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Magnesium Direct Chill Casting: A Comparison with Aluminium

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Abstract

Strong growth in demand for magnesium automotive die cast components is driving growth in the magnesium industry. However, wrought alloy direct chill (DC) cast products are now also receiving some attention. It is instructive to compare the DC casting of magnesium and aluminium. We briefly examine the current state of magnesium DC castings' production, product mix, industry characteristics and costs. The basic properties of the two metals and the status of DC technology are compared. The fact that the tonnage of aluminium DC castings is about one hundred times that of magnesium accounts largely for the relatively small research and development effort in magnesium DC casting compared to aluminium. Improvement of magnesium DC casting is however, taking place, including development of hot top moulds, safety systems and horizontal direct chill casting. The good news for magnesium casters is that there is much know how being generated and published on aluminium DC casting which can be applied to magnesium. Conversely some of the technology generated for magnesium may be applicable to casting of high magnesium aluminium alloys. Mutual awareness between the two industries will be beneficial to both.

1. INTRODUCTION

The high strength to weight ratio of magnesium makes it a very attractive material for achieving good fuel economy and reducing green house gas emissions in transport applications. Magnesium is characterised by small production tonnages compared to aluminium. Current world aluminium production is around ~20 million tpa while magnesium is only ~400,000 tpa i.e. ~2% of Al tonnage. In 1997, shipments of primary magnesium remelt ingot increased by 16% over that of 1996 to around 340,000 tonne [1] primarily due to demand for die cast components in automotive applications. In 1998 magnesium shipments totaled 421,000 tonnes, a further 23% increase [2]. This rapid growth rate is expected to continue well into the new century [3]. Consequently, there are 18 proposals for new magnesium smelters around the world [4]. Some have already started (Dead Sea Magnesium), some are commissioning at the time of writing (Magnola) and some are finalising financing (AMC).

We estimate there are of the order of 200 DC non-ferrous casting machines in operation around the world, producing predominantly aluminium (~10 million tpa) but also smaller amounts of zinc, copper and magnesium alloys. Ingot sizes and shapes range from small diameter 20 mm forging stock, to 500x3000x5000 mm rolling slabs. The machines are predominantly vertical direct chill (VDC) machines. About 5% to 10% are expected to be horizontal direct chill (HDC) machines.

While magnesium and its' alloys have been DC cast since the process was developed in Germany [5] and the USA [6], only a small tonnage is currently produced by DC casting [7]. VDC casting of magnesium extrusion billet and slab is carried out, but the demand for magnesium wrought alloy products is low. All magnesium DC casting is by the VDC process and HDC casting of magnesium has never been practiced on a commercial scale. Magnesium DC casting can be greatly improved by "piggy backing" on the know how applied to aluminium, but there are important differences. In this paper the DC casting of magnesium and aluminium is compared.

2. INDUSTRY OVERVIEW

2.1. DC Production Capacity

The magnesium industry as previously mentioned is significantly smaller in scale than the aluminum industry. Furthermore, because the metal is little used for wrought product applications such as extrusion and sheet & plate, the proportion produced as DC cast product is smaller.

The major applications for DC cast magnesium are listed in Table 1.

Table 1 – DC Cast Magnesium Applications

Product	DC Format	Size	Alloy
Remelt ingot	Maxi-T	605 kg/m	pure
Remelt ingot	Mini-T	250 kg/m	pure
Anodes	Billet	200–450 mm	AZ31
Structural sections	Billet	200–450 mm	AZ31
Lithographic plate	Block	200x 400 mm	AZ31 (low Mn)
Nodular Iron making	Billet	500 -700 mm	pure

Global magnesium DC casting capacity has recently undergone some major adjustments primarily related to the closure of the Dow Freeport plant and the cessation of VDC operations at Norsk Hydro's Becancour plant as a consequence of their recent explosion. Previously these two locations were responsible an estimated 80% of the total global magnesium DC production [8] where now neither location produces any DC product. Production of DC cast T-bar and round for nodular iron production is currently performed only by Magcorp who have only recently installed their VDC casting process (commissioned mid-1999). There are however, several new VDC facilities targeting this market such as Dead Sea Magnesium, Magnola, and an eastern European producer. Australian Magnesium Corporation currently has no plans to include VDC capacity in their Green field smelter project. Table 2 lists the current estimated DC capacities of various plants, based upon the plant equipment specifications.

Table 2 - Estimated DC Capabilities

Plant	Current Capacity (t/y)	Planned Capacity (t/y)
Becancour	0	0
Magcorp	15,000 – 20,000	15,000 – 20,000
DSM	0	15,000 - 20,000
Magnola	0	10,000 – 15,000
AMC	0	0
Timminco	10,000 – 15,000	10,000 – 15,000
Spectrulite	5,000 – 10,000	5,000 – 10,000
MEL	3,000 – 5,000	3,000 – 5,000
TOTAL	33,000 – 50,000	58,000 – 95,000

Actual production tonnages generated from the existing and future facilities will depend upon the market. It is interesting to note that the additional capacity from the proposed Magnola and DSM DC facilities is almost the sum total of the DC capacity removed by the closure of Dow and the Becancour explosion

2.2. Industry Structure

In the western world, the major industry participants in the production of primary magnesium are ;

- Norsk Hydro ; Porsgrunn / Becancour
- Magcorp ; Salt Lake City
- DSM ; Beer Sheva
- Northwest Alloys ; Addy

Magnola is currently in commissioning and will add a further 58,000 t/y. Numerous other new capacity projects of significant size at varying stages of development, are proposed to add further capacity over the next five years. Of the major partcipiants listed above only one has a DC casting process in operation although as previously discussed plans are in place for additional facilities.
When comparing the magnesium industry and its development to the aluminum industry, it is useful to look at the ownership of the major participants. The dominant western producer is Norsk Hydro Magnesium, a wholly owned subsidiary of Norsk Hydro whose predominant business is oil & gas. Norsk Hydro Magnesium represents approximately 8% of the total corporate business. Current major western magnesium producers are commonly owned by larger organisations whose primary business is not magnesium related. Furthermore, it is commonly the case that historically, many of these firms became involved in the magnesium business as a consequence of World War II production needs rather than commercial incentives. The comparison with the structure and ownership of the aluminum industry, even when in its infancy, is stark – major aluminum producers established themselves in the business because of commercial incentive and the dominant commercial interest of the owners remains aluminum production.

3.TECHNOLOGY COMPARISON

3.1. Material Properties

Since much of the DC casting literature relates to aluminium it would be useful to know how the properties of magnesium differ from aluminium and what effect these differences will have on casting behaviour. In this section the thermal and fluid properties are compared.

Table 3 summarise the thermophysical property data for pure aluminium and magnesium and alloy AZ91. Alloy 6061 is included as a typical DC casting wrought aluminium alloy for comparison. The property data shows magnesium has a low thermal conductivity [9] compared to aluminium, making it harder to remove a given amount of heat, however because the density is lower there is less heat to remove. A 100x100 mm bar DC cast at 400 mm/min, for example, has a total heat flow of 193 kW for aluminium and 131 kW for magnesium. The thermal diffusivity (α) is the ratio of the thermal conductivity (k) divided by the specific (C_p) heat times density (ρ) ie,

$$\alpha = \frac{k}{\rho C_p}$$

and is a measure of how easy it is to cool or heat the material. Thermal diffusivities for the two metals are reasonably similar (Table 1). Values are also given at 300°C as a rough average value over the temperature range of the solid. This value has more influence on the behaviour during the casting process than the room temperature value. It is apparent that pure magnesium is harder to cool than aluminium. This does not, however, apply to the liquid.

Table 3 – Thermal Properties

Property	Al [13]	A6061 [14] [15]	Mg [16]	AZ91 [16] [17-19]
Thermal Conductivity at Room temperature(W/m°C)	236	180	156	51
Thermal Conductivity at 300°C (W/m°C)	233	205	150	76
Specific Heat of solid (J/°C kg) at room temperature	901	900	1028	980
Specific Heat of solid at 300 °C (J/°C kg)	1029	1000	1151	1135
Specific Heat of liquid (J/°C kg)	1300	1300	1357	1156
Density at room temperature (kg/m^3)	2690	2720	1738	1810
Density at 300 °C (kg/m^3)	2640	2660	1681	1772
Density of liquid (kg/m^3)	2368	2410	1580	1580
Liquidus (°C)	660	648	650	595
Solidus (°C)	660	600	650	424
Freezing range (°C)	0	48	0	171
Thermal conductivity of liquid at solidus (W/m°C)	91	95	79	55
Thermal diffusivity of solid (m^2/s) at room temperature	9.6×10^{-5}	7.4×10^{-5}	8.7×10^{-5}	2.9×10^{-5}
Thermal diffusivity of solid (m^2/s) at 300 °C	8.5×10^{-5}	7.7×10^{-5}	7.8×10^{-5}	3.7×10^{-5}
Thermal diffusivity of liquid (m^2/s)	3.0×10^{-5}	3.0×10^{-5}	3.7×10^{-5}	3.0×10^{-5}
Latent heat (J/kg)	397000	33500	368000	368000
Volumetric latent heat (J/m^3)	9.4×10^{8}	8.1×10^{8}	5.8×10^{8}	5.8×10^{8}

The thermal diffusivity of liquid magnesium is substantially greater than liquid aluminium. This means that a given volume of liquid magnesium looses it's superheat faster than liquid aluminium, where flow is negligible. The volumetric latent heat is also substantially less, making initial solidification easier in magnesium. In practice, it is found that magnesium begins to freeze more easily than aluminium.

It is well known that a liquid pool forms during DC casting (Figure 1) and that as the casting speed or ingot size increase, or the thermal conductivity of the alloy decreases then the liquid pool becomes deeper. The temperature distribution during the steady casting is determined by a balance between the convective heat input and heat extraction by diffusion and convective cooling. Convective heat input is determined by casting speed V, density ρ, ingot size R, specific heat C_p and latent heat L, and heat extraction by diffusion is determined by diffusion path length R and thermal conductivity k, while convective cooling is determined by the heat transfer coefficient h. Two non-dimensional numbers have been used to characterise the heat balance [10-13] the Peclet number,

$$Pe = \rho C_p V R / k$$

= the ratio of convective to diffusive heat flow

and, the Biot number,

$$Bi = hR/k$$

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

The pool depth was found by Flood et al in a modeling study to be a function of the Peclet number [20] and the Biot number. This was later confirmed experimentally[21]. The normalised pool depth Δ_{ss} (absolute pool depth divided by radius) was found to be linear with Peclet number i.e.

$$\Delta_{ss} = \left(a_1 + b_1\, Pe\right)\left(c_1 + Bi^{-d_1}\right)$$

where a_1, b_1 c_1, and d_1 are constants. For the 100 mm billet example above this predicts a pool depth of 119 mm for magnesium and 116.5 mm for aluminium; not a big difference. The normalised temperature distribution for magnesium and aluminium cast under the same conditions will be quite similar.

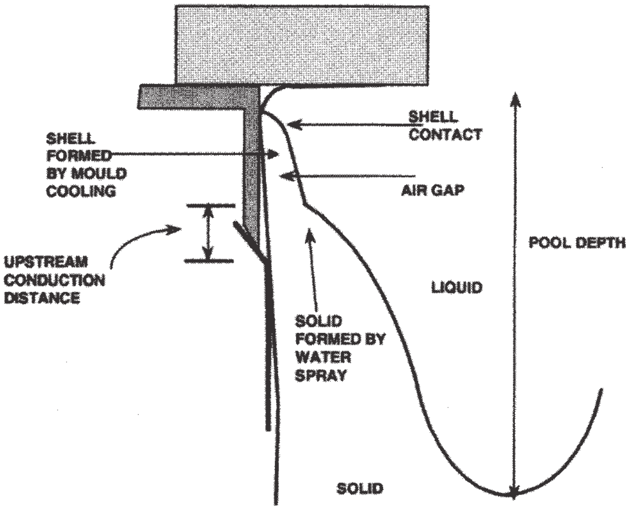

Figure 1 Typical shape of solidification front in VDC casting.

The implications of this analysis are that magnesium DC casting will behave in the same way as aluminium with pool depth increasing as a function of increasing ingot size, decreasing alloy thermal conductivity and increasing casting speed. Since pool depth is an indicator of the tendency to hot crack [21,22] then magnesium might be expected to hot crack at faster casting speeds than aluminium.

The properties of the liquids are summarised in Table 4. They are important because they affect the fluid flow and temperature fields. The liquid thermal expansion coefficient, for example, affects the strength of the natural convection flow in the metal pool. The surface tension is important because it affects the meniscus shape and dimensions. Viscosity and density determine whether the flow is turbulent or laminar and the degree of heat transport by convection versus conduction in the liquid.

The Reynolds number indicates under what conditions the flow will be laminar or turbulent and is given by

$$\mathrm{Re} = \frac{\rho r V}{\mu}$$

where ρ is the density, r is the diameter of the flow chamber, V the flow velocity and μ the dynamic viscosity. The ratio of dynamic viscosity to density, ie kinematic viscosity, is slightly different for the two metals, the dynamic viscosities being similar (Table 4) but the density of magnesium being lower. The transition to turbulent flow therefore occurs at higher velocities for magnesium than aluminium.

Table 4 Properties of liquid aluminium and magnesium[23]

Property	Aluminium	Magnesium
Viscosity (mPa.s)[1]	1.2	1.2
Surface tension at melting point (mN/m)	868	583
Liquid thermal expansion (kg/m^3°C) [2]	3.2×10^{-4}	2.3×10^{-4}
Density of liquid (kg/m^3)	2304	1575
Vapour pressure @ 1000 K (atm)	7.4×10^{-11}	3.55×10^{-3}
Kinematic viscosity (m^2/s)	5.3×10^{-4}	7.94×10^{-4}

The measure of the strength of natural convection is given by the non-dimensional Grasshof number which is the ratio of buoyancy forces to viscous forces and is given by;

$$G_r = \frac{g\rho^2\beta(T_m - T_s)R^3}{\mu^2}$$

where g is acceleration due to gravity, T_m the melt temperature, β the thermal expansion coefficient of the liquid and R the section size. For the same conditions aluminium will have a Grasshof number almost three times that of magnesium and therefore will have stronger natural convective flow.

The height of a meniscus is a function of the ratio of surface tension to density. This ratio is 3.8×10^{-4} for aluminium and 3.7×10^{-4} for magnesium. Under the same metal head pressure conditions, the meniscii for aluminium and magnesium will be similar, if wetting angles on the mould and refractory are the same.

Liquid magnesium spontaneously combusts in air and some means of oxidation control must be used during DC casting of magnesium. An inert atmosphere cannot be used because magnesium vaporisation will still occur and vapour deposit on cooler surfaces within the container. Later, when the container is opened to air, this finely divided elemental magnesium is prone to combust, resulting in a violent reaction.

Traditional measures have been to use a salt flux as protective cover during alloy preparation with powdered sulphur or SO_2 mixed with air during casting to prevent oxidation (Figure 3). SF_6 has been widely used as an alternative to SO_2, mainly to avoid the operational issues associated with SO_2 and the formation of sulphuric acid. Unfortunately SF_6 is a gas with a high global warming potential (GWP), with a rating 24,000 times greater than CO_2. Such a GWP tarnishes the "environmentally friendly" nature of the magnesium industry. Consequently, other gases are being investigated as alternatives to SF_6 [24], which has lead to the development of Magshield by Hatch and Associates and R134a (1,1,1,2-tetrafluoroethane) by AMC/ CAST/CSIRO[25]

3.2. *History of DC Casting Technology*

Early this century, the oscillating long mould continuous casting process of Junghaus, also known as the Rossi process, led to commercial application for aluminium, magnesium, brasses and later steels. The Rossi vertical process cast billets fully continuously, with pinch rolls to support the ingot and to control the casting speed (up to 500 mm/min). A flying saw was positioned in-line to cut the billets at predetermined lengths.

It was the forerunner of today's steel continuous casters. One reason it was not universally adopted for aluminium and magnesium is that it required a very large metal supply to keep it going and was prone to some mechanical breakdowns [26]. Continuous VDC has been employed by Dow for magnesium, where a flying saw mounted in the pit below the moulds cuts cast product at the desired lengths to allow casting to continue [9]. Dow had two such machines, one is now operated by Spectrulite, in Illinois USA, while the other is installed at their Freeport, Texas, USA facility, but is currently decommissioned. The short mould vertical direct chill process of [27] and [29] became the more common process for aluminium and magnesium.

Aluminium DC casting technology has shown steady development. Mould technology has progressed from open top moulds to hot top, then gas pressurised hot top for extrusion billet. Flooded table, level pour stations with over a hundred strands are currently in use. New sheet ingot mould technology including electromagnetic casting, Low Head Composite™[3] mould and variable width moulds have been introduced. Trends toward bigger and wider sheet ingot have also taken place.

Magnesium Hot Top technology was developed by Norsk-Hydro and applied to the production of T-Bar and large diameter billet and commercially applied at the Becancour plant in Canada [28]. Recently, the Becancour VDC suffered a serious explosion which

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[1] Note that viscosities are often quoted to three dimensional places however considering the range of experimental values quoted can be one order of magnitude this seems excessive.

[2] Metals Handbook, 75th ed, D.R. Lide ed, CRC press, p 4-126

[3] Trade Mark of Wagstaff

caused irrepairable damage to the pit structure. Norsk Hydro made the decision to demolish the VDC and have no current plans to re-install it. More recently, Hatch have installed another version of the multi-strand Hot Top VDC process at Timminco's new remelt and VDC casthouse facility at Haley, Ontario. This highly confidential state-of-the art magnesium casthouse embodies many new process features. It has been in commercial operation for the past 12 months.

Figure 2 shows a sample of alloy M1 billet cast by this process showing the high surface quality obtainable from the use of short mould lengths.

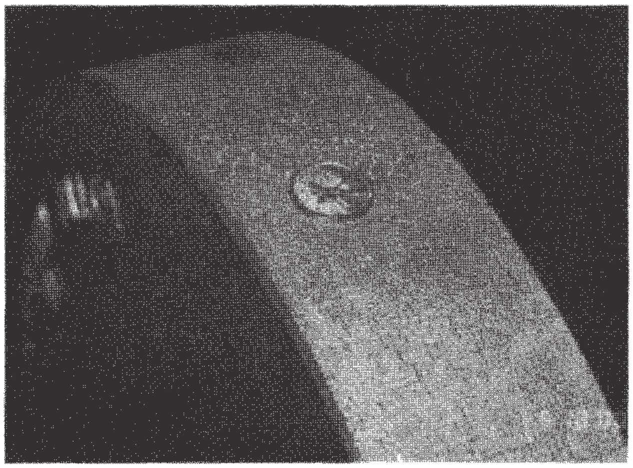

Figure 2 Magnesium billet cast by Hot Top tooling

In recent years HDC casting of aluminium has become more popular, especially in extrusion plants for recycling in-house scrap into billet. The low capital and operating costs make it suitable for the small volumes. Other applications include small diameter forging stock, remelt die casting ingot, slab, T-Bar and semi-solid feedstock.

Casting machines used for magnesium represent the full range of DC casting equipment. Simple cable driven vertical machines are still used through to the more modern hydraulically driven platens. A typical early configuration is shown in Figure 3 [30] and [31]. Horizontal DC casting is also practiced, to a limited extent by Norsk Hydro in Porsgrunn, and is under development by AMC. Dow also used it as a development tool. Here again the basic machines are similar to those used by aluminium HDC producers. Norsk Hydro have issued two patents on HDC casting of magnesium[32] and continue to make specialty thixotropic feedstock using a grain refining method by HDC.

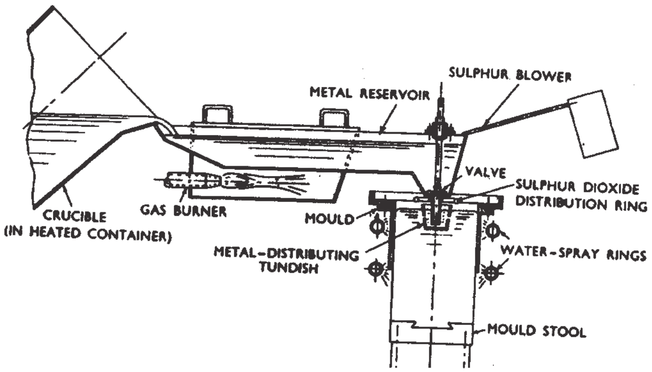

Figure 3 Basic configuration for VDC casting magnesium.(from [31])

The application of the Showa gas pressurised hot top VDC process has been investigated for magnesium[33]. No modification is made to the Showa process as used for aluminium other than to use CO_2 with 10% SF_6 as the pressurising gas rather than air. The usual behaviour seen with aluminium of gas pressurisation reducing mould cooling and giving a smooth cast surface occurred with magnesium. No parties seem yet to have adopted this technology for commercial magnesium production.

The current best practice is the Wagstaff AirSlip™ style moulds that have been used at Norsk Hydro .

3.3. Metal Supply Technology

While aluminium is normally supplied from a large (25 - 100 t) tilting furnace, magnesium is usually supplied by a pump or siphon system. The materials useable in the feed systems for both metals are different. Steel is used for magnesium transfer systems but not for aluminium..

3.4. Research and Development

The status of DC casting has been described in more detail elsewhere (see [34], [35] and [36]). Extensive R&D has been and continues to be conducted on aluminium DC casting. This is reflected in the number of articles on DC casting (Figure 4). Around 2/3 of the articles were published in the last decade. Many of these are on mathematical modelling of DC casting: there were fourteen articles on mathematical modelling presented at the TMS annual meeting alone in 1999.

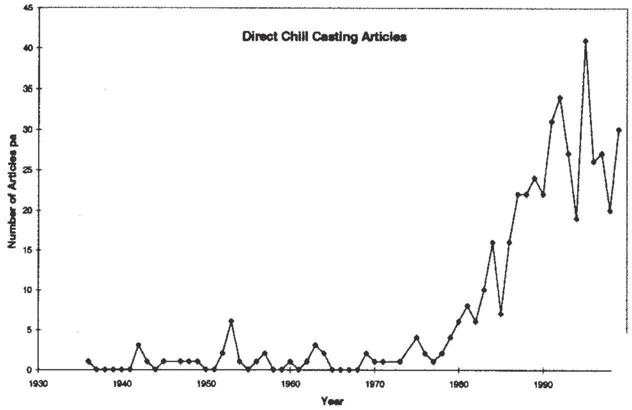

Figure 4: Number of articles on DC casting per annum.

The main drivers for development into DC casting have always been: productivity, quality and safety. Conversion cost has been used overarching determinant. Aluminium has had the advantage of market size and maturity, while the development of the magnesium industry is reflected in the amount of development work. The principal difference in behaviour of the two metals during DC casting is the sensitivity of the magnesium surface to defects. These sensitivities in turn will drive the research and development effort.

Common problems facing magnesium DC casters are:

- Drags and tearing
- Folding
- Oxide patches
- Discolouration

Examples of typical surface defects produced during HDC casting of magnesium are shown below.

The likely explanation is that the difference in behaviour is a consequence of a combination of effects: the surface tension is dissimilar, the oxidation potential is different and the interaction with lubricants and the presence of a cover gas will also affect the liquid's casting behaviour. All of these factors affect the flow behaviour of the liquid surface, which in turn dictates the surface quality of the casting.

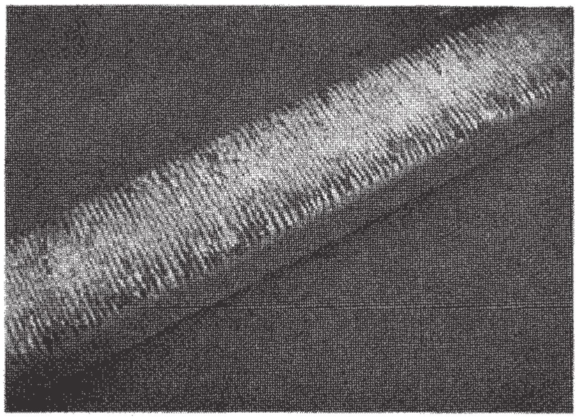

Figure 5 HDC cast pure 100x80 mm Mg bar.

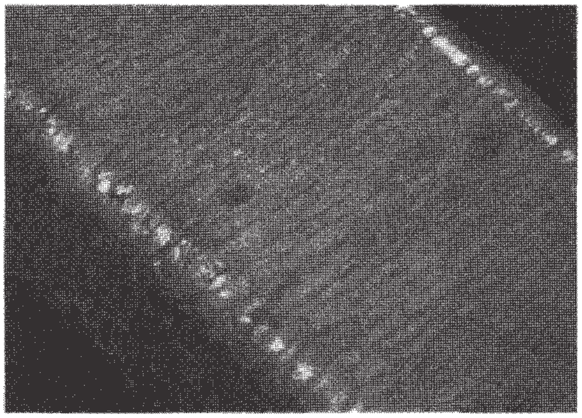

Figure 6 HDC 100x80mm pure Mg bar showing cold folding.

However the potential for the application of HDC to magnesium casting is great and research in HDC and commercial developments in Hot Top casting indicate that these problems may be overcome. Figure 7 below shows the HDC process in operation producing high quality ingot.

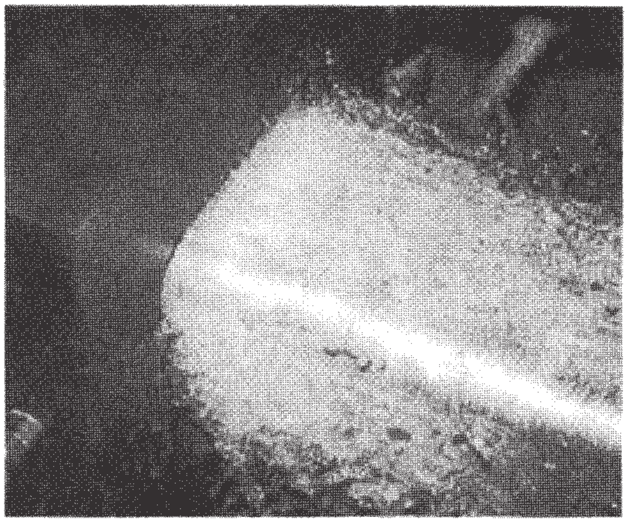

Figure 7 Magnesium HDC Process

In the case of hot top casting there is the possibility of a reaction with the orifice plate. Norsk Hydro's experience during development of their hot top casting system is detailed in their patent. Refractory selection and development for magnesium will be an ongoing issue

Surface discolouration is also a major concern. Breakdown of the protective gas or reaction with water, either as vapour or liquid from the secondary cooling, can lead to a blackening of the surface. Other colours have been seen, the causes of which are unknown.

Lubrication is an area that has seen little development. Static mould lubrication using grease is practised while a number of other operators using continuous lubrication employ a vegetable based oil, such as peanut or castor oil. The reactivity of magnesium is likely to drive the development of specific lubricants to suit the casting process and improve the surface quality.

4.SAFETY ISSUES IN MAGNESIUM DC

Magnesium can cause a molten metal explosion in the same way as aluminium. The mechanisms are considered to be similar i.e.

1. Steam explosion
2. Reaction and chemical reduction of the water
3. Hydrogen explosion

In the case of magnesium however the likelihood of a magnesium fire increases the risk of the reaction with water by providing an initiating source which is at >2000 °C. As in the aluminium industry, there have been explosions during magnesium DC casting resulting in equipment damage and injury. As with aluminium, the usual DC casting precautions should be taken with magnesium i.e.

1. Good Automation
2. Regular pit maintenance
3. Protective clothing
4. No operator intervention during dangerous situations
5. Safe cast abort procedures

The risk of a fire when a molten magnesium bleedout occurs during DC casting has prompted the development of bleedout detection systems. Vision based (CCD or spectral) similar to patented systems for aluminium [37] are in use for magnesium.

5.FUTURE DIRECTIONS

Trends in magnesium DC casting will include continued adoption of the latest technology such as flooded table hot top gas pressurised casting. HDC should play a role due to its suitability to small production volumes. Such issues as development of tailored lubricants and refractories for magnesium DC casting, will be subject to ongoing research.

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