DC Casting of Aluminium: Process Behaviour and Technology

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Synopsis

This paper reviews the physical phenomena and technology of DC casting of aluminium. The basic process, its variants, history and commercial aspects are described. The process physics such as heat and fluid flow, solidification microstructure, thermal stress, deformation and cracking are discussed. We illustrate how understanding the physical phenomena occuring during DC casting has lead to modifications and new variants of the technology. This understanding has in the past ten years often been aided by the application of mathematical models, and many examples are given. The mechanisms of formation of the surface region and various mould technologies used to control this region are reviewed, including low metal level casting, hot top moulds, gas pressurised hot tops, and electromagnetic casting. Methods of controlling deformation at cast start, and cracking are discussed. Some engineering and safety aspects are considered and the article concludes with a brief discussion of future prospects.

1. Introduction

This paper deals with the physical phenomena taking place during direct chill or “DC” casting of aluminium and the technological methods used to control them. Emley’s [1] 1976 review deals with DC casting as well as other processes, but there have been many advances since.

2. History

In the early 1930s DC casting was invented independently by VAW (Germany) and Alcoa (USA) [2,3,4]. Today it is the premier process for producing aluminium shapes suitable for subsequent processing in extrusion, rolling or remelt operations. Around ten million tonnes per annum of aluminium is DC cast worldwide. The process is also used to cast copper, zinc and magnesium.

Before DC casting, feedstock for rolling mills was cast by the book mould process, where a two piece steel mould contained the aluminium while water sprays cooled the outside of the mould. DC casting enabled a finer grain structure to be obtained as the direct cooling provided by the water contacting the casting itself produced a much higher rate of heat extraction. This reduced microstructural variation and segregation.

The first Australian DC castings were produced in August 1956 at Comalco Aluminium Limited’s Bell Bay smelter [5]. Four inch square bars of commercial purity aluminium were cast for fabrication into high tension conductors. There are currently six aluminium smelters and four remelt facilities in operation in Australia and New Zealand, using three horizontal and over a dozen vertical DC casting machines, representing a fraction of approximately two hundred DC casting units in operation worldwide.

3. Commercial Aspects

3.1 General

DC casting of aluminium provides the link between liquid metal, as obtained from reduction cells or from scrap melting, and the semi-fabricator. Products include large rectangular sections known as rolling blocks, rolling ingots or slab (typically ≈500 x 1500-2000 mm in section) which are used by rolling mills for plate, sheet or foil production. Alloys are typically 1000, 3000, or 5000 series. Circular sections, known as rounds or billets, up to 1.1 metre diameter, are usually sent to extrusion operations but can be used to supply forging presses. For most extrusion applications 6000 series alloys are used, although high silicon foundry alloys, high conductivity 1000 series and high strength 2000 and 7000 series alloys can also be DC cast. Remelt ingots, both pure and alloyed, in small rectangular sections (eg. 150 x 50 mm) or large T sections (500 x 1200 mm), can be produced and are seen as an alternative to the traditional ingot casting method of open steel moulds mounted on a belt moving through a water bath.

3.2 Competing Processes

Continuous twin-roll~~s~~ cast strip (1-12 mm) or continuously cast slab (20-75 mm) can be used for sheet production. Use of twin-roll casters is well established for certain products such as foil. Slab casters are gaining increasing acceptance. These processes have inherent advantages over the DC cast hot rolling route: they are fully continuous and the energy costs to roll the material to final gauge are reduced. Conversion costs for liquid metal to final sheet have been quoted as being about 60%, and investment costs about 40%, of the conventional DC route. However, at this stage the full range of sheet alloys cannot be produced on these machines. For a more detailed discussion of these processes and comparisons with DC casting see references [6-16]. There is currently much effort being applied to developing higher productivity twin-roll casting methods using thin gauges [17].

There are many other continuous casting processes such as Castex/Conform [18], Properzi [19] and Southwire but these are generally suited to more specialised applications such as overhead power cable production. These processes use a wheel or block with a groove machined on the periphery in which the metal solidifies, as a bar which is taken directly into a forming operation. These are currently being promoted for remelt ingot production.

4. Process Description

DC casting produces ingots of uniform cross section, initially by containment of the liquid metal in a cooled mould and then by direct cooling of the casting (Figure 1).

Almost universally, the cooling medium is water, both for the mould cooling (primary cooling) and the direct or secondary cooling[1].

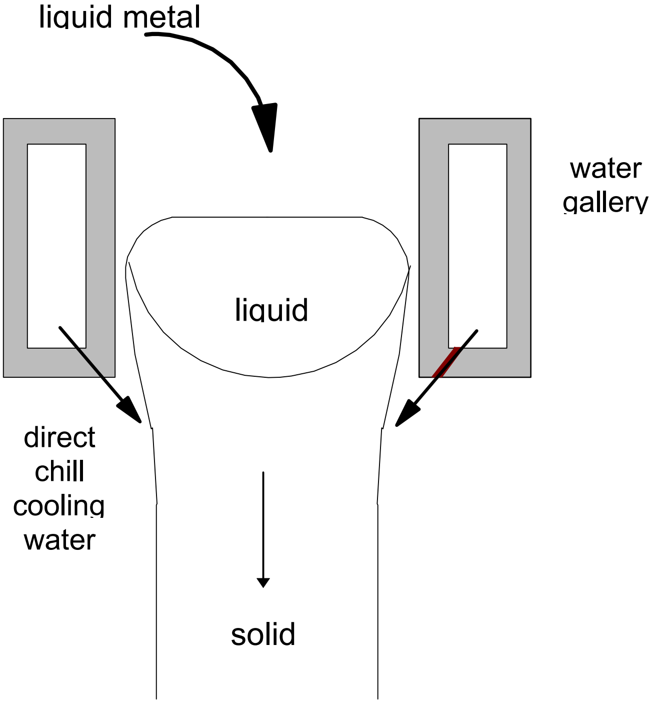

Figure 1: Schematic of the basic DC process. The solid moves out of the mould, liquid is fed into the mould opening and is contained by the water cooled mould, the direct chill water spray cools the ingot as it emerges, extracting enough heat for the solid shell to form above the spray inside the mould and contain the liquid.

At the start of casting, the open ended metal mould has to be plugged with a starting head or “dummy” block to contain the liquid and allow the cast to proceed. Metal is poured into the water cooled mould, freezing onto the starting head. After a delay, the

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[1] This terminology as used throughout the industry is somewhat misleading, as it is the secondary cooling which extracts ~95% of the heat.

starting head is lowered into a pit, or onto a runout table for the horizontal process(Figure 2). In the vertical process casting stops when the bottom of the pit is reached. In the horizontal version, a flying saw cuts the ingot to length as it emerges and casting can be fully continuous. There is a version of the vertical process for copper which also has a flying saw, and the ingot is supported by pinch rollers. The casting speed depends on alloy and size, but is typically in the 1-3 mm/s range.

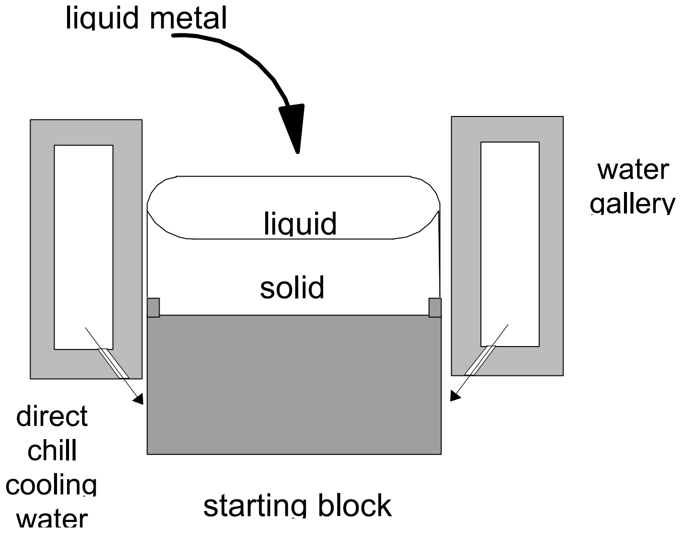


Figure 2: Schematic of cast start.

Alloyed and refined liquid metal is supplied to the caster. Distribution of the metal to the moulds depends on the technology employed. Distribution can be by separate launders to each mould with individual flow control or by a flooded table, where the moulds are mounted in a common water jacket and the metal flows through a refractory pan mounted on top.

A typical casting plant is shown in Figure 3. A furnace, or more often multiple furnaces, contain the liquid metal allowing it to be alloyed. The furnace tilts, or a drain or plug hole is opened, initiating a flow of metal along the launder. In-line treatment is usually employed to remove dissolved hydrogen, alkali metals and solid impurities prior to entering the casting station. Water cooling is supplied either directly from a river or lake or by a recirculating system with the moulds being fed from a header tank. Used casting water is pumped from the pit to an evaporative cooling tower and a holding tank.

The liquid pool depth depends on casting speed, alloy and size of the casting but is typically around 0.7 times the billet radius. The moulds are short and casting speeds low compared to steel continuous casting. A typical 200 mm diameter billet mould would have only a 30 mm long mould and a pool depth of 70 mm with a cast speed of 1.7 mm/s. Typical water flows are from 2,000-4,000 mm^3/s per mm of mould perimeter. Water slots or holes are used to spray the water onto the ingot at about 2 m/s.

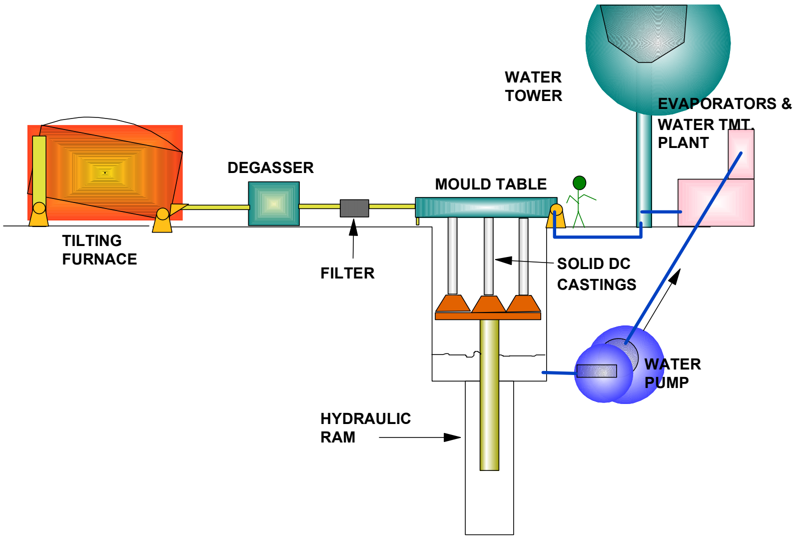


Figure 3: Basic layout of a typical vertical direct chill casting installation.

5. Process Behaviour

5.1 Heat Flow and Solidification

5.1.1 Importance of Heat Flow

The temperature distribution within the ingot is fundamentally important. It dictates the position of the solidification front, cooling rates, microstructure, final properties and stresses which determine final ingot shape and whether cracking occurs.

The casting process can be divided into two distinct phases: the run or steady state phase, and the start or transient phase.

5.1.2 Typical Thermal Conditions During Steady State

The surface temperature at the water impact point on the ingot is around 250-300 °C [20-23] and drops rapidly (Figure 4). Water spray heat transfer coefficients are high, in the order of 40,000 W/mK, due to nucleate boiling. This produces heat fluxes in the 5-6 MW/m^2 range. High heat flux values and the high thermal conductivity of aluminium ensures that the solid interface forms above the water quench point (Figure 5). Measurements of final water temperature show that 99% of the heat is transferred to the water. The water temperature typically rises 40-50 °C during casting, and although the water is boiling on the ingot surface, most of the steam bubbles collapse in the water film.

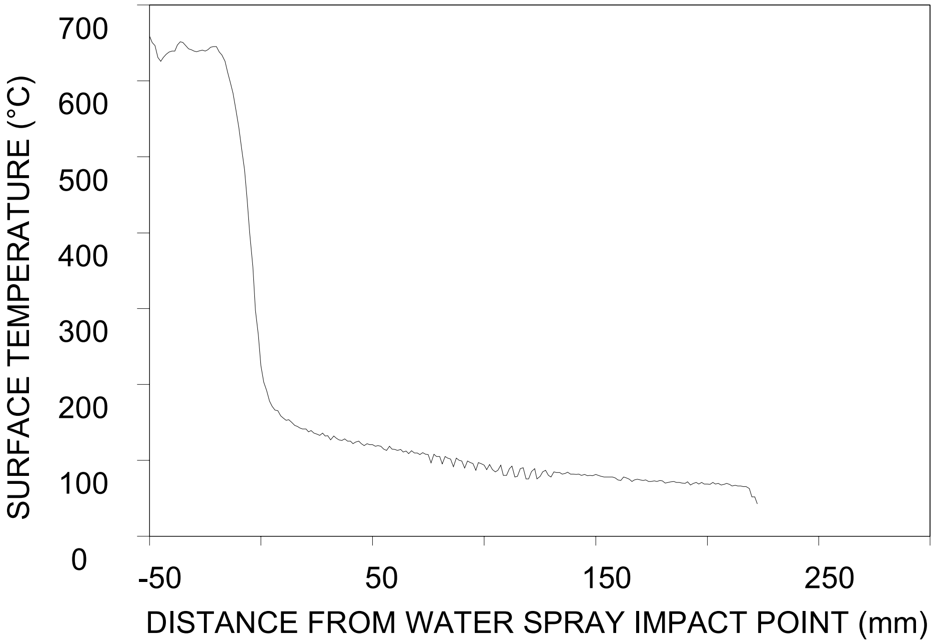


Figure 4: Typical surface temperature cooling curve.

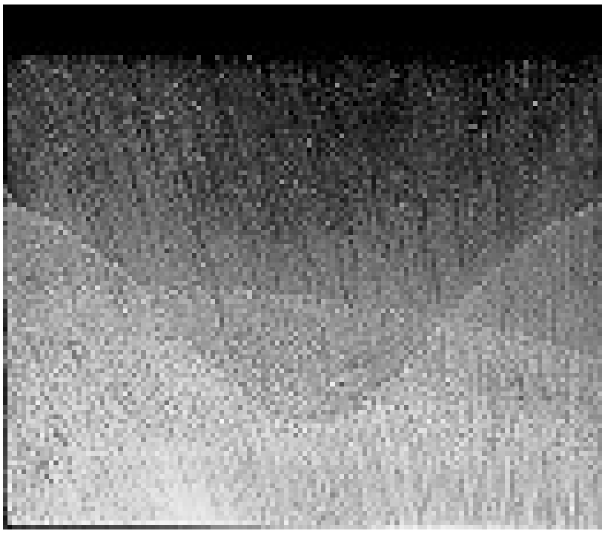


Figure 5: Shape of liquid pool in a 6063 alloy 155 mm diameter billet casting as shown by doping with liquid of different composition.

5.1.3 Understanding Heat Flow

The temperature distribution can be examined and understood using the thermodynamic principle of conservation of energy. Heat transport is mainly by convection and conduction (solid and liquid) with little radiation. Heat transfer is by convective boiling at the cast surface. The temperature distribution in the ingot is a function of factors determining heat input and output.

Heat input is a function of the energy content of the material and the casting rate. The energy content comprises the specific heat of the liquid C_{pl} (~5% of total), latent heat of solidification L (~35% of total) and specific heat of the solid C_{ps} (~60% of total). The solidification rate depends on the density ρ, casting speed V and ingot size R. Taking a specific example, a 200 mm billet cast at 2.5mm/s has a heat flow of around 160 kW.

The final position of the isotherms are determined by a balance between the convective heat input ρVRC_{pL}, and heat extraction by diffusion (determined by diffusion path length R and thermal conductivity k) and convection cooling (described by the heat transfer coefficient h). Two non-dimensional numbers characterise the balance:

Peclet number Pe $= \rho C_p VR/k$

= the ratio of convective to diffusive heat flow and,

Biot number Bi = hR/k

= the ratio of resistance to heat flow from conduction to convective cooling.

Typical values for aluminium DC casting are: $1.8<Pe<4.5$ and $2<Bi<60$. It can be seen that diffusion and convection are both strong in this process. In contrast, steel continuous casting has much higher V and lower k values giving large Peclet numbers, ie. the diffusive heat flow in the casting direction is very small compared to convection. The low Pe for aluminium explains why the solid forms upstream of the water quench point.

5.1.4 Effect of Casting Variables

The above analysis provides a context for examining the general effects of casting variables. For example if one increases casting speed, heat input increases. Increased temperature gradients result, leading to greater diffusive heat flow, which balances the increased heat input. Similarly, a consequence of larger ingot size is increased heat input and a longer diffusion path. In practice, casting speed is reduced as diameter increases and the Peclet number remains virtually unchanged. The casting temperature has a small effect on the heat flow as the specific heat of the liquid is only ~4-5% of the total heat input . Latent heat accounts for about 35% of the heat input and specific heat of the solid the remainder.

Since the specific and latent heats for the various aluminium alloys are very similar, variation in temperature distribution from alloy to alloy is due to changes in thermal conductivity. As alloy content increases, thermal conductivity decreases, the pool depth deepens and temperature gradients increase. Figure 6 shows the effect that alloy content has on room temperature thermal conductivity. Little published data exists for high temperatures. Alloy content also determines the liquidus and solidus temperatures, ie. the freezing range.

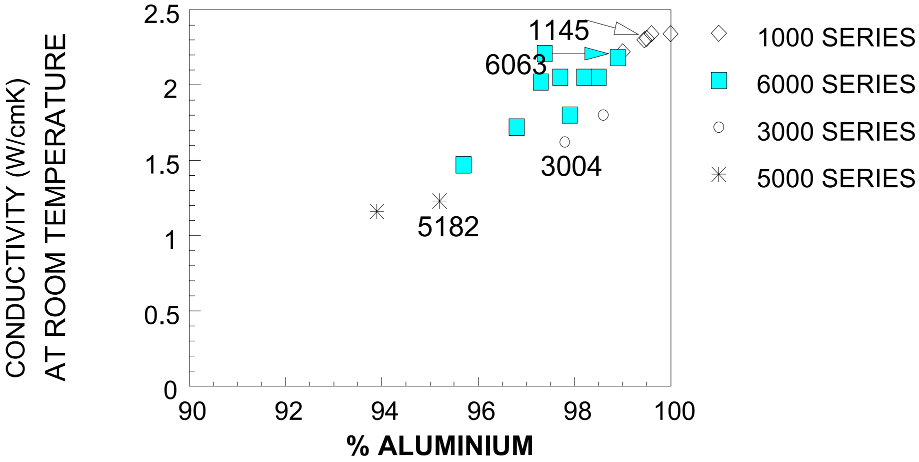


Figure 6: Effect of alloy content on room temperature thermal conductivity.

Examination of Biot numbers shows that due to the high heat transfer coefficient of the water spray, diffusion through the solid controls heat flow. Variation in water heat transfer under normal circumstances has little effect on the temperature distribution. Thermal conductivity and ingot size control the heat flow for a given casting speed. Water cooling will only have an effect if the heat transfer coefficient goes to a low value, ie. a low Biot number.

While the above scaling analysis explains the general effects of the casting variables, mathematical models allow detailed examination of the effect of changes in process variables. The advection diffusion heat flow equation and appropriate boundary conditions can be solved for temperature.

$$\rho VCp\frac{\partial T}{\partial y}=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+L\frac{\partial f_s}{\partial t} \qquad (1)$$

This equation arises from conservation of energy. The left hand side is convective heat flow, the first term on the right, the diffusive heat flow and the second term the latent heat generation (f_s being the fraction solid). Many numerical methods exist to solve this equation, along with the equations for stress analysis and fluid flow. A review of these is beyond the scope of this paper. These methods are well established and experimentally verified. Much of the process improvement in the last ten years is attributable to the use of these models.

As an example, Flood et al., [24] calculated a normalised temperature distribution from cast start, using a numerical model to solve the advection diffusion equation for the case of a cylindrical ingot over a range of Biot and Peclet numbers. An equation was fitted to the results for steady state normalised pool depth (pool depth divided by radius), giving a response surface for pool depth as a function of Bi and Pe. This surface is plotted in Figure 7, showing clearly that normalised pool depth is linear with Peclet for normal high Biot number conditions. This means that pool depth increases with the square of the diameter, linearly with cast speed, and is inversely proportional to alloy thermal conductivity.

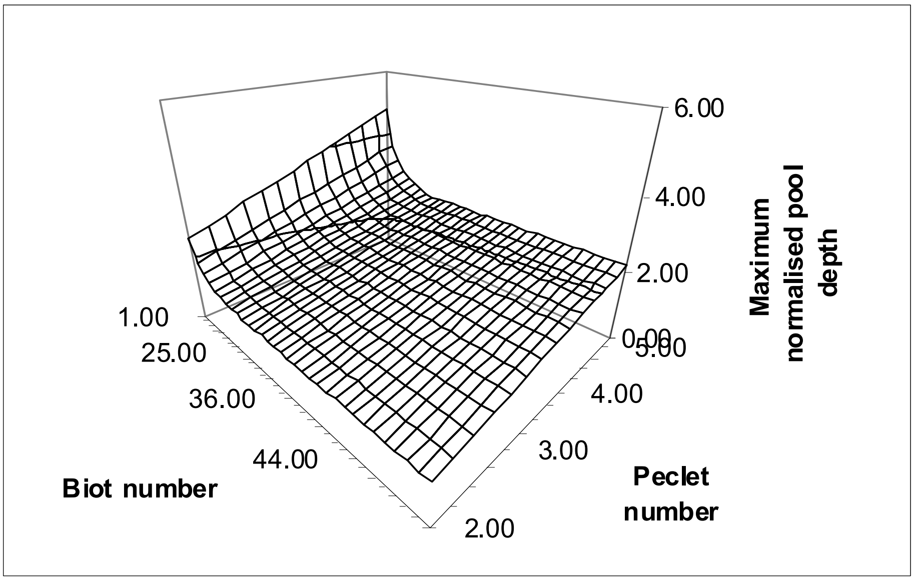


Figure 7: Normalised pool depth as a function of Peclet and Biot numbers (based on equations from [24]).

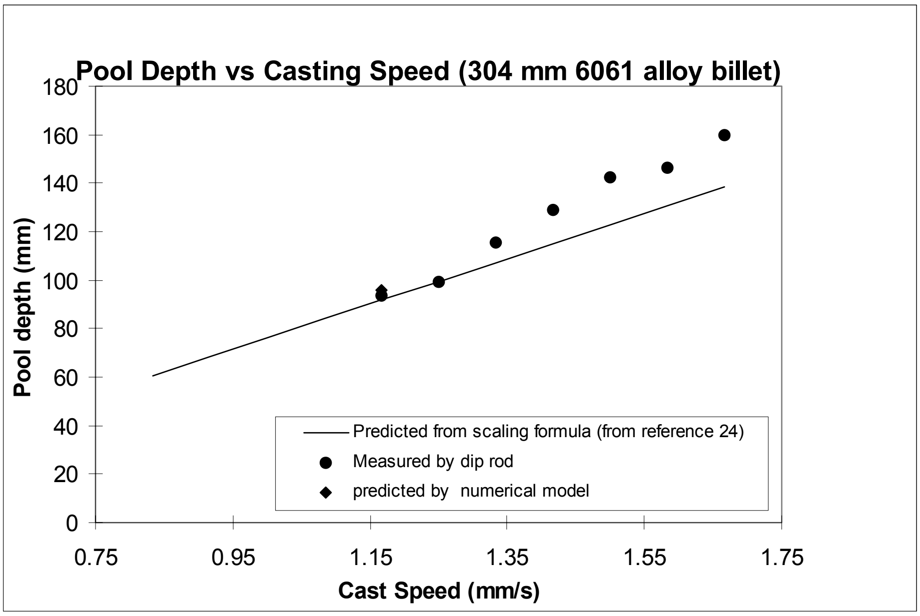


Figure 8: Pool depth as a function of casting speed, from measured values, full numerical model predictions and predictions from the fitted response surface of reference [24].

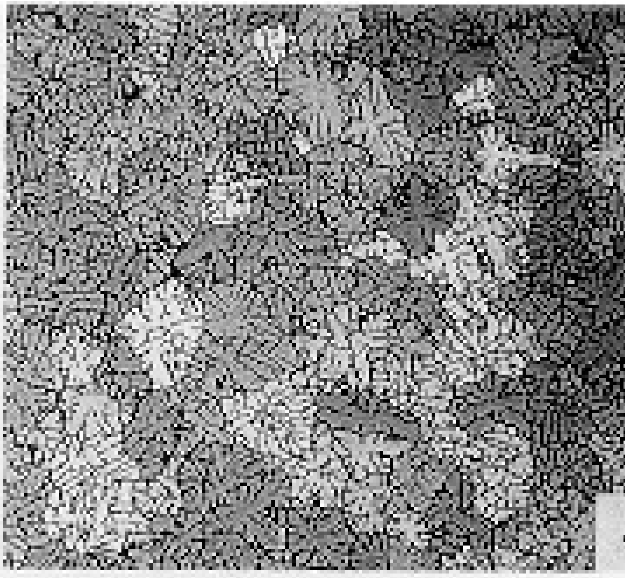
Hakonsen and Myhr [25] constructed process maps for round and rectangular ingots, showing the sensitivity of temperature distribution to Pe and Bi. The same behaviour was found: pool depth was a linear function of the Peclet number once Biot numbers were above twenty. They also examined the effect of cast speed and ingot size on dendrite arm spacing, finding that in the limiting case speed had no effect and ingot size alone would determine microstructure. This has been borne out in the experimental findings discussed below.

5.1.5 Solidification

Under the influence of the temperature distribution, solid forms where the liquid temperature goes below the liquidus for a given alloy. With aluminium DC casting, TiB_2 grain refiner is added to provide nucleation sites for the formation of solid alpha aluminium crystals, giving a very fine equiaxed structure (Figure 9). This structure displays dendritic features on the grains. If casting is performed without grain refiner, the classical grain structure of a columnar exterior and equiaxed centre results (Figure 10). The smaller equiaxed grain size prevents cracking at normal casting speeds. Cracking is discussed further below.

In addition to the level of grain refiner, cooling rate also determines the fineness of microstructural features such as dendrite arm spacing (DAS), grain size and intermetallic particle size. The cooling rate decreases from surface to centre as the diffusion path from the water spray increases. This gives rise to a variation in microstructure from the surface to the centre which is particularly apparent with larger castings. In many cases, this variation is not important, however for some AlFe alloys it causes a change in intermetallic particle phase producing a fir tree structure [26-28]. This in turn causes anodising streak defects. The volume fraction, shape and size of intermetallic will also vary due to cooling rate variation from edge to centre. Very little can be done about this variation as it is a function of the size and thermal diffusivity of the ingot. Large changes in casting practice, for example a 50% change in casting speed, were found to have no effect on intermetallic particle size or cast structure in alloy 5182 rolling ingot [29]. Composition was the controlling factor for microstructure. Apart from composition, ingot dimension and alloy thermal conductivity are the main parameters affecting cooling rate and refinement of microstructure.

Figure 9: Fine equiaxed structure of a grain refined DC casting.



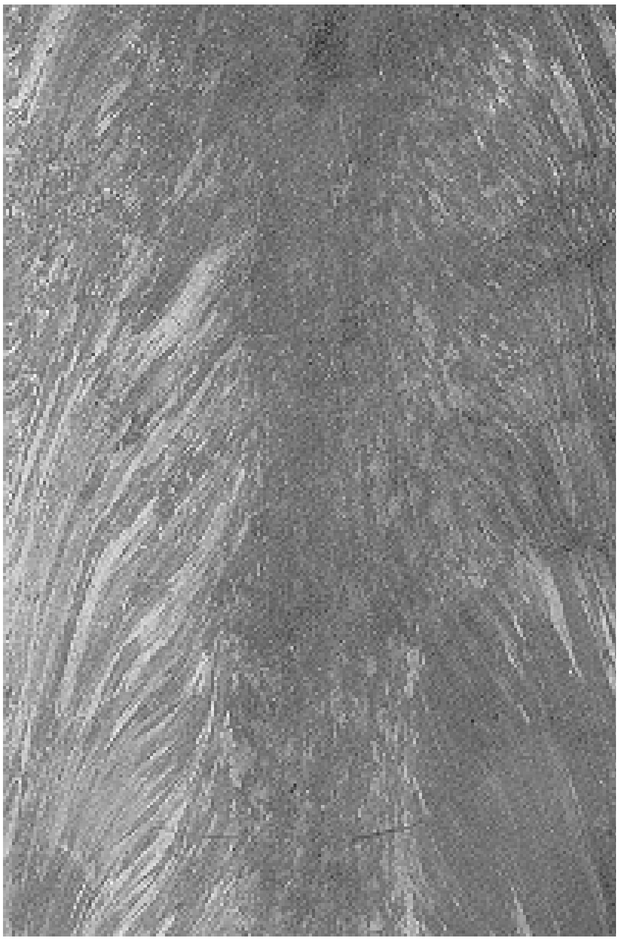


Figure 10: Grain structure of a non grain refined 178 mm diameter billet.

5.1.6 Water Cooling

During cast start the severity of quench affects the incidence of cracks, while during steady state, water spray heat transfer coefficients are normally well above the threshold where it controls heat flow. It is only when a problem arises that water spray heat transfer becomes significant. Therefore to control the process one needs to know what changes in heat transfer coefficient are significant and secondly what produces those changes.

The heat transfer coefficients for water cooling depend principally on ingot surface temperature, as shown in Figure 11. When the surface temperature is below ~100 °C, heat is extracted by convection. Above this temperature boiling occurs and heat extraction is by nucleate boiling. At higher surface temperatures a continuous layer of steam covers the hot surface, i.e. film boiling. In between nucleate and film boiling there is an unstable film boiling regime. Nucleate boiling has a high heat transfer coefficient while film boiling and convection have much lower values.

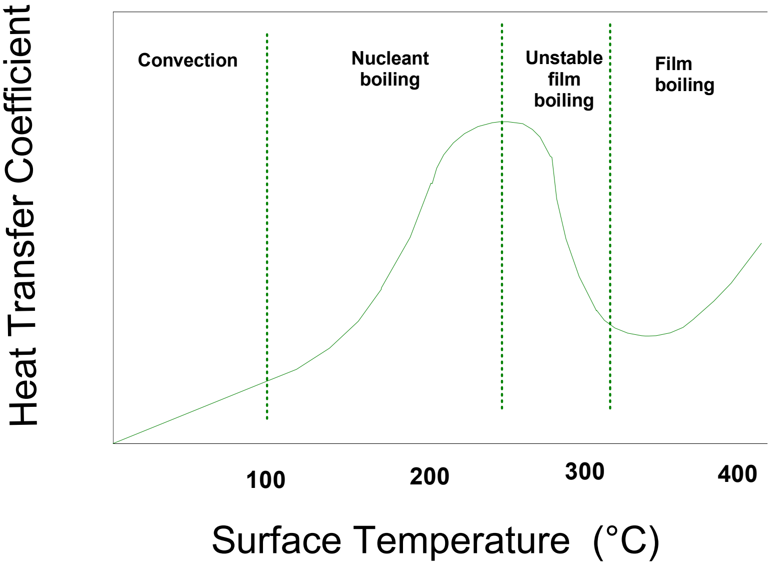


Figure 11: Heat transfer coefficient and boiling regimes for water cooling as a function of surface temperature.

In most situations the ingot surface temperature at the water quench point during steady state is below the critical temperature and only nucleate boiling occurs. However, changes in water temperature, impact velocity or chemistry can promote film boiling. Water chemistry changes due to casting lubricants, treatment chemicals and concentration of species due to evaporative cooling.

Weckman and Niessen [20] developed equations to predict the heat transfer coefficient as a function of flow rate and surface temperature in the convective and nucleate boiling regimes. These values produced a good fit between predicted and experimentally measured ingot temperature, indicating film boiling was not occurring. Measured heat transfer coefficients during casting gave peak values around 50 kW/m^2K [22,24,25] and heat fluxes of about 6 MW/m^2 [30]. If the impact velocity of the water jet is too low (<1 m/s), film boiling occurs [22]. Bramberger and Prinz also developed an equation for the heat transfer coefficient [31]. While their equation predicts values lower than those measured in DC casting of aluminium, they found increased water temperature decreased the heat transfer coefficient. Other measurements [32-35] have been made with various quench tests showing the effects of water composition, but they do not exactly duplicate the conditions during casting.

5.1.7 Mould Lubrication

Mould lubrication is used to separate the casting from the mould preventing sticking which causes drag marks on the cast surface. Successful selection and application of a lubricant will prevent contact, while an incorrect choice or poor practice will have the opposite effect. Lubricants range from grease, or static lube, applied at the start of the cast, through natural oils such as castor or rape seed oils, to synthetic oils with compositions specially developed to match the casting technology in use.

The oil also serves to reduce the amount of heat that flows through the mould wall. As has been outlined elsewhere the quality of the casting is inversely proportional to the amount of primary cooling, consequently having a uniform lubricant film between the casting and the mould wall will increase the gap and significantly reduce the heat flow. ~~In the casting environment the oil is used to separate the casting from the mould surface. The purpose is to prevent the casting dragging and sticking to the mould and, more importantly, to reduce the amount of heat that flows through the mould wall. As has been outlined elsewhere the quality of the casting is inversely proportional to the amount of primary cooling, consequently having a uniform lubricant film between the casting and the mould wall will increase the gap and significantly reduce the heat flow.~~ Oil properties that are important for this function are thermal stability and the variation of viscosity with temperature [27]. An oil that is excessively thin at higher temperatures will not produce a uniform film. Thermal stability relates to the propensity for the lubricant to burn or break down at the temperatures experienced during casting. On the casting side, temperatures are well above the flash point of the oils and the oil decomposes forming a gas of H_2, H_2O and hydrocarbons [26]. On the mould side, temperatures are lower and a liquid film is maintained. However, if the mould is not well cooled and the temperature is too high the oil film becomes thin and patchy.

Suitable pumping and flow control systems are required to get even distribution of lubricant to all moulds and around the mould perimeters. Viscosity at room temperature will affect pumping, piping and distribution to the moulds. The oxidation resistance of the lubricant will determine its shelf life. It is also important that the oil can be separated from the cooling water, to prevent environmental contamination and a detrimental effect on the cooling efficiency of the water. Lubricant can be supplied to the mould face through small ~100 micron channels or porous carbon.

5.2. Surface Microstructure Formation And Control

5.2.1 Surface Microstructure Formation

The surface microstructure of DC cast material is characterised by a segregation zone[2], coarse dendrite arm spacing (DAS), a large grain size and various other anomalies. These defects can lead to problems in subsequent processing, such as edge cracking during rolling, anodising streaks, and back end defects in extrusions. Control of surface microstructure and the minimisation of defects have been the driving forces for many technical developments in DC casting.

In conventional open top DC casting (Figure 12), where molten aluminium contacts the mould at the base of the meniscus, some solid and semi-solid material forms due to heat flow to the mould. The heat transfer coefficient for this contact point has been calculated from mould temperatures at around 1000 W/mK [36, 37]. Thermal contraction of the ingot causes the shell to pull away from the mould. This action causes a marked reduction in heat flow to the mould and even a reheating effect if it occurs above the area of influence of the water spray. A solid/liquid mushy zone may form at the surface due to the reheating, through which solute rich interdendritic liquid is forced by the pressure of liquid metal in the pool. This produces bumps or “blebs” of high solute

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[2] The surface segregation is often called inverse segregation. However, in this case the term is actually a misnomer. Most segregation is caused by rejection of solute in front of a progressing solidification front. So called inverse segregation occurs due to liquid feeding into the mushy material at the mould wall to take up the volume change due to the phase change. In the case of DC casting much greater bulk liquid displacement occurs due to the metal head pressure, and material actually oozes out of the semisolid surface.

concentration on the surface of the ingot. The smoothness of the surface is therefore an indicator of sub-surface microstructural quality. Additionally, the reduced cooling rate produces a coarser DAS and grain size (Figure 13). This mechanism has been well established by many workers [38-48]. Engler and co-workers [49-51] confirmed that metallostatic head was the main driving force for the flow of interdendritic fluid rather than the volume change on solidification.

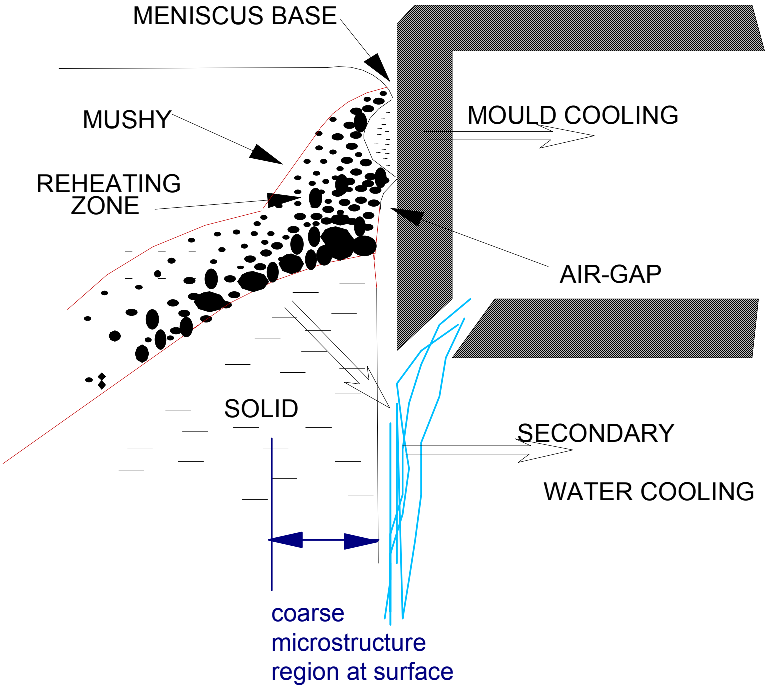


Figure 12: Surface formation during DC casting.

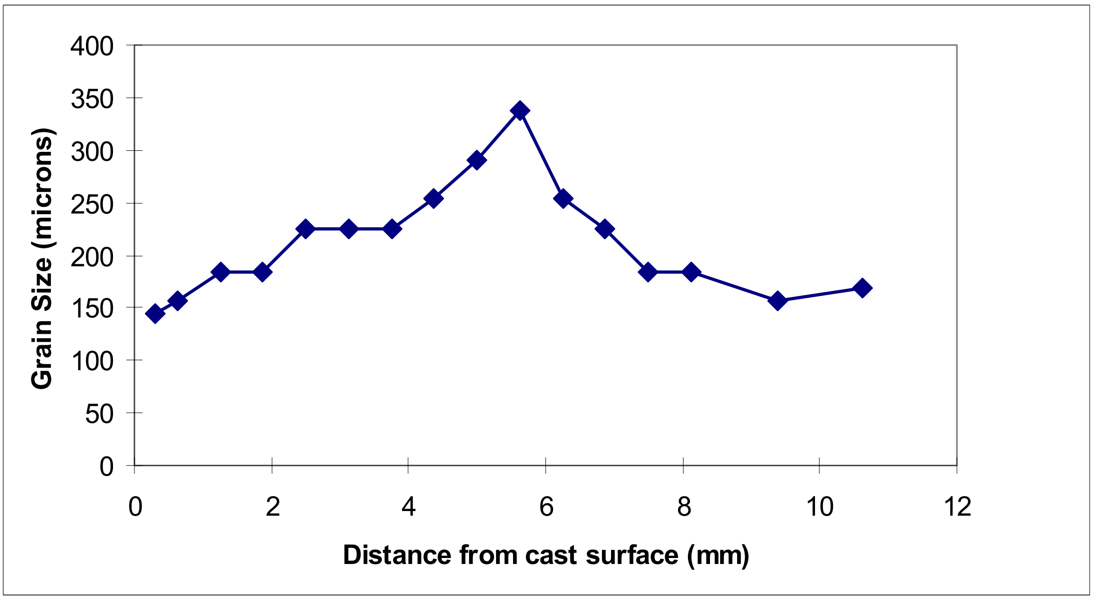


Figure 13: Measured grain size showing coarse microstructural zone in DC cast 3004 alloy.

To control the reheating effect, mould technologies have been devised over the years which reduce or eliminate mould cooling. These methods are discussed in more detail below.

5.2.2 Molten Metal Level Control

Controlling the liquid level is the simplest method of improving the near surface microstructure. There are several practical problems however, such as knowing the optimum level. If the level is too low, the meniscus freezes; and as casting continues it moves down the mould and new liquid laps over it forming a fold in the surface (Figure 14). One simple way to find the optimum level during casting is to reduce it until folding occurs and then to slightly increase it. To know the optimum metal level one needs to know how far into the mould the solid extends. Harrington and Groce [52] defined the length of solid in the mould as the upstream conduction distance (UCD). They presented a method of calculating the UCD based on the assumption that the heat flow at the surface, above the water spray, is all toward the water spray point. This is a good assumption as only a small amount of heat crosses the air gap to the mould. Their equation simplifies to:

$$UCD = \frac{Fk}{V}$$

where F is some factor dependant on density, specific heat, latent heat, liquidus and the surface temperature at the water spray quench point. $UCD = \frac{F}{kV}$ Obviously as cast speed increases and thermal conductivity decreases, the UCD decreases (Figure 15).

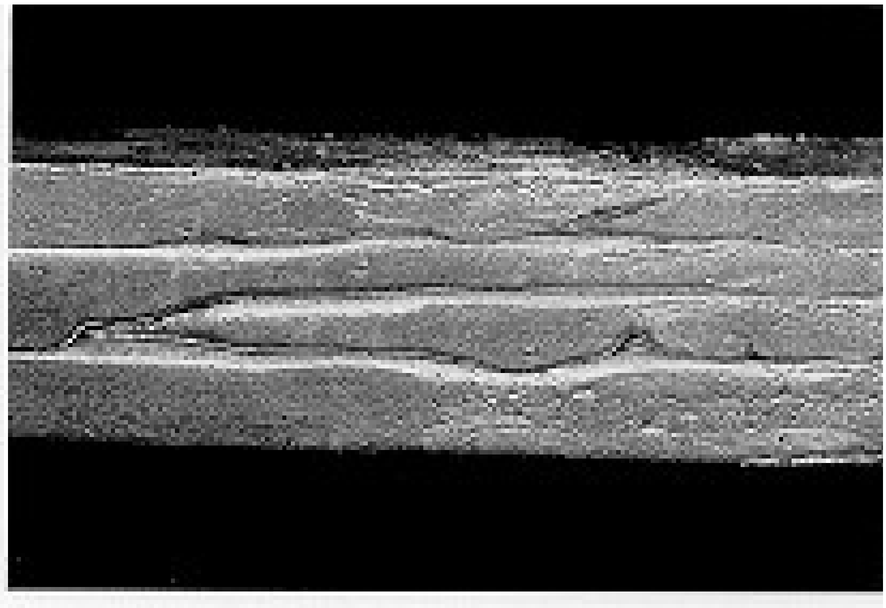


Figure 14: Cold folds formed on the surface of a DC casting (typical fold spacing ~8mm).

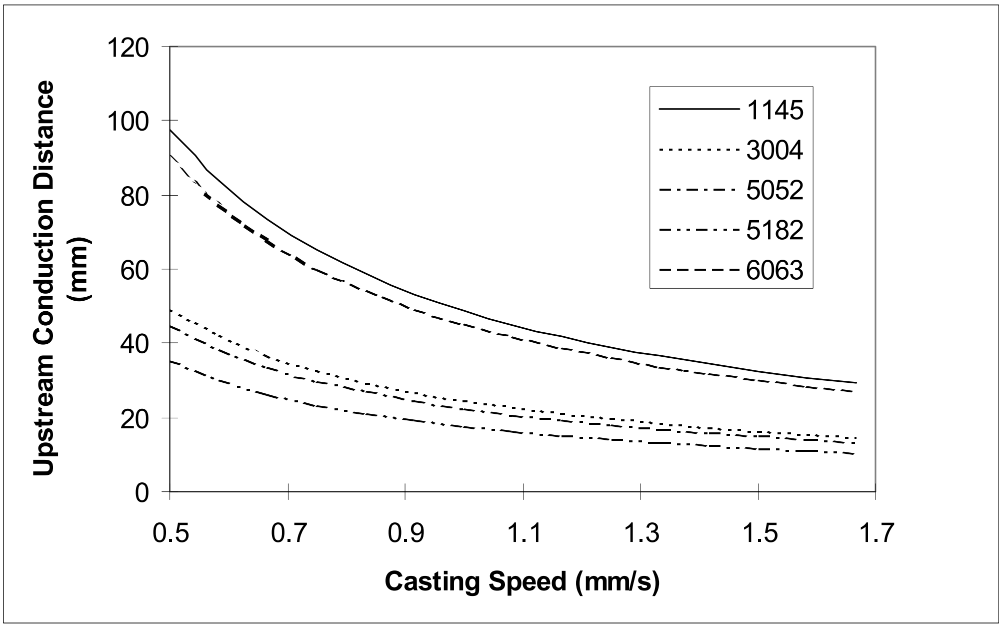


Figure 15: Upstream conduction distance as a function of alloy conductivity and cast speed.

The UCD can be calculated more accurately by more complex two dimensional numerical models solving the full heat flow equations. Grandfield and Devadas' modelling results showed how decreasing metal level reduced the reheated area [53], while Brochu and Hank measured the reduction in mould chill zone with lower metal levels [54], which matched the full solute and heat flow modelling work of Mo and others [55, 56].

The inverse relationship between cast speed and UCD or mould length has been found in a number of instances. Weckman and co-workers modelled horizontal continuous casting for various non-ferrous metals and showed that the optimum mould length could be calculated as a function of Peclet number [57,58]. Vorren and Brusethaug calculated UCD as a function of alloy and diameter using a two dimensional heat flow model, finding that, only at diameters less than 150 mm, was there any change in UCD with diameter [59]. One of the difficulties of casting rectangular sections over rounds is that the corners introduce regions with very small radii and the UCD is much higher there. In practice the mould design is modified so that the water quench point is lower on the corners, or even eliminated.

With float and spout technology, low metal levels are not used because of a perceived danger from bleedouts and freezing the spout in at cast start. The Isocast system was intended to solve this by moving the whole mould table up during the cast, bringing the metal level down. However, now available automatic level control systems give very accurate control within a millimetre and allow the level to be adjusted during the cast [60].

5.2.3 Hot-Top Casting

Insulation placed at the top of the mould was introduced to control the location of the initial contact point of the liquid against the mould [61] (Figure 16). In this way, the liquid metal contact point was fixed at a point below the insulation and was independent of the metal level used. This point should coincide with the UCD minimising reheating and improving surface quality. Modern hot top moulds are similar in principle, with a refractory header inserted into the top of the mould (Figure 17).

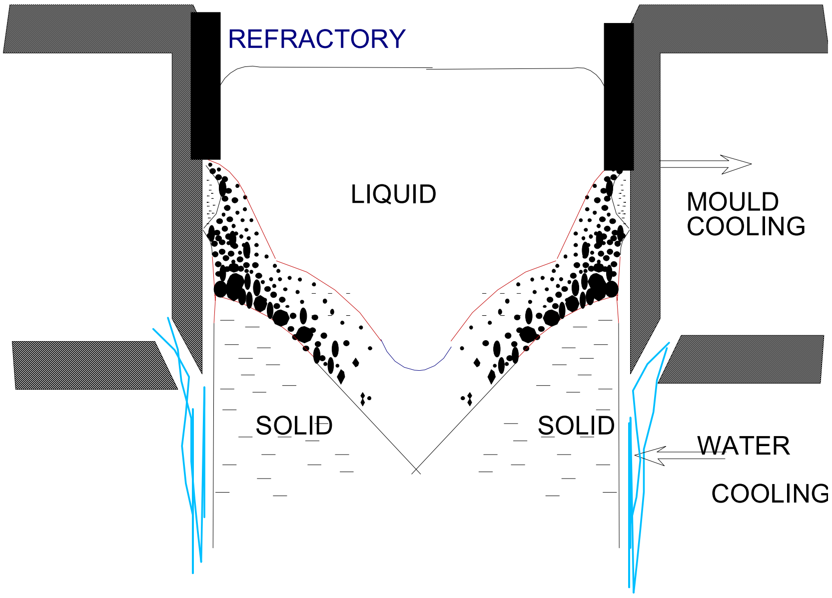


Figure 16: Simple hot top mould formed by addition of thin insulating paper to an open top mould.

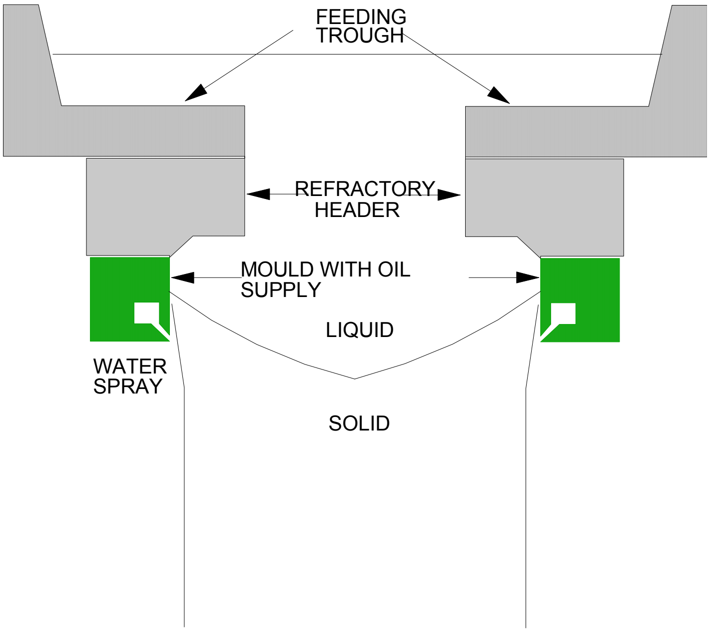


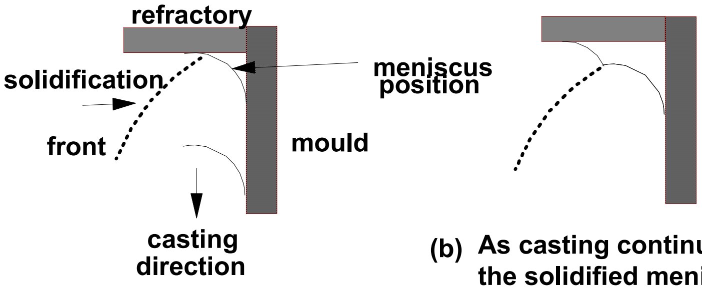
Figure 17: More sophisticated hot top mould.

The change to hot-top moulds was a significant change in technology because:

1. The flooded table was developed to replace the launder/float arrangement.
2. Level pour from the furnace could be used when tilting furnaces were employed, where the level above the mould matched the level in the furnace, reducing melt turbulence and dross generation.
3. Increases in packing density: the number of moulds in a given table area doubled, increasing the tonnage of each cast and total throughput.
4. Manning levels were halved.

Hot-top casting can suffer from cold folding if the mould length is too short for a given casting speed and alloy, causing the water cooling effect to extend up to the refractory. However, folding is usually due to heat flow from the mould causing freezing of the meniscus immediately below the refractory (Figure 18). Bergman established the mechanism for these folds [62]. The meniscus freezes, it is pulled down, solidification proceeds inward and then upward until the path is too long and liquid breaks through to fill the gap and the cycle repeats. Weckman and co-workers modelled this defect and were able to calculate the value of the mould heat transfer coefficient from the angle the fold made and the casting speed [37,63]. Formation of folds is controlled by the mould heat transfer, the casting speed and the geometry of the refractory overhang. Higher mould heat transfer and slower casting speeds increase the spacing and depth of folds. As metal head pressure increases so too does the mould heat transfer, and this is why horizontal DC casting tends to be more prone to cold folding as the metal heads are usually about 400 - 500 mm compared to 100-200 mm for vertical DC casting. Lubrication also plays a role in affecting the mould heat transfer and cold fold formation. If the refractory overhang is shorter then the liquid metal floods back into the corner sooner.

Another method for controlling cold folds is to cast at a speed such that the UCD extends to the base of the meniscus. In this way the shell pulls away from the mould and there is no mould contact. Alcan developed a mould design based on this principle [64]. The difficulty with this approach is that if the UCD extends only slightly further, it freezes metal up to the refractory and may even pull the refractory out of the mould.



(a) Solidification front position in relation to meniscus position.

(b) As casting continues the solidified meniscus descends, allowing liquid metal to fill the void.

(c) The fresh liquid freezes against the mould, forming a new meniscus and corresponding void.

(d) The cycle is repeated as casting continues.

Figure 18: Schematic of the mechanism of cold folding in a hot top mould.

5.2.4 Air Assisted Hot-Top

In 1977, Showa Aluminium Limited (SAL) found that better control of the meniscus contact point could be obtained by injecting air just below the refractory [65-70] (Figure 19). The Showa process produced billet with a very smooth cast surface and low mould chill zone depth compared with conventional float cast and hot-top technology. In effect gas pressurisation makes the mould self controlling. Gas pressure rises in the meniscus region until it finds an escape route. As pressure rises, the meniscus is pushed away from and down the mould. Eventually the meniscus base reaches the UCD where the shell is contracting from the mould allowing the air to escape. The pressure in the meniscus region then equilibrates against the metal head pressure. This technique significantly reduces heat flux through the mould wall. For example, measurements showed a reduction of heat flux from 1270 kW/m^2 to 420 kW/m^2 [71] on a 155 mm mould. Mould temperatures reduce from around 100-150 °C to 30-40 °C (Figure 20).

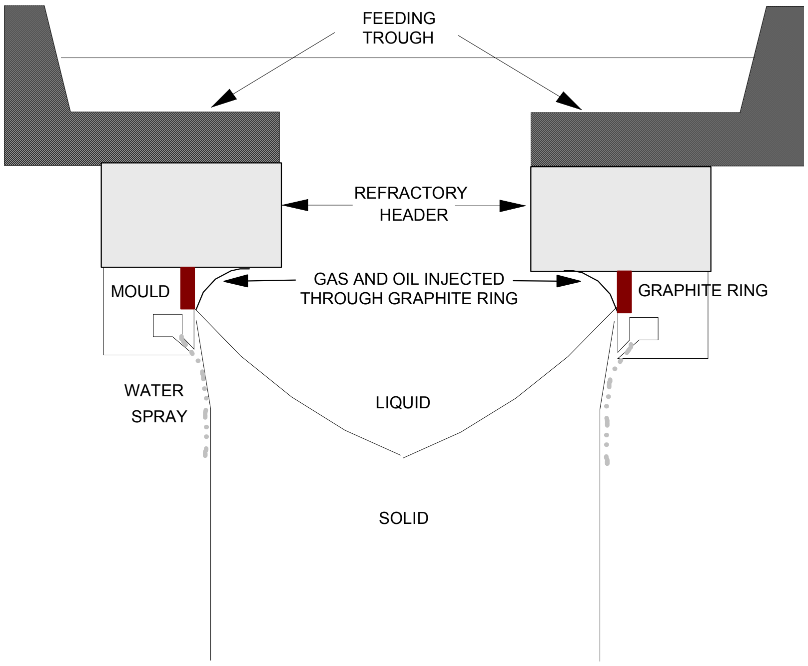


Figure 19: Gas pressurised hot top process.

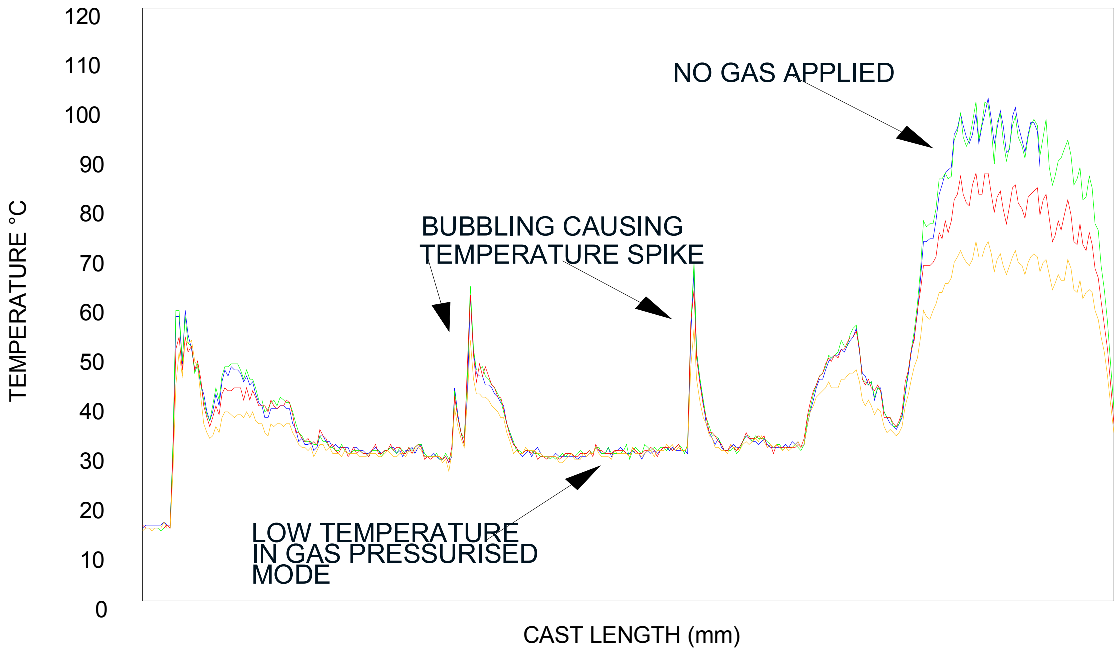


Figure 20: Effect of gas pressurisation on mould temperatures.

By 1986, licences for the SAL technology had been sold to many companies. Since that time many companies have developed their own in-house hot-top technologies, eg. VAW [72], MOSAL (now Elkem Aluminium), Hydro Aluminium, Alusuisse [73], and Pechiney [74]. Approximately fifty SAL casting stations have been installed, mostly in Japan. In 1980 Wagstaff began development of a gas-pressurised mould where the gas was injected through a graphite ring, and was granted an Australian patent in 1983 [75-77]. Since then they have become the dominant supplier of air-assisted billet moulds.

Papers presented to The Extrusion Technology Conference in 1988 showed air-pressurised billet casting was widespread [78]. Extruders were asking for smooth surfaced air-pressurised billet, even though it was widely accepted that factors such as homogenisation and composition control were more important than sub-surface microstructure or surface appearance.

Air-pressurised billet casting does have a number of drawbacks, but they are considered minor in relation to the benefits obtained from the technology:

1. The Showa system in its original form is labour-intensive and sensitive to operator interaction. The manual control of air flow can cause difficulties. The VAW version of the process has individual automated mould pressure control.
2. Showa moulds were designed for sliding tables, not the newer (generally preferred) tilting tables.
3. The porous graphite ring is an expensive consumable, its permeability changing with age, causing variation in gas flow and deterioration in billet quality.
4. Wagstaff moulds require individual attention between each cast.
5. All air-assisted casting technologies are more complicated than conventional casting systems and are reliant on an informed, well-trained and motivated work force.
6. A commitment to specialist mould maintenance is required.

5.2.5 Air-Assisted Sheet Ingot Casting

Showa Aluminium Limited, SKY Aluminium[79], Comalco Aluminium Limited and Wagstaff [80] investigated the possibility of air-assisted sheet ingot casting in the late 80’s and early 90’s. The principle being identical to air-assisted billet casting. Although much pilot plant trials have been conducted, little commercial implementation has occurred to date. One problem was that a fixed, short mould length meant that no deformation of the butt could be tolerated or the butt would deform and lift into the refractory. This problem was solved with the development of the Turbo Curl Reduction Technology [81], as discussed below. At Comalco Research Centre, studies showed very high quality surface microstructures, equivalent to air pressurised technology, can be obtained with open top casting using automatic metal level control without the complication of air pressure control. Wagstaff have also taken this route with a modification using a carbon mould liner and automatic level control [82].

5.2.6 Electromagnetic Casting (EMC)

The electromagnetic casting mould uses an inductor coil through which a high frequency (typically a few kHz) current is passed. The currents induced in the liquid metal interact with the magnetic field of the coil. This produces a restraining force on the liquid which acts against the metallostatic head pushing the metal away from the mould. Lack of contact between liquid and mould eliminates mould cooling and the problem of reheating, producing very good surface microstructures.

Getselev and Cherepok at Samara Metallurgical Works in the Soviet Union first developed EMC casting in the 1960s. They were granted a US patent in 1969 [83]. The history was reviewed by Yoshida [84]. Kaiser [85, 86] and Alusuisse [87-89] developed the process further. EMC promised to reduce or eliminate scalping losses as the mould chill zone depths were small. However, reduced scalp depths necessitate flat rolling faces, which, in turn, necessitated development of metal level control. It is the balance between metal level and the magnetic field that controls shape and position of the free surface and final dimensions of the block.

Another problem which had to be solved was the start-up of EM casting, which presented additional difficulties compared to normal DC casting[87]. Over the last 10 years automated systems have been developed and extensive mathematical modelling carried out to solve these problems [90,91].

Emley said "a new Russian development termed electromagnetic or 'mouldless' casting holds promise of benefits scarcely imaginable with any other form of DC casting" [1]. Sixteen years later, while EMC is used (at least 2 million tonnes are cast per year world-wide), it has not been universally accepted. Certainly, better microstructures result and reduced scalp depths are taken, but little sheet is produced without scalping. High capital and licensing costs do not outweigh the improved recoveries. Some EMC installations are now being decommissioned because of the royalty costs, and there are unlikely to be any more built. Development of EMC led to improvements in conventional DC casting. For example, control of metal level and development of automation systems were originally driven by EM casting.

A variant of EMC, the Pechiney CREM process, uses low frequency 50 Hz current to induce a high degree of stirring in the melt [92-97]. This stirring gives rise to dendrite fragmentation and grain refinement. In this way, use of costly TiB_2 grain refiner can be eliminated. The process also gives rise to good cast surface microstructure by controlling the meniscus contact point on the mould. Consequently, reduced scalp depths and edge trim are taken [90].

5.3 Stress, Cracking And Shape

Thermal contraction occurs on cooling. Because of the different thermal history of various parts of the casting they contract at different times and at different rates. This differential in contraction produces stresses, as one part restrains another. The level of these s~~Stress in an inherent aspect of the DC casting process. Inability to acknowledge and control the stresses produced during casting will inevitably lead to scrap and hazardous situations.It is the s~~tresses ~~that help~~ defines the final shape of the casting and determines whether a crack free product is made.

~~Once one area has solidified and contracted it resists further contraction. Consequently when adjacent areas solidify and attempt to shrink stress is usually produced. Similarly the shrinkage of the solid will not be uniform but will be determined by the thermal gradients present. It is this difference that gives rise to the variation in shape of the roll face of cast rolling ingots.~~

With circular sections, (Figure 21)~~In the mould,~~ , metal first solidifies as a ring or annulus of solid ~~forms~~. It is cooled by the water spray and thermal contraction takes place. As casting continues the metal in the centre will freeze and its natural tendency would be to shrink. However, at this stage the surface material is almost at the water temperature and has no tendency to contract. ~~As the cast continues heat is removed from the centre of the billet, when sufficient heat has been removed solidification will take place, with its attendant shrinkage. Now, depending on the casting condition prevailing, stress will be established across the cast section. This follows from the constraint imposed on the central section by the outer area that has already solidified and contracted.~~ Therefore the central section, as it cools, is placed under tension by the restraint from the outer material and the outer material is placed under compression by the internal material. ~~shrinks produces a compressive stress in the outer region and a tensile stress in the centre.~~ If the stresses generated exceed the strength of the material a crack will form. Examination of crack surfaces shows that some liquid is present when cracking occurs. These are hot cracks which occur at the last stage of solidification. Measurements by Bryson during casting, with an ultrasonic crack detector, confirmed that cracks formed at the base of the liquid pool during the final stage of solidification [98].

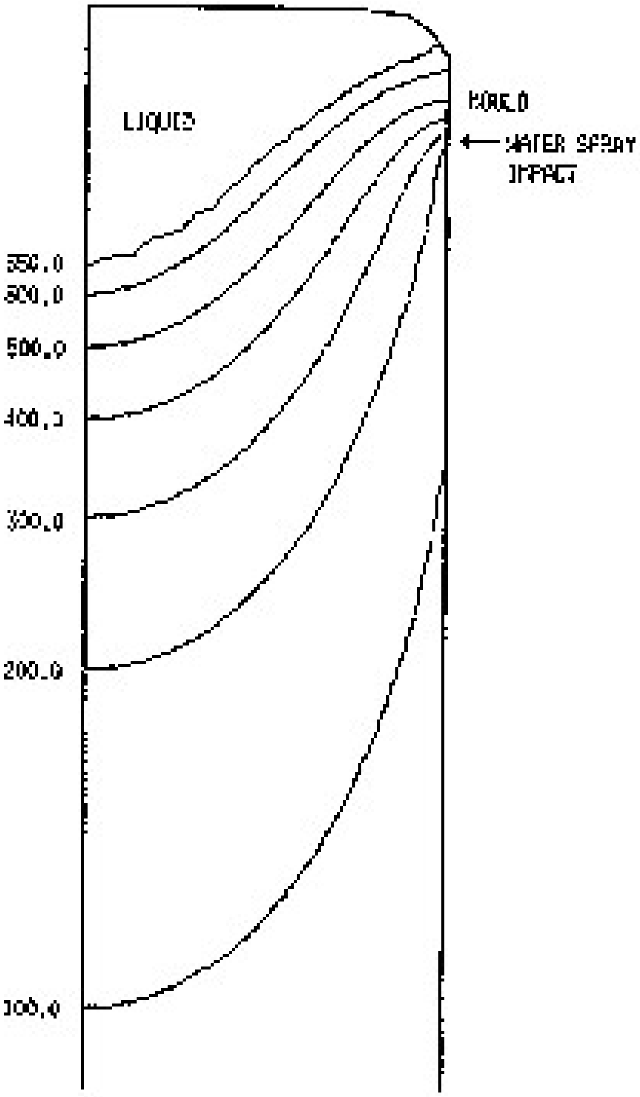


Figure 21: Predicted temperature distribution during steady state casting of a 152 mm diameter 6063 alloy billet cast at 2.5 mm/s.

For a given alloy type and diameter there is a casting speed above which internal hot cracks occur. Interestingly, this maximum casting speed is found to be inversely proportional to diameter [99]. This is understandable in a general sense. As the speed increases, the temperature gradient increases and so do the temperature gradient differences between surface and centre. This limit on casting speed can limit the productivity of a casting installation.

Much work has been done on defining cracking criteria and hot tearing mechanisms [100-103]. Bryson, having regard to the basic argument above, proposed a very simple criterion; the difference between the surface and centre cooling rates. Bryson also proposed a method of reducing the stresses. The initial water quench is made less severe so the surface stays hotter and, at the point corresponding to the base of the liquid pool, a second quench is applied so that the surface and centre cool and contract together. Nawata et al., [104] found they could increase the casting speed of a 6063 alloy 178 mm diameter billet from 1.5 mm/s to 10 mm/s without cracking using this delayed quench system. Considerable stress modelling has been applied to the problem [103, 105-117]. Modelling by Fjaer, et al. [103], for example, predicted that the strain rates in the mushy region during casting with a delayed quench were reduced over that of a normal quench. They proposed the ratio of strain rate to cooling rate in the mushy region as a cracking criterion.

~~Conditions that encourage crack formation are higher casting speed, highly alloyed metal and poor grain refining practice. The first two increase the depth of the liquid sump making feeding more difficult, while the third will reduce the strength of the solid as well as affecting feeding.~~

Another parameter affecting the incidence of hot tearing is alloy microstructure. If the grain size is small, cracking is far less likely. Ohm and Engler found that addition of grain refiner increased the maximum strain tolerable to mushy material before fracture [49]. Additionally, cracks can form at the start of the cast. Jensen and Schneider examined the formation of internal cracks at the start of billet casting [118-119]. They found that as the liquid pool develops, it goes through a maximum depth before it reduces to the steady state value. As the stress imposed on the solid increases with pool depth, the stress similarly went through a maximum. For many years the practice has been to start a cast at a slower speed and increase to run speed, preventing sump overshoot. Jensen and Schneider invented another method: the centrally raised dummy block. By having the centre higher, the pool does not overshoot and internal cracks are eliminated.

To roll ingots, the rolling face must be flat. Variation in contraction along the roll face varies and must be accounted for in mould design as the deviation from flatness must be scalped off. Contraction is greatest in the centre of the face. The main casting parameters that affect shape are casting speed and alloy, as they are the factors that most influence the thermal gradient through the casting. A typical profile of a commercially produced rolling block is given in Figure 22.

The factors that affect roll face shape are generally well known, but historically mould profiles have been developed empirically [120]. This is achieved by using the errors in current block shape as input to the design of the next set of moulds. Such a system works well for castings made under the same conditions, but does not work for different casting speeds or alloys. The other disadvantage is that it takes one life cycle of the mould to correct the shape. A number of shape models have been developed to predict the shape of the roll face when the conditions change or new mould sizes are required [120]. Further, the ability of machine tools to produce the desired contour has improved so that now moulds can be produced that cast very flat rolling block.

Currently, the only reason that some rolling block is not flat is that a compromise has been made on the number of moulds that are purchased. When different alloys are produced in one plant, normally only one set of moulds is used for each size. Consequently, one mould set up to produce flat 3004 rolling block, for example, will not produce flat 5182. While some compensation can be made by changing casting speed, the resultant shape is not perfectly flat.

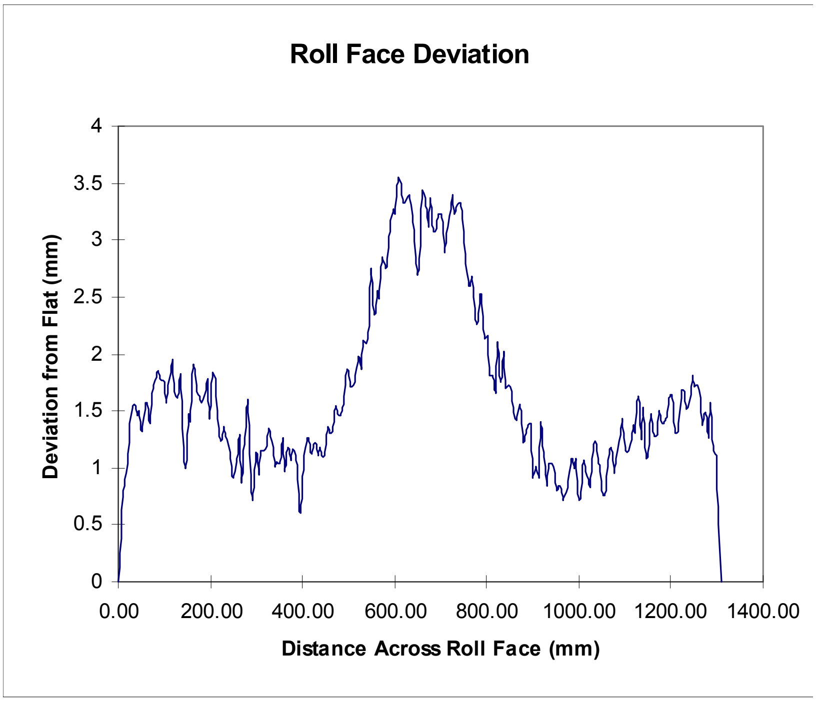


Figure 22: Typical rolling face profile.

5.4 Cast Start

Because of the semicontinuous nature of VDC casting, cast starts are important. The transient nature of the heat flow dictates that the stresses generated and resultant deformation is quite different to that occurring during steady state. When the starting head and mould are filled at the start, a permanent mould casting is made with heat flow predominantly into the water cooled dummy. After a delay, the platen commences its descent, with the casting parameters changing with time to accommodate the change from stationary casting to the run condition. Cast speed, water flow and liquid level are all altered in an attempt to minimise the effect of the heat flow changes. This transition lasts for about one diameter or one thickness.

The phenomena associated with cast starts are:

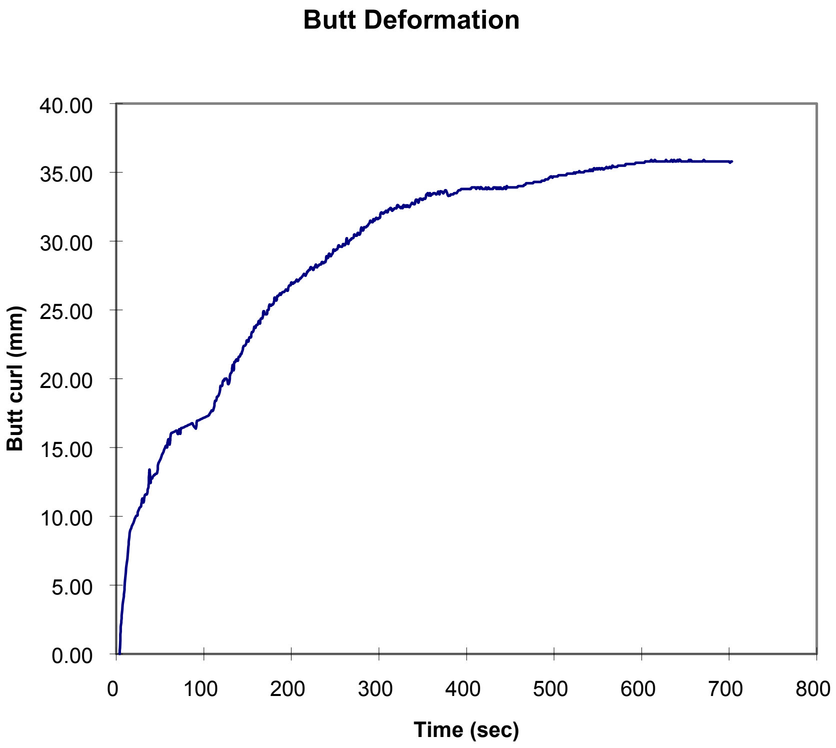
1. Butt curl: where the first part of the casting lifts off the dummy block.
2. Hang ups: where the deformation of the butt is such that the ends wedge in the mould.
3. Cracking: the stresses generated can exceed the strength of the material.
4. Bleed outs: as the butt deforms it can move away from the mould and the cooling water, producing an unsupported and uncooled shell. The superheat of the liquid pool and the metallostatic pressure are sufficient to force the liquid through the shell. Similarly the deformation can move the shell away from the mould producing a gap which can allow the metal to escape.
5. Surface defects: with the changing conditions experienced at the start it is often difficult to obtain the correct balance to avoid surface defects such as cold folding, oxide patches or, for air assisted moulds, a generally poor surface due to the incorrect position of the meniscus.
6. Swell: the cross section of the first part of the casting is greater (~7%) than the steady state section. This is a big problem for rolling block where the thickness

dimension may be greater than specification for a large part of the cast length. The excess material must be removed

These phenomena are generally worse with larger sections and higher alloy content. Measurements by Droste and Schneider showed the butt deforms when it first emerges into the water spray [121]. The deformation rate is greatest at this stage (Figure 23). There is still considerable debate about the mechanisms of butt curl, but the basics are that the water quench rapidly cools the exterior of the casting while the interior is cooled slowly, causing different contraction rates. The solution is then obvious; reduce the intensity of the water cooling. This is achieved by promoting film boiling. Reducing the water flow will promote film boiling and is probably the easiest and most effective method of controlling cast starts. There is often a conceptual problem to overcome when this approach is suggested. More water is often associated with safer casting. With cast starts the reverse is often true. Similarly increasing speed to the run speed or even faster at cast start, will raise ingot surface temperature and promote film boiling.

Figure 23: Deformation of the butt at cast start for 610 x 1300 mm ingot.

One problem that arises with reduced water flow is that the water curtain can break. A discontinuous curtain leads to uneven cooling, causing cracking and bleed outs. A solution to this dilemma is to use moulds that have water holes instead of water slots. The advantage is that, providing the hole size is correct, the water chamber remains pressurised thereby maintaining a good distribution even when the flow rate is reduced.



Three other methods that have been developed to promote film boiling. The Alcoa CO_2 process [122], and the Wagstaff Turbo process [82] use gases to promote film boiling. The Alcoa process dissolves CO_2 into the water stream, which remains dissolved in the pressurised water system and mould gallery. When water exits the mould the CO_2 comes out of solution forming gas bubbles which act in a similar way to steam bubbles and form an insulating layer over the cast surface. In the Wagstaff process air bubbles are introduced into the cooling water on exit from the mould. Air is insoluble in water and so the bubbles stay entrained assisting the formation of the steam layer. The Alcan Pulsed Water process uses a special rotary valve to turn the water on and off [123]. In this way the average heat transfer rate is low and the surface temperature stays high enough to cause film boiling.

A number of methods have been developed to control the water quench contact point. The first is Wagstaff's Dual Jet concept [124] while others use an air film or baffle to move the water film up and down the casting's surface [125]. As the name implies two water jets are used in the Wagstaff system. The contact point and angle are different for each. The lower impacting jet is used at cast start to increase the mould length and reduce quench severity. At a certain point in the cast, water is supplied by the second jet, moving the mould length back to its conventional position. An added advantage is that the interaction of the two jets on the cast surface produces an even greater cooling effect than single jet systems. In the other system an air jet is introduced above the water curtain at cast start. The air pushes the water contact point down the casting, increasing the effective mould length. As the cast proceeds, the amount of air is reduced and the contact point moves up the casting.

5.5 Liquid Flow

Liquid flow affects the temperatures within the liquid pool, and therefore cooling rate and microstructure. It can also affect compositional variation within the casting.

Measurement of liquid metal flow is very difficult. Vives developed a magnetic probe to verify model predictions [96]. However, to investigate flow conditions and their effects, much mathematical modelling has been done [90,91,107,126-128].

Liquid metal flow is determined by three drivers:

1. The direction and velocity of the initial inlet to the liquid pool,
2. Natural convection in the pool, and
3. The shape of the liquid pool.

If a float and spout is used in vertical billet casting , jets of hot liquid exit the float horizontally. Natural convection arises due to cooling of the liquid at the solidification front. This colder liquid is denser than the hotter central liquid, flowing down the solidification front toward the centre. These two driving forces set up a recirculation of the fluid. In the case of horizontal DC casting, because gravity acts across the casting direction, the natural convection flows are asymmetric. This can contribute to microstructural variation from top to bottom across the cast product.

The flow is even simpler for the hot top case, with a fairly even flow coming down the throat of the hot top. Studies have shown that the size of the inlet to the hot top can effect the temperature distribution in the liquid pool [129]. If the inlet is narrow there is some asymmetry created in the temperatures in the liquid pool. The liquid distribution issue is more important with rolling ingot where the rectangular section requires use of special distribution systems. Fluid needs to be directed to the short faces as it has further to travel. The temperature around the perimeter changes with the feeding system. Brochu et al., using experiments and numerical simulation showed that metal temperature can affect the size of the mould chill zone and that certain feeding systems were better than others [130]. Raffourt et al., have also modelled the flow for different feeding systems although they did not take into account the true shape of the liquid pool [127].

5.6 Macrosegregation

In larger DC castings, significant compositional variation is found. Elements that form eutectics with aluminium rise in concentration away from the edge of the casting, with the centre being depleted. Elements that form peritectics with aluminium show a reverse trend (Figure 24). This composition difference is likely to give rise to a variation in properties across the sheet width when rolled. Interestingly, the authors know of no study which has actually linked final sheet property variation to macrosegregation.

The central microstructure of the casting shows a duplex structure with a mixture of large and small grains and DAS [131,132]. The general mechanism for macrosegregation in castings is movement of solid (generally purer than the liquid) or liquid (generally solute rich) formed during solidification. The duplex structure suggests crystals have been transported to the centre. The modelling of Flood and Davidson showed that the natural convection driven flow is very important in its effect on macrosegregation [126]. The strong flow down the solidification front is proposed to transport crystals to the centre and additionally that flow gives rise to a nearly isothermal central liquid pool which is conducive to growth of large crystals. As ingot size increases macrosegregation becomes stronger [126]. Garepy and Caron studied the effect of various feeding methods and grain refiner additions on macrosegregation [133]. They found that liquid flow, which worked against the natural convection, and reduced amounts of grain refiner, reduced macrosegregation. Mortensen and Harkonsen's modelling showed natural convection and turbulence must be included for prediction of DAS and liquid temperatures, and also found a course centre zone [128].

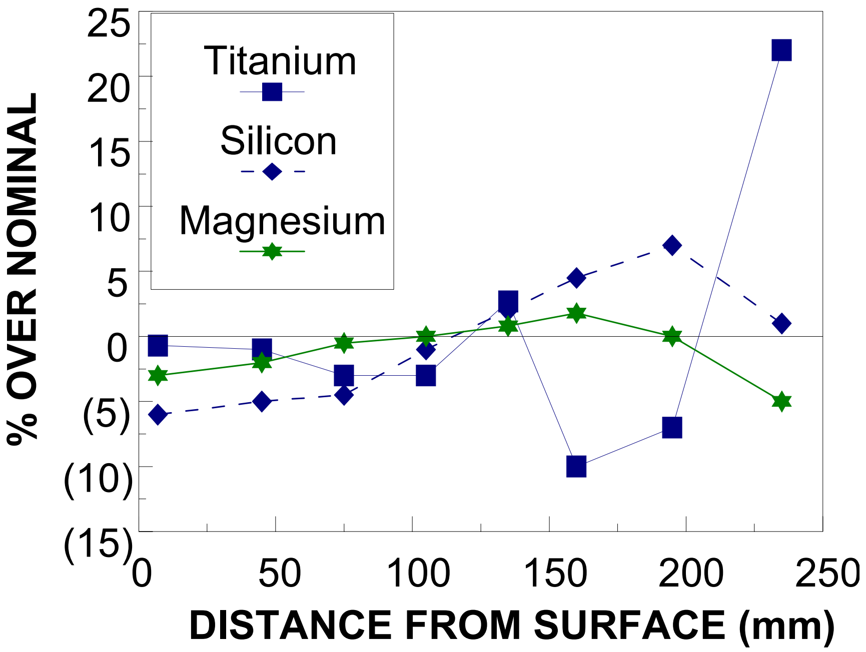


Figure 24: Compositional profile across a rolling ingot.

6. Engineering Aspects

Engineering aspects of the process are important. Due to space limitations, however, only a few points can be raised here.

Over the years, increasing quality demands on dimensional tolerances such as straightness, and the desire to cast greater weights have driven development of improved platen and hydraulic systems. Increasingly, VDC pit operators are using self guided rams. These large diameter rams (up to Ø1000 mm) do not use external guides to prevent horizontal movement during platen descent, but rely on the stiffness of the ram and an internal keyway to prevent rotation or lateral movement. The advantage of this design is that there are no guiding shoes or rollers running down a rail. Therefore nothing can catch on the guides and upset the smooth action of the platen.

DC operators faced with greater quality demands have responded by increasing the level of supervision and control. Sensing, automation and control have provided the greater attention to detail essential for precise casting. Casting parameter sensing and control have followed the development of increasingly intelligent sensors. Casting speed and water flow are the key casting parameters and so require exact control. As sensing technology improves, other parameters such as air flow and pressure, and sometimes both, grain refiner feed, melt temperature, metal level and mould fill rate are being added to the list. Automation systems are currently available that enable the entire cast to be run without human intervention. The great advantage of this is the accuracy of control that not only enables more difficult alloy / size combinations to be successfully cast, but also improves repeatability.

Mould design is becoming increasingly complex as casters strive to meet the demands of downstream manufacturers. The delivery systems for air, lubricant and water must be carefully designed to ensure even distribution between and within moulds on a mould table. Reduction in the size of the moulds is desired to increase packing density and productivity. Also, the designs have improved to give greater robustness and cheaper manufacture.

7. Safety

The main concern during DC casting is that water can be trapped by the liquid metal. The transformation to steam results in a huge, and often rapid, volume expansion and a blast of considerable force. Such an event can occur during furnace charging, especially when wet scrap is loaded into a partially full furnace, or during DC casting when the liquid breaks through its shell. An added complication for those casting aluminium and magnesium is that these metals have a high affinity for oxygen, which leads to a reaction between the water and the metal, producing metal oxide and hydrogen and a great deal of heat and the possibility of a subsequent hydrogen explosion. Furthermore, the affinity for oxygen can allow the metal itself to burn, particularly in the case of magnesium. Finely divided aluminium, such as the powder or liquid ejected from a water explosion, will also burn violently.

A special case is aluminium-lithium alloys, which can react violently with water even in the solid state. Special coolants are employed such as glycol, to avoid contact between lithium and water.

The best defence in DC casting is to be aware of the water entrapment problem. Engineered solutions to the problem centre around controlling molten metal spills to ensure they do not trap any water. In addition special coatings, such as coal tar epoxy paints, are applied to pit walls and equipment. Other coatings are being developed to replace coal tar epoxy paint, as they have safety concerns of their own. These coatings have been found to prevent the violent reactions associated with trapped water.

Automation of the casting process is seen as a positive contributor to safety [53]. The accuracy and repeatability of process control associated with automation means that the desired safe casting procedure will be followed precisely. Secondly, automation enables “hands free” operation of the process and controlled aborts without human intervention. This means that people may be removed from the potential hazard and so minimise the risk.

8. Future Developments

When predicting the future of DC casting one must consider the driving forces for and impediments to change. In the past, ingot surface quality has been a strong driver in the development of new versions of the process. Process productivity and versatility will drive change in the future. Impediments to change include capital tied up in existing plant and organisational and customer acceptance of change. Any new machine or process has to offer considerable advantages before the old one can be discarded or modified.

For many installations, tonnes cast per day is limited by liquid metal supply not casting speed, but this is because the facilities have been sized that way. If casting speed could be increased, greater tonnages could be cast with less capital cost. If higher speeds were used it may be possible to go to fully continuous vertical type operations as used in steel casting.

The other area activity is occurring is new products for DC casting such as more complex shapes. The strength of the process is its product flexibility and versatility. While continuous strip and slab casters are taking over some of the production of sheet product, extrusion billet production will remain with DC casting. The process will continue to be widely used well into next century.

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