next axis, point D gives the area at the top of the sprue as 800 mm² which could be satisfied by a square sprue of about 28 x 28 mm or a round sprue of 32 mm diameter.

Aluminium
(Ingate Velocity 250 mm/s)



Source: JC 22 Nov 1989

Sprue Height

We then need to decide how high the sprue will be. This will be determined by the height of the casting, plus any feeders on the casting, and by the minimum sand thickness over the top of the casting. In this case, a sprue height of ~500 mm was required. This is entered on the nomogram as point E on the left-hand axis. A straight line is then drawn between points D and E, to give an intersection at point F of the Sprue Exit Area axis. The value can be seen to be 300 mm², which could be satisfied by, for example, a square sprue of 17 x 17 mm or a round sprue of ~19.5 mm diameter. This sprue exit area will act as the 'choke', i.e. it will control the flow of metal so that the fill time will be 10 seconds, which is the value selected at the start of the calculation.

Running Systems for Diesel Engine Sump Casting

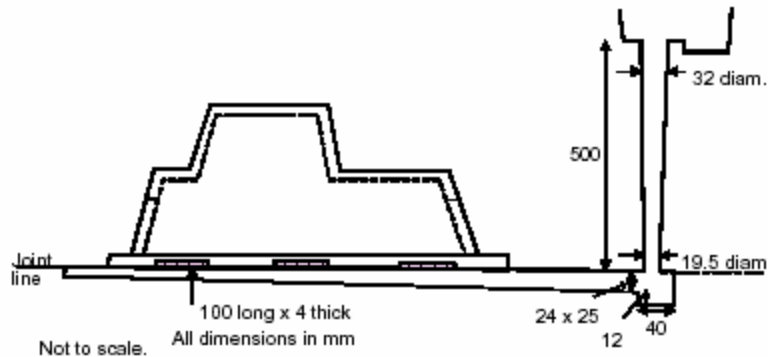


Figure 3203.00.20 shows the calculated dimensions of the runner system. It has been assumed that square sections are used for the sprue and runner, although other cross sectional shapes could be used, so long as the areas are correct. The remaining important feature to be designed is the well base which is based on the optimum dimensions which have already been defined in **Figure 3203.00.13**. When working out the dimensions of a running system, it is helpful to follow a logical sequence of calculations. It is recommended to use a worksheet such as shown here (**Figure 3203.00.21**) which is designed to be used in conjunction with the nomogram.