Hot Top Mould for Casting Aluminium T-Bar

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Abstract

There has been increasing interest in the potential productivity improvements available through the use of Hot Top technology for Vertical Direct Chill (VDC) casting of aluminium T-Bar. Hot Top technology greatly simplifies molten metal distribution and level control when multiple strands are being cast simultaneously. Aluminium T-bar is sold as high quality remelt ingot and often attracts a price premium because of its freedom from dross and dangerous shrinkage porosity. Hot Top T-bar technology can improve productivity without the complexity of additional metal control sensors and actuators. Modern VDC stations are large enough to accommodate as many as a dozen T-bar moulds at which point the simplicity of Hot Top becomes a significant operational advantage over conventional tooling which requires a dedicated level control system for each mould. Hatch has developed this technology for casting magnesium T-bar and believes that it can be easily adapted to casting aluminium. This paper discusses why Hot Top may offer advantages in aluminium T-bar production and also describes the Hatch technology, results obtained in magnesium casting, and the changes required in order to be used with aluminium.

Keywords: VDC Casting; semi-continuous casting; Hot Top T-bar; multi-strand casting

1. Introduction

In recent years, primary aluminium and magnesium producers have noted a market preference for DC cast T-bar over sow. As a firm that provides engineering services and technology to both industries, Hatch has responded to a range of requests from our clients reflecting this growing market preference. Starting with the magnesium industry, several clients have contracted Hatch to design and supply Hot Top systems for both large diameter billet and T-bar. Recently, Hatch designed and tested a T-bar mould prototype for another major primary magnesium producer. Although Hatch has never promoted its Hot Top technology for aluminium production we have received several unsolicited inquiries regarding its potential application.

2. Hot Top or Conventional Tooling Technology?

The decision to utilize Hot Top or Conventional tooling must consider a range of performance factors which are influenced by the particular circumstances of the Casthouse operation in question. The following discussion works through the factors that the Casthouse operations team must consider when making this decision.

2.1. Operational Simplicity and Robustness

Hot Top tooling is the dominant technology for the production of aluminium extrusion billet given that the number of strands cast each drop can often exceed 100. Conventional tooling would require individual control of metal level for each mould and with such a large number of moulds would simply be too complex to accept. Additionally, the desirable short effective mould lengths can be safely maintained with Hot Top technology independent of metal level control. The lack of moving parts and the tolerance to metal level variation makes Hot Top technology a more robust process.

There are considerably less T-bar moulds installed on a typical VDC, so the level control hardware is correspondingly less onerous than would be the case for a billet table. Nevertheless, 10-20 laser sensors with their associated downspouts, motor driven control pins and metal distribution bags assembled on a mechanically actuated feed launder still makes this a very complex arrangement overall.

Conventional DC casting of magnesium requires even greater mechanical complexity with each mould being independently supplied from a dedicated metal pump that is speed controlled by a laser level sensor signal. It does not take much imagination to see that casting more than two strands simultaneously quickly becomes a nightmare of pipes, pumps and control elements. Additionally, using short mould technology requires precise metal supply control which is difficult to achieve and is often the cause of aborted casts and short drops. Hot top technology can reduce the complexity and improve reliability while at the same time increasing productivity by adding strands.

2.2. Productivity

Provided that metal supply is not a bottleneck, VDC productivity is driven by three factors:

- Number of strands
- Casting speed
- Pit turn-around time

The number of strands that may be installed in a table of given size will be controlled by:

- **Minimum centreline distances of the moulds** – Hot Top moulds and conventional moulds are similar in the horizontal plane but larger in the vertical dimension
- **Ability to feed metal to the moulds** – Hot Top moulds often have a trough in between the moulds whereas conventional moulds are fed from above. However, if necessary, Hot Top tooling may be configured with a perimeter trough which does not occupy table area.
- **Practicality of the level control hardware -** At a certain point the operational practicality of the level control hardware impacts the decision of how many moulds can be installed in the table. This always favours the Hot Top technology but may not be a significant factor if the number of moulds is limited by other factors.

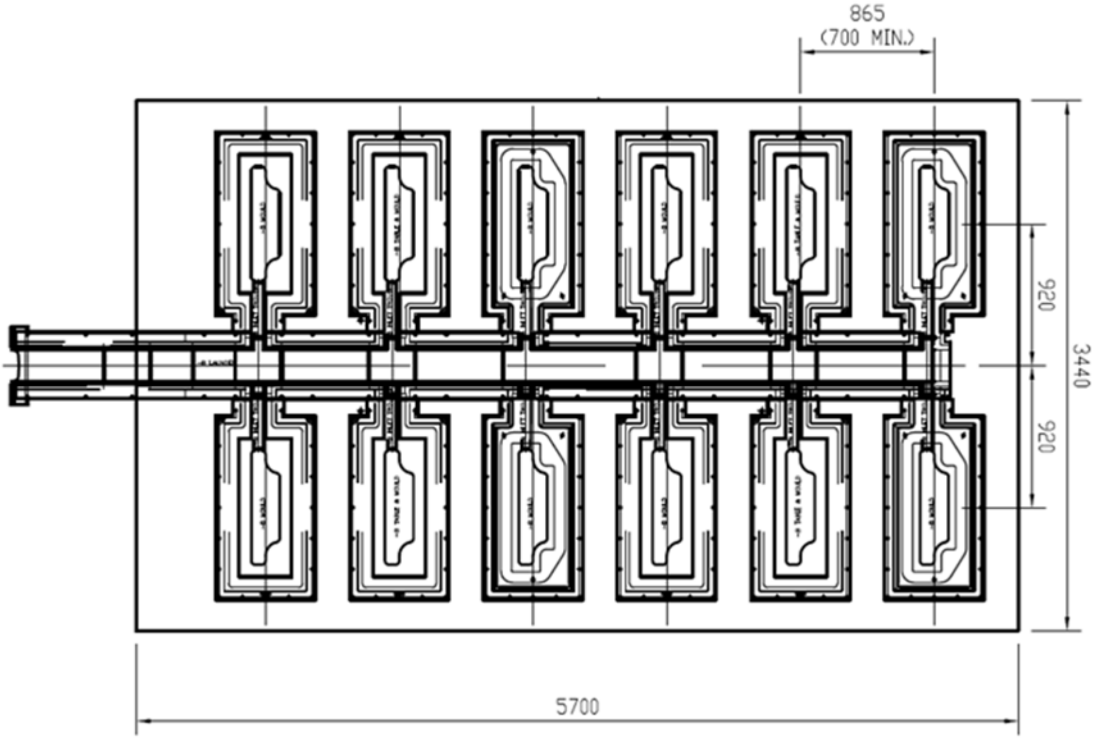

Figure 1. Strand Hot Top T-Bar typical layout.

The maximum sustainable casting speed for pure metal is controlled by thermal balance rather than by hot cracking as it is the case for alloys. Thermal balance threshold is primarily a function of the boiling properties of the cooling water. Therefore, as casting speed is increased the total heat flux and the ingot shell temperature increases and the zone of nucleate boiling expands to compensate. However nucleate boiling mode transitions into film boiling mode, when a critical surface temperature is reached. As a result, the heat transfer coefficient falls sharply creating a thermal imbalance that results in a bleed-out. In pure metals there is no distinction between Hot Top and conventional tooling in this respect.

Pit turnaround time is the time required to prepare the VDC station for the next cast and is the outcome of the complexity, number and sequence of the tasks that must be performed, and the amount of labour available to perform them. If one table has more moulds installed than another then it will likely take longer to turnaround irrespective of being either Hot Top or conventional technology. However, there are some notable differences between the two technologies with respect to turnaround time.

Conventional open top moulds require little attention between casts and the metal feed trough assembly can often be moved away from the VDC allowing maintenance work to be performed in parallel with pit stripping and starting-head preparation tasks. Hot Top tooling installed on a combination rolling/tilting table also offers this same advantage but Hot Top tooling installed on a tilting-only mould frame cannot be worked on freely during pit stripping due to safety reasons. Unlike conventional tooling, Hot Top tooling must be accessed from both the topside and the underside during turnaround. However, once preparation has been completed the Hot Top tooling is faster to start because conventional tooling requires the installation of the distribution bags and metal feed trough with all associated level control hardware as the final step in the turnaround process. In summary, there is little difference between the two technologies with respect to turnaround time for stations containing an equivalent number of moulds.

2.3. Product Quality

Quality requirements for a primary metal ingot intended for remelt are understandably less stringent that for a semi-fabricated ingot such as an extrusion billet or rolling block. However, when two products of differing quality are offered to a customer at the same price, the higher quality product will always be more saleable irrespective of the actual impact physical differences may have on the end use.

Important quality parameters for T-bar product are listed below in order of importance:

- **Freedom from cracks and voids -** For DC cast T-bar a key intrinsic and expected quality parameter is that it shall be free from any cracks and voids so often found in stationary mould cast sow. This is unaffected by tooling technology.
- **Internal quality** – this is related to melt treatment and fundamental metal chemistry. This is unaffected by tooling technology.
- **Profile** – customers by unit mass and are not specifically concerned with dimensional precision. However, stacking performance is relevant and as such T-ingot that exhibits a broad face crown would be undesirable. A slight hollow is optimal.
- **Surface quality** – more perception that reality, surface finish still impacts the customer's perception of quality. Surface defects such as deep cold folds, oxide or dross patches, drag marks, shell tears or discolouration and staining. Low head open top tooling and Hot Top should both produce excellent acceptable quality surface finish. Hot Top ingot typically exhibits fine evenly spaced folds whereas conventional open top moulds are more prone to fold of meniscus size (~10mm). Hot top surface finish is optimum with minimum refractory overhang size, however this can make the mould more vulnerable to in service mechanical damage as a small chip might require the refractory hot top component to be replaced. Hot Top technology ensures that oxides on the melt surface are not carried into the product whereas conventional open top technology frequently experiences this defect, even when using distribution bags.

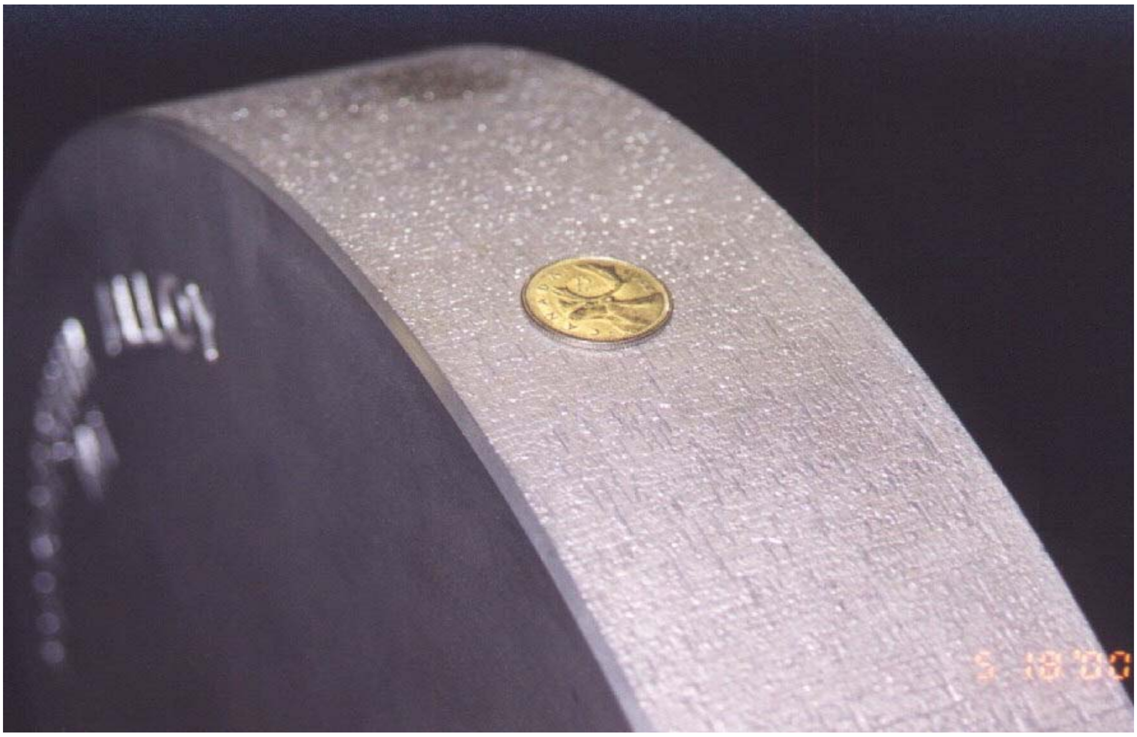

Figure 2. Hot Top cast surface finish (Mg large diameter billet).

Overall the quality offered by both technologies is considered acceptable for remelt T-bar although it could be argued that because Hot Top is under-pour, the Hot Top ingot will always be cleaner internally and free from surface oxide patches.

2.4. Capital Investment Cost

To compare capital cost between Hot Top and conventional tooling we must first ensure that the scope is equivalent. In essence this means that all items required to cast metal have been included within the scope of supply.

Table 1. Comparison of scope of supply.

Hot Top Tooling– N strands	**Conventional Open Top Tooling – N strands**
N+1 mould assemblies complete w/refractory Hot Tops & steel housing plus continuous lubrication	N+1mould assemblies complete w/distribution bags plus continuous lubrication.
N+1 starting heads	N+1 starting heads
One (1) mould table	One (1) mould table
One (1) starting head pedestal assembly	One (1) starting head pedestal assembly
Simple refractory lined trough system fixed to mould table including one (1) emergency pneumatic waste gate.	Independent metal trough system complete with N down spouts, N mechanized control pins and actuated lift system
One (1) laser metal level sensor	N+1 laser metal level sensors (one sensor is required to control the level in the trough)

Either of the tooling technologies can be fitted to a standard VDC with no cost differential. Maintenance facilities needed are also similar in scope with both requiring refractory and mechanical areas. Hence these being judged equivalent are not included in the above comparison table.

The key difference is the scope of supply is that additional refractory is required for the Hot Top system whereas multiple sensors and actuators are required for multi-strand conventional tooling. The cost associated with the additional hot top refractory and its steel housing will be more than offset by the cost of the additional laser sensors and mechanized control pins. Hence, all other things being equal, it is most likely the cost will be higher for the conventional tooling when there are more than 12 strands.

Outside the scope of the comparison above, other design features that are applicable to both technologies can increase total cost but at the same time deliver worthwhile a benefit. For example, Hatch moulds are designed to be integrated with the mould table.. Hatch uses this design because it eliminates all hoses on the underside of the mould table and although this adds some cost when more than 6 moulds are installed it provides a much cleaner design with a minimized risk of water supply failure by contact with hot metal (refer to Figure 3). This also makes access to the underside of the moulds easier as water hoses would likely impede that access.

Figure 3. Underside of Hatch Hot Top mould table free from water hoses.

2.5. Safety

Many factors contribute to safety in DC casting and most are common to both these technologies. However there are a few differences that should be pointed out.

The first difference is the ability to automatically detect a run-out. Before the advent of reliable metal level control hardware, mould metal level was difficult to measure and dangerous if a short effective mould length was the desired set-point value. Hot Top technology was then a solution to this problem. However, nowadays, these control systems have become highly reliable and precise in their ability to control metal level – at least this is the case in aluminium casting. Modern mould level sensors have an additional safety function wherein a run-out can be quickly detected with a sudden fall in the mould metal level. Having detected an excursion, the VDC automation system can abort the cast without the need for operator intervention. In comparison, a standard Hot Top system has no similar capability to detect a run-out. Fusible detection systems can be installed to provide a signal following molten metal contact with a fusible sensor fitted below the mould. At this point it is also worth mentioning that Hot Top billet casting systems are operated widely with no run-out detection system.

The second difference relates to the mass of metal available to be dumped into the pit which is always higher in the case of a Hot Top system than for an open top or conventional tooling system. Less metal available to be dumped into the pit or to be thrown into the air in the event of an explosion is better. Here again, a Hot Top system has a greater potential for damage than a conventional system.

In the final analysis both systems are acceptably safe when operated correctly. Hot top systems can be made safer if desired but long history with Hot Top billet systems indicates that this is not necessary.

2.6. Reliability

There is a saying in the Reliability industry that goes:

“There’s no equipment as reliable as no equipment”.

This means that simple systems that do not rely upon mechanical and electrical systems are intrinsically more reliable than those that do. In that vein, Hot Top systems are fundamentally more reliable because they have significantly less dependence on mechanical and electrical systems. Metal is distributed under the force of gravity and mould length is fixed by the construction of the mould. Even though today’s level control systems are highly reliable, it takes only one system to fail to cause the entire cast to be aborted.

If the probability of failure of a level controller is P(f) then the probability of failure of a multi-strand system using identical controllers is N•P(f) where N is the number of strands.

3. Magnesium Vs Aluminium Casting

3.1. Thermal balance

Although the Hatch Hot Top tooling was specifically designed to cast magnesium, early design work indicated that the two metals can be both cast using the same tooling and casting parameters even though their physical properties vary considerably. The salient physical properties are compared below.

Table 2: Comparison of Physical Properties

Material Properties:	**Mg**	**Al**
Thermal conductivity @ 300 °C (W/m/K)	150	233
Specific Heat @ 300 °C (J/kg/K)	1151	1029
Density (kg/m^3)	1681	2650
Thermal diffusivity	7.75E-05	8.54E-05
Latent Heat (J/kg)	3.68E+05	3.97E+05
Liquidus (°C)	650	660
Process Parameters:		
Casting Temperature (°C)	680.000	690.000
Surface Temperature at water impact point (°C)	350.000	350.000
A (m^2/s)	4.802E-05	4.760E-05
A (mm*mm/min)	2881	2856

It is important to note that DC casting is a volumetric process wherein a product of certain cross section is cast at a particular rate such that we are more concerned with volume/time than mass/time. Although magnesium has substantially lower thermal conductivity making heat extraction more difficult, the amount of heat contained per unit volume is lower in similar proportion to the ratio of the densities of the two metals. The net effect of these properties is that magnesium can be cast on similar tooling using similar casting parameters to aluminium.

Harrington & Groce [1] demonstrated that a simple relationship exists between casting speed and the distance between the water “hit point” and the secondary cooling solidification interface known as the Upstream Conduction Distance or UCD (see Figure 4).

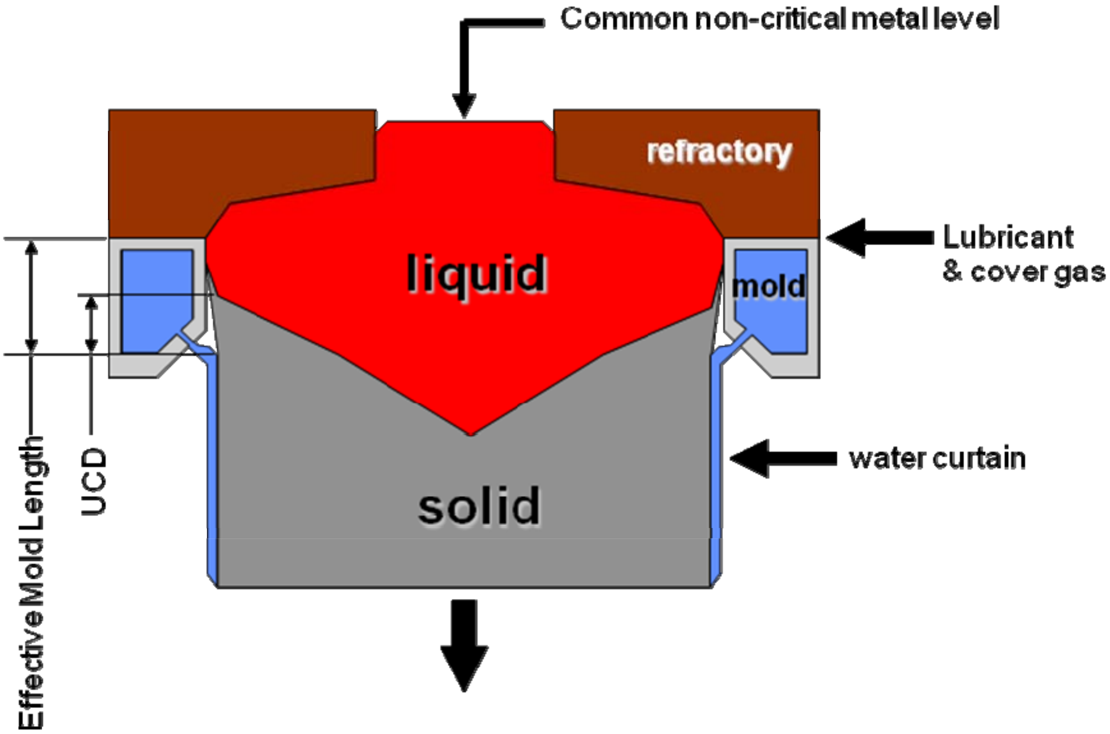

Figure 4. Schematic of Hot Top casting.

$$UCD = -\frac{\alpha}{V_c}\ln\left[\frac{C_p(T_m - T_l) + H}{C_p(T_m - T_w) + H}\right] \tag{1}$$

Where:

- α Thermal diffusivity = $k/\rho Cp$
- V_c Casting speed
- k Thermal conductivity
- ρ Density
- C_p Specific heat
- T_m Casting temperature
- T_l Alloy liquidus temperature
- T_w Surface temperature at water hit point
- H Latent heat of fusion

If we plot the UCD against casting speed (V_c) from the relationship defined in Equation (1) using the physical properties for the pure metals (Table 2) and also for a range of common alloys we can see that unalloyed magnesium and aluminium demonstrate almost identical behavior. Equation (1) can be simplified to Equation (2) for a single material exhibiting constant physical properties.

$$UCD = \frac{A}{V_c} \tag{2}$$

Referring to Table 2 we can see the value of constant A is similar for both Mg and Al indicating that the relationship between UCD and casting speed (V_c) is almost equivalent. This is confirmed by Figure 5 shown below.

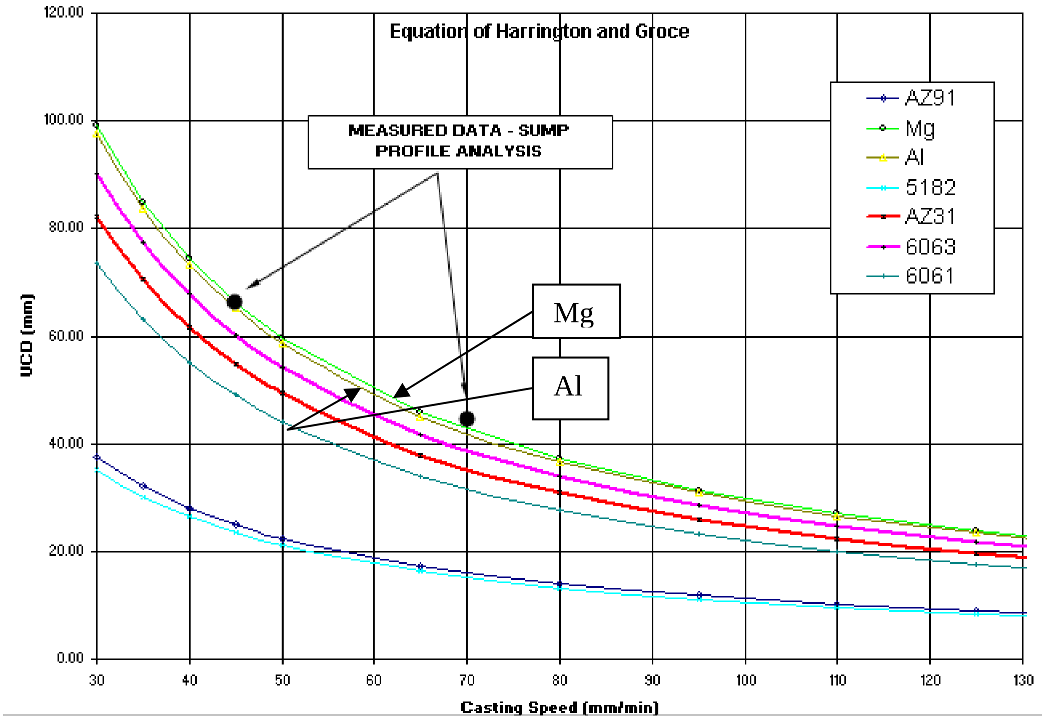

Figure 5. Upstream conduction cistance vs. casting speed.

It is worth noting that although the UCD position for both metals will be very similar, the profile of the sump in magnesium will be deeper than for the same ingot cast at the same speed in aluminium.

During the initial commissioning of the round Hot Top moulds, 6063 aluminium was used for the first test casts to avoid the complications associated with casting magnesium. As predicted by theory, the moulds cast the dilute aluminium alloy without difficulty using the same recipe. Figure 5 shows the location of two experimental points taken during these initial test casts. While the sump profile measurements indicate a somewhat larger UCD than predicted, it must be appreciated that experimentally the primary cooling shell masks the real position of secondary cooling interface. Prediction of its position relies on local extrapolation of the sump profile. Nevertheless the data falls sufficiently closely to the predicted curve and can be considered to be in agreement with the theoretical relationship.

3.2. Other important differences between Magnesium and Aluminium

Other important differences exist between magnesium and aluminium cast include:

- **Vapour pressure** – magnesium has approximately 10 times the vapour pressure of aluminium at the melting point. This makes it prone to form fine crystals on nearby cold surfaces. This powder can be explosive. At elevated temperatures increasing vapour pressure with superheat makes the metal particularly hard to protect from reaction with atmospheric gases particularly O_2 and N_2
- **Oxide properties** – the volume of MgO is substantially less than the volume of metal it replaces preventing it from protecting the underlying reactive metal from atmospheric gas reaction. Aluminium oxide on the other hand provides a continuous self repairing barrier between the metal and the atmospheric gases. Active cover gases typically containing compounds of sulphur and fluorine are required to protect the metal.

- **Surface tension** – the surface tension of magnesium at 0.542 N/m is almost half that of molten aluminium at 0.972 N/m. This requires tighter clearances between the starting head and the mould bore in order to prevent flashing when filling the mould. Furthermore, both reactivity combined with low surface tension promotes penetration of porosity and gaps which forms metal fingers unless porous surfaces are properly sealed with non-wetting inert coatings
- **Flammability** – molten magnesium will burn in air if not protected. The flame temperature of burning magnesium is more than 2 000 °C, a temperature high enough to reduce water to hydrogen and oxygen. If enough burning surface is available moisture in the air will generate hydrogen gas and an explosion will result when the Lower Explosive Limit (LEL) is reached.
- **Heat Capacity** – magnesium's lower energy per unit volume means that temperature loss during trough, pan and mould filling is greater making cast start more prone to freeze–ups
- **Density** – reduced density of magnesium means reduced driving force in open channel flow resulting in greater head drops over launder lengths than for aluminium.

While the above characteristics are important considerations when adapting aluminium tooling for magnesium casting they represent design features that may be eliminated when adapting magnesium tooling to casting aluminium.

3.3. Safety design features

Both metals have been shown to be hazardous in DC casting however, magnesium brings additional hazards related to its flammability, increased reactivity and its ability to reduce water and generate hydrogen gas. Furthermore, magnesium spills result in copious clouds of MgO smoke which obscures vision and makes fighting fires much more difficult. There are a range of features included in Hatch magnesium tooling that are designed to mitigate these additional risks.

- **Run-out detection** – magnesium flashes brightly if a run-out occurs. Hatch installs an optical flash sensor which if triggered initiates an immediate cast abort sequence.
- **Submerged starting head pedestal assembly** – because magnesium tends to adhere to exposed surfaces when either spilt or splashed it then combusts and generates hydrogen gas. To mitigate this Hatch designs both pedestals and grids to always be submerged.
- **Hydrogen accumulation avoidance** – the underside of the mould table and the VDC frame is designed to allow hydrogen to escape rather than be accumulated below the table.
- **Positive pressure sweep** – blowers are installed beneath the table to ensure a sweep flow is maintained to clear any hydrogen generated. This also reduces obscuration by steam.
- **Distribution pan waste gate** – In the event of a cast abort, a pneumatic waste gate is opened to drain the metal from the distribution pan into a preheated and cover gas fed sow.
- **Remote control room** – the control room is as far from the DC station as may be operable. Windows are made from impact resistant glass.
- **Remote pit monitoring -** the ingot surface is visually monitored via CCTV with the control room to provide advance warning of failure indicated by surface degradation.
- **Type D extinguishers and breathing apparatus** – burning magnesium must be attacked using type-D extinguishers. Breathing apparatus is required due to rapid accumulation of MgO smoke.

Some of the above measures are, or may be, usefully applied in DC casting of aluminium. The remainder specifically addresses the hazards unique to magnesium casting and do not need to be installed in an aluminium casting operation.

4. Potential Changes to Hatch Hot Top Magnesium Tooling for Aluminium Casting

As discussed in detail above, Hatch does not anticipate that the tooling will require significant changes to adapt it to aluminium casting. The required changes would be implemented more for simplification and cost reduction rather than to compensate for differences between to two metals.

- **Cover gas porting** – this detail can be eliminated
- **Refractory** – a wider range of refractory materials and coatings are acceptable for aluminium and the mass of the components used can also be reduced. Both these factors would reduce investment cost.
- **Mould length** – for moulds dedicated to casting commercially pure aluminium T-bar the effective mould length can be optimized (reduced)
- **Starting head design** – hang-ups are less likely in aluminium casting and butt curl is a bigger issue. Staring heads can be made more shallow hump-backed design and be designed with reduced anchor bolt separation force
- **Spray box design** – Hatch prefers the spray box concept to water hose systems but cost driven changes would require confirmation through CFD and FES modeling.
- **Mechanical component optimization** – again to minimize fabrication cost Hatch would explore options that would minimize the number of components in the mould assembly.
- **Mould packing density** – to maximize the mould packing density, an investigation into developing more compact mould designs as well as non-sacrificial routing of metal distribution troughs. Such changes would be confirmed using CFD modeling.

5. Conclusion

Hot Top technology offers certain well known advantages over conventional open top technology. In the production of aluminium T-bar these advantages might be significant and offer worthwhile improvements to productivity and savings in operating costs through process simplification.

As a direct response to customer’s requests, Hatch has developed Hot Top tooling for commercially pure magnesium. This tooling is currently used to produce magnesium T-bar in Russia and is currently on trial in North America. Hatch has also received several inquiries from major aluminium industry clients regarding the suitability of this tooling for casting commercial pure aluminium T-bar.

The present paper shows that the thermal balance of casting commercially pure magnesium and aluminium is very similar for both metals, and as a consequence the Hatch Hot Top tooling would be directly applicable for aluminium T-bar production. Value improvement opportunities where simplification, cost reduction and productivity optimization of the Hatch technology can be further pursued if a project to develop the aluminium Hot Top T-bar tooling was initiated.

Figure 6. Magnesium T-bar Cast using Hatch Hot Top Technology.

6. Reference

1. D. G. Harrington and T. E. Groce, US Patent No. 3612151, 1971.