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REMELT INGOT PRODUCTION TECHNOLOGY

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Abstract

The technology related to the production of remelt ingots (small ingots, sows and T-Bar) is reviewed. Open mold conveyors, sow casting, wheel and belt casting and VDC and HDC casting are described and compared. Process economics, capacity, product quality and process problems are listed. Trends in casting machine technology such as longer open mold conveyor lines are highlighted. Safety issues related to the operation of these processes are discussed. The advantages and disadvantages of the various machine configurations and options e.g. such as dry filling with the mold out of water and wet filling with the mold in water for open mould conveyors are discussed. The effect of mold design on machine productivity, mold cracking and mold life is also examined.

Introduction

Remelt ingot production has always been a very important economic activity for the aluminium industry but in many ways the technology has been somewhat neglected compared to the effort spent on wrought semi-finished and foundry alloy final product casting processes.

These remelt casting processes must convert liquid metal into a saleable form. A variety of formats and alloys are produced as remelt ingots driven by transport, handling and customer considerations. In this paper, the casting process options for producing remelt ingots are reviewed. The criteria for selection and the various attributes, potential problems and advantages are listed.

Market Requirements

Shipping costs dictate that ingot formats should have a high packing density. During transport it is important that bundles of ingots do not fall apart causing delays in loading/unloading or potential for injury.

The customer chooses ingot formats according to their furnace type and handling equipment. Some use tower melters that 22kg ingot bundles can be charged to. Others charge sows, T-bar and 23kg ingot bundles ingot into doors on the side of furnaces. Top charge melters can use buckets to charge scrap and ingot. Some die casters prefer small <10 kg ingots enabling manual handling.

Customers expect to be supplied with low dross ingots giving a good yield on melting. Accuracy of weight is also a concern. Most importantly, they expect the ingots to be able to be charged safely after preheat.

Cast house requirements

The cast house requires casting processes that have low capital and operating costs per tonne, suitable capacity and that are safe to run with minimal environmental impact.

Liquid Metal

The cheapest approach to converting liquid metal to a saleable form is to do nothing i.e. sell liquid metal. This is often done where customers are relatively close and even over considerable distances. It has the merit of saving energy to remelt ingots. Crucibles must be designed specifically for transport.

SOW Casting

Benching

One of the oldest methods of casting a remelt ingot is to pour direct from hot metal crucibles into cast iron sow molds on benches. This is unfortunately often done with manual control of the pouring with subsequent spillage of metal. Despite being what the author would consider a last resort approach, it is still practiced due to low capital costs.

Sows are large ingots approaching 1 tonne with a T shape to enable pickup by forklift. They generally have considerable dross in them due to the high fall into the mold. Deep shrinkage cavities are also inevitable because of the size and aspect ratio. Sow molds need to be kept dry, crack free, oiled and well preheated to ensure no rust or moisture reacts with the molten metal during filling causing an ejection of metal.

When charging to liquid melts, sows need to be carefully preheated because of the potential for cavities to contain moisture and cause metal explosions. Studies by the Aluminum Association led to better sow mold designs with much improved cavities but these do not guarantee completely cavity free sows[1]. Lower aspect ratio designs produce smaller shrinkage cavities. Worst of all are closed over cavities with micro-cracks to the surface. If these get water in them they will not be dried out by the normal preheat practice and the chance of a molten metal explosion is high. For this reason, sows are best charged to a dry hearth rather than into liquid metal. Preheating of sows on furnaces sills is not recommended.

Sows produced from remelted secondary ingot (RSI) can also contain traces of hydroscopic salt fluxes from the salt furnace dross processing operations requiring adequate preheat time and temperature before charging to furnaces [2].

Sow Carousels

A step up from benching is to have the sow molds on a rotary carousel. Sophisticated straight line sow casting machines have been developed for the zinc industry. These include hot topping with heated lids to eliminate shrinkage cavities.

Open mold conveyors

Open mold conveyors are the major casting process for producing remelt ingots; millions of tonnes per annum are cast on these machines. Many new smelter cast houses are being installed solely with conveyor lines. In the last decade the process has seen considerable improvement in technology [3-13].

Conveyor casting involves filling cast iron or steel molds, mounted on a conveyor with liquid metal, usually by a wheel-type system at one end of the conveyor. The line is run at a speed such that the ingots have time to solidify as they travel along the conveyor line, and are then de-molded, cooled, stacked, strapped in bundles and labeled. In the case of primary smelter machines, the molds are generally water-cooled in order to achieve a high production rate. Remelt smelter or small foundry alloy lines are sometimes air-cooled. Some machines fill the mould after it has entered the water bath ("wet fill") and others fill the mould before it enters the water bath ("dry fill").

Machines casting 23 kg ingot are typically 20 m long with a production rate of 18-20 tonnes per hr. Of the order of 10 million tonnes is cast through these machines every year, dwarfing the production of remelt ingot through other processes. Ingot sizes vary from 7 to 23 kg. Standard 99.85% Al is generally produced in 22-23 kg trapezoid ingot. Foundry alloys are also produced in all sizes.

Most of the operating costs are fixed costs e.g. labour, therefore the cost per tonne will decrease if one can increase the tonnes per hour.

Figure 1 Typical ingot conveyor line [4].

Productivity and Economics

A typical conveyor line costs around $2.5 million and can produce over 110,000 tonne per annum.

Since caster operating costs are predominantly fixed costs e.g. labour, the cost per tonne decreases with increasing tonnes per annum., which depends on the line speed and the percentage up-time. Up-time is a function of the melt delivery, alloying melt preparation cycle time, machine maintenance schedules and breakdown or shut down due to mold change out (mold life is thus important). Typical percentage up time casting is around 50% while best practice up-time is approaching 85-90% with long continuous runs.

To maximize productivity it is essential to have two adequately sized furnaces such that one is filled while casting out the other so that furnace capacity is not the bottleneck and the machine is never waiting for the furnaces. Often the machine is ready to cast but the metal from reduction is too hot. Attempting to cast with too hot metal results in semi-solid ingots at the knockout and major equipment problems. Some plants destroy perfectly good product by charging it to the furnace to bring down melt temperature. Attention to metal scheduling and furnace design are needed to get reduce this problem.

Conversion costs for liquid metal to bundled ingot are relatively low for conveyor machines at ~20-40 $US/t depending on labour cost and productivity.

Fundamental Heat Transfer

The line speed is set such that the ingots are solid at de-molding. Thus, the line speed is a function of the ingot solidification time and the maximum ingot handling capacity. Assuming handling is not the bottleneck, the maximum productivity P in tonnes per hr is given by

$$P = \frac{3.6WL}{I_s t_s} \tag{1}$$

where, W is ingot weight (kg), I_s is mold spacing (m), L is line length (m) and t_s is ingot solidification time (s). Longer conveyors are being installed and old lines lengthened. Generally, the 20 m lines are being replaced by 25 m lines, but up to 40 m lines have been installed, but with a greater footprint and building infrastructure. In recent times, conveyor chains and molds have been reconfigured to allow some small reduction in mold spacing, giving 4-5% productivity increase. Other productivity gains have been made through control of ingot weight variation, water cooling, mold coating and casting temperature. Smelters planning incremental production increase can use the increased casting machine capacity, rather than buying a new machine, and increase flexibility of product scheduling.

If ingot solidification time can be reduced the line can be run faster or shorter (cheaper machine scan be built with the same capacity). The solidification time is a function of the heat flow and the heat content of the ingots (set by size and pouring temperature). Early work measured solidification time on an ingot line and modeled the heat flow. Productivity was predicted to be increased up to 4% by using lower casting temperatures[14]. Water level, die coating thickness and skimming were also found to effect solidification time.

The early modeling did not predict air gap formation however, it is well known that in many permanent mold casting processes the casting and mold deformation can result in the formation of an air gap between the mold and the casting during solidification [2] due to mold expansion and ingot contraction. Examination of the heat flow resistances in ingot casting shows that if an air gap forms it will be the greatest heat flow resistance and control the heat flow [3]. It is therefore of interest to understand how this gap forms and what controls its evolution and any model needs to be a fully coupled thermal stress model.

The CAST cooperative research centre has been investigating conveyor ingot casting in collaboration with its industry partners, o.d.t. Engineering and Rio Tinto Alcan. A rig (Figure 2) was built which allows the casting machine molds to be instrumented for temperatures, air gaps and mold deformation measurements while duplicating the water bath cooling conditions on an ingot conveyor (see for [9]more detail). Solidification time was found to vary with ingot weight and casting temperature. Linear regression of the data found

$$t_s = b_0 + b_1 W + b_2 T_m$$

where t_s is the solidification time, W the ingot weight, T_m the melt temperature in the ingot and b_0=-220 s, b_1=12.8 s/kg and b_2=0.32 s/°C. It is clear that higher melt temperatures will lead to increased solidification times and reduced productivity. If all ingots were the same size then ingot weight would not have an effect on productivity since solidification time is linear with weight and this cancels out in equation (1), however since there is variation in ingot weight the line must run at the speed required for the heaviest ingot to be solidified. Thus, there are useful gains to be made in productivity by reducing ingot weight variation.

Figure 2 LVDTs and thermocouples inserted in mold on ingot rig to measure air gap formation, solidification times and heat flow [9].

CAST's air gap and mould deformation studies revealed that in the early stages <50s after filling the mould heats rapidly while there is no air gap and expands outward from the walls and base. When the ingot shell starts to form and becomes stiff enough it parts from the mould (except for those places where it rests). The air gap formed ~ 100 mm restricts the heat flow to the mould and the mould temperature drops and the mould contracts back toward the ingot but since the ingot is not also contracting, the air gap dimension gets bigger[11]. Note that the ingot takes the shape of the bowed out mold.

CAST developed and patented a faster-solidification-time mold design, known as "CASTmould" allowing a 20% productivity increase. Supplied through o.d.t. Engineering, the design is such that the mold deformation gives rise to smaller air gaps and higher heat flow. Water cooling effectiveness depends on water level, relative to metal level in the mold, and boiling behavior. There is a growing awareness of the importance of mold design to boiling behavior and mold life, and as a result, a number of plants have redesigned their molds using mathematical modeling.

Helium was investigated as a potential means of increasing air gap heat transfer due to its substantially higher thermal conductivity than air. Injection of helium through holes in the base of the mold resulted in 40% faster solidification times[10, 11, 15]. This was less than the expected 100% increase due to the fact that the increased heat transfer resulted in higher mold temperatures and bigger mold expansion and bigger air gaps in the case of helium. Given the difficulties of engineering helium into a machine it was decided to pursue mold design as a preferred lower risk approach to increasing machine productivity.

Ingot Quality

The amount of dross present and the appearance of the ingot depend primarily on the filling system wheel design. Upstream melt handling also plays a role; cascade from stationary furnaces into the launder will obviously make more dross than a level pour tilting furnace. Skimming is used in some smelters to remove the surface dross, but the procedure results in ~0.3%melt loss. With the trend for higher production rates of 25 and even 30 tonnes per hr, with filling times of less than three seconds, there is greater potential for more turbulence and dross generation.

Low dross casting wheels were developed by the various casting machine manufacturers. Recently, CASTfill a low-dross patented wheel was developed by CASTcrc. It is specifically designed for high production rates using specialist modelling tools and a full-size casting machine supplied by o.d.t. Engineering. The first smelter customer replaced an existing wheel design, following oxide-content measurements of the pilot plant ingots and making a comparison with their skimmed ingots. CASTfill has proven easier and cheaper to maintain than the previous wheel and has exhibited a good service life. CASTfill has a modular cast-iron construction, allowing individual nozzles to be replaced if damaged, making the casting cost cheaper. CASTfill was adapted to different metal flow rates, mold pitches and ingot sizes down to <10 kg on foundry alloy ingot lines. Such designs are operating at two Australian smelters and three Asian smelters. Two other installations, each of three new machines fitted with CASTfill, have been ordered.

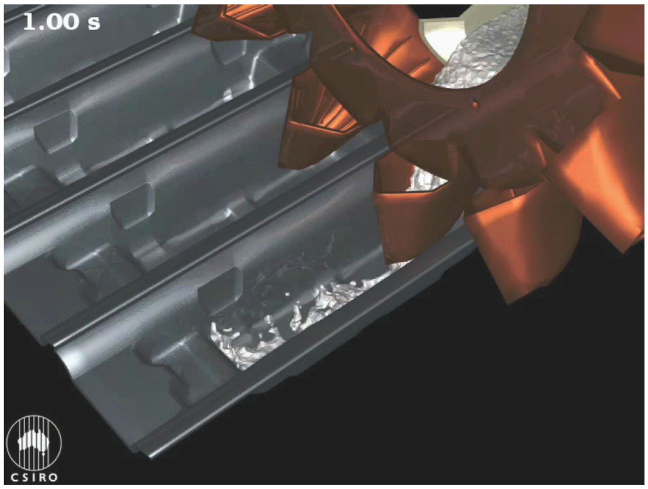

Figure 3 CASTfill flow simulation model [12].

As with sow ingots, open mold ingots usually contain shrinkage cavities which may contain water thus presenting potential for explosions if charged to liquid melt. Cavity formation is a function of ingot width to height aspect ratio, alloy, mould design and cooling arrangement. Certain high silicon alloys are particularly prone to formation of closed cavities and present an ongoing challenge for the industry. The type of modifier and grain refiner also affects the cavity formation. High hydrogen gas levels actually help disperse the porosity into small <500 µm pores. The recent trend to degas foundry ingot has thus exacerbated these shrinkage problems.

Bundle weight variation is generally around ±30 kg. Casting wheels with a distinct split between the feed nozzles rather than a nozzles being fed from a reservoir have less ingot to ingot variation.

Melt treatment

In the past ten years there has been a growing trend to supply degassed and filtered metal to the foundry industry. The desire to degas remains somewhat contentious in that most foundries upon remelting the ingots will find they pick-up hydrogen back to the equilibrium level before casting. The marketing priorities seem to have taken precedence over the technical issues. In-line degassing does give some additional inclusion removal however as mentioned above it tends to encourage large cavities rather than smaller dispersed porosity.

Typical systems incorporate an inline degasser and a CFF filter. The CFF filter needs to be correctly sized for long runs if continuous operation is the norm. Parallel filters enabling change out on the run can be used.

Automation Systems

Machine control systems and engineering are becoming more advanced. Laser metal level sensing and good ingot height control are now used routinely, giving reduced ingot and bundle weight variation.

Some machines have detailed logging of individual molds and can identify molds with ingot-release problems. Occasionally an out of dimension mold is supplied from the foundry which has inherent ingot sticking problems. Stuck ingots are detected and on some machines they are released at the fill end, or the wheel is automatically lifted clear, allowing casting to continue. Automated ingot handling, strapping and labeling systems have become the norm and plastic strapping has become preferred because of cost, performance, safety, and gives no iron pickup (Figure 4). Bundle compression before stacking is a recent innovation to ensure the stack is tight.

Figure 4 Plastic strapping used on 23 kg bundle.

Mold coating is an important area of ingot casting technology which is now receiving attention. Within the industry, oils, boron nitride, carbon and refractory coatings are used. Fuming can be a problem with oil coatings, while the lower thermal conductivity of refractory coatings reduces solidification. If over applied carbon coatings can cause the same problem. Automated coating application and mold cleaning are recommended. Again module change out of equipment allows the machine to continue running and maintenance to be carried out in a more suitable work space.

Typical problems

Mold life is important to conveyor casting both because of the direct cost of molds per tonne of metal produced but also because mold change out reduces casting up time. Mostly, iron molds are used but on some lines steel molds are used. Steel lasts substantially longer than iron but the cost per tonne cast is not significantly different.

Poor mold life can occur due to casting defects in the molds but also due to poor design, particularly if a wet fill design mold is used on a dry fill machine. Wet fill designs tend to be thinner walled and thus when operating a dry fill configuration the exterior temperature can exceed the film boiling temperature before it enters the water. This causes reduced cooling rate, high mold temperatures and corresponding high mold deformations and stresses. Another aspect of mold design is to ensure there are no exterior hot spots or pockets where steam can collect on the mold.

If the wheel design is not good and the wheel temperature is low then drips and stalactites of metal can form on the spouts which drop onto the ingots and the area between molds. These tags are bad for ingot quality but also cause problems in the handling downstream. Monitoring of the wheel temperature and an adequate burner heating system is thus important.

Control of the water boiling mode is important. If film boiling occurs it tends to result in water spitting up onto the moulds and ingots. It also results in lower heat extraction, slower solidification times and higher mould temperatures and stresses and poor mould life. Film boiling occurs if the mould exterior temperature goes above ~135 °C. This can easily happen in the case of thin walled moulds and with dry fill practice. Those areas of the mould where the ingot rests are also hot spots where the higher heat flow results in higher exterior temperatures and the mould needs to be carefully designed to account for this. Application of mathematical modeling can assist the redesign.

Ingot release at the end of the conveyor has been an ongoing problem with these machines. Ingots can stick for a variety of reasons;

a) poor mould coating resulting in welding to the mould
b) ingot too hot and has not contracted away from the mould
c) poor mold design with areas where the ingot can contract onto the mold
d) asymmetrical mold design resulting in asymmetrical mold distortions and ingot shapes.

Further work on ingot sticking is warranted.

The knockout area is often a problem with wear and tear and a large proportion of machine down time can be due to equipment failures in this area. Modern machines have monitoring of timing events which can be used to diagnose excessive wear and flag the need for preventative maintenance. The use of equipment modules can allow fast change out and gives maintenance personnel safe and easy access to the equipment.

OHSE aspects of conveyor casting

As with sow casting Metal ejection during mould filling is a possibility if the moulds are not dry and correctly coated. This can happen on dry fill, wet fill or air cooled machines. A suitably sized mol pre-heater and mould temperature monitoring system should be in place.

The industry is somewhat split on the practice of filling the moulds in or out of the water bath and the topic remains debated. As the need for high production rates and capacities grew water cooling has become the norm. Concerns over water getting into mould before filling and metal spilling into the water bath promoted some machine manufacturers to go to a dry fill configuration. There are advantages and disadvantages to both approaches.

Dry fill is considered safer by some, since metal cannot spill into the water bath if an overfill occurs. Also, water cannot enter into the mould through any cracks during filling. Dry fill does not however guarantee absence of metal explosions. Water may enter a crack after the mould enters the water bath (although the ingot shell is expected to have formed by then) or wet and or rusty moulds can return to the filling end. Poorly preheated moulds with a small amount of rust can also give small metal ejections. This can happen in completely air cooled machines. In the event of a major metal spill metal could still run along the top of the machine to where the water bath is. However, systems should design for overflows to occur safely upstream.

A potential downside of the dry fill practice is that unless a thick mould is used, very poor mould life can result. Note that combination of a poor mould design and a dry fill practice resulting in mould life and mould cracks results in more exposure to the possibility of explosions than a wet fill machine. Depending on the design and exact dimensions, thicker moulds may or may not result in longer solidification times. For a given mould design however, dry fill does result in longer solidification times requiring a longer line for the same capacity.

There seems to be a trend to dry fill machines within the industry with many of the new machines installed with dry fill configurations. Dry fill does eliminate the possibility of a major explosion catastrophe caused by large amounts of metal running into the shallow water bath; assuming the water bath is not too close to the filling point. Such an incident occurred in China and destroyed the plant. On the other hand, if proper control of metal feed (high level sensors, automatic furnace tilt back, automatic dams to drain sows, overflow points etc.) is in place then the risk of this eventuality is very low.

Noise pollution due to the hammers used on some machines to release the ingots can be a problem.

DC casting

Direct chill casting has long been used to produce small ingots or T-Bar remelt ingots both on vertical and horizontal casting machines. As opposed to sow and open mold casting, DC cast product has much lower dross levels, tight dimensional controls and usually no cracks or shrinkage cavities.

VDC casting heat flow has been widely studied and is not covered here.

VDC

Generally, purity alloy is produced as T-Bar. Few shape casting customers can handle T-bar, however the galvanising industry prefers Al-Si alloy as T-bar. Fully automated VDC installations casting T-Bar with up to 8 strands can be very productive[16], up to 300 t/day. While small ingot can be produced by VDC casting it is generally not economic to do so because of the high mold capital cost and necessity for a separate sawing operation.

Conversion costs for VDC T-bar are generally higher than 23 kg remelt ingot, but premiums also tend to be a little higher.

Cracks sometimes form in T-Bar due to hot tearing caused by butt curl at cast start, insufficient grain refiner or casting too fast.

HDC

HDC machines are being used by a number of companies to make small <10kg foundry alloy ingot and purity and foundry T-bar[17-21]. Ingots are cut to length using a flying saw. Twenty to thirty strands of small ingots can be cast at once depending on the ingot size. Casting strands are pulled out of the mold using pinch rollers which clamp the strands to a conveyor.

The high quality ingot produced by HDC casting assisted HDC to make major inroads against conveyor machines during the early years of the century but recently more conveyor machines seem to have made a comeback for production of small ingots.

Figure 5 Typical HDC layout [19].

A typical configuration would have two furnaces 50 or 60 tonnes each feeding the HDC. However, in installations with T-Bar as the predominant product mix which has a higher production rate, 100 tonne furnaces are used. Lines are generally highly automated.

Sawing losses are generally around 1%. The chips are collected, compacted and can then be remelted.

As with conveyor lines making foundry product HDC lines usually have in line degassing and filtration.

Metal level in the tundish is an important control parameter as it effects the degree of contact between the metal and the molds.

OHSE

As with VDC casting, HDC can experience liquid metal breakouts when the shell tears. The usual DC casting precautions with appropriate water pit coatings need to be taken to ensure no molten metal explosions. Shell tearing can be related to a variety of issues including lubrication and metal ingress into the mould. HDC introduces a considerable amount of oil into the water which needs to be removed both for environmental and casting process heat transfer reasons.

HDC problems

HDC casting has its share of problems and defects. For the wide tundishes it is important to minimize variation of melt temperature across the tundish else some strands may experience freezes up and others bleedouts due to too high casting temperature. Often, one tundish is used for T-bar and another for small ingots because of the vastly different flow rates.

Problems can also occur with build up of particles in the transfer tubes between the tundish and the molds. These particles can be dross and chloride related or TiAlSi particles[17, 22]. Phosphorous has also been implicated in causing defects related to poor lubrication when concentrations were greater than 12 ppm [19].

Straightness of the bars can also be an issue. The conveyor bed should sit slightly higher than the bottom face of the mould because of the ingot contraction. However, because the initial butt is thicker than the bar the offset needs to be different at cast start. There are means of lowering the mould after cats start. The movement of bowed bars can also result in tears and run outs.

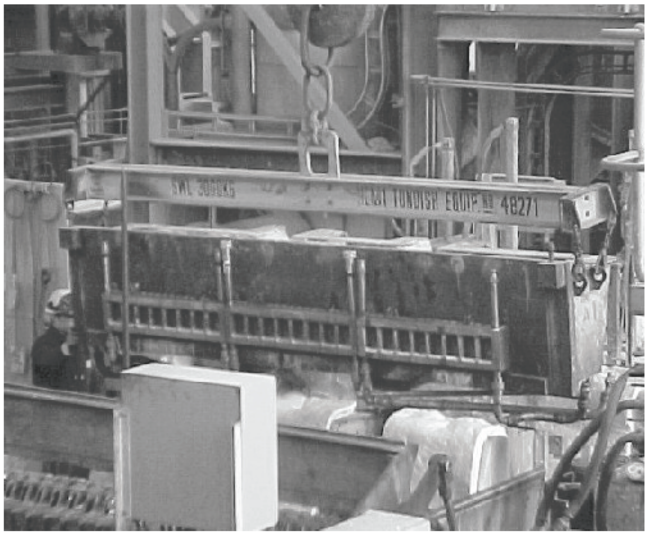

Figure 6 Tundish changeover on HDC caster [19].

Implementation of HDC T-Bar casting in the Alma and Dubuc plants involved solving some defect problems[22]. If gas is generated at the transition plate either due to steam or vaporized oil, worm hole porosoity can form below the top surface

Economics

HDC machines are higher capital cost per tonne capacity than ingot conveyors. However, HDC machines are often installed to cast bus bar for new smelters and generally, this activity pays for a machine.

Generally, HDC has slightly higher operating costs than conveyor casters. Product flexibility is a feature of HDC casting since one can switch from T-bar to small ingots relatively easily (Figure 6).

As with conveyors the operating costs are predominantly fixed costs and thus throughput controls conversion cost. Casting speed, the number of strands and the size of the strands determines the productivity. Since maximum casting speed is set by the speed at which crack occurs which varies inversely with ingot dimension and the productivity is a function of the area of the ingot, the bigger the ingot the greater the throughput. Small ingots are around 7-8 t/hr while a 3 strand T-bar installation would be typically 12 t/hr. Thus, casting small ingots, a typical HDC annual capacity would be around 50 ktpa whereas casting T-bar annual capacity would approach 150 ktpa.

Wheel and Belt Casters

Wheel and belt casters have a long history as the casting process feeding bar continuously to a rod mill to produce rod for electrical cable. First developed by Properzi, a copper wheel with a tapered groove the shape of the ingot has a steel belt passing around a section of the wheel and molten metal is fed into the groove. The wheel and belt are water cooled and the metal exits the wheel as a bar and is straightened. To produce remelt ingot the bar is then sheared on a rotary shear rather than sawn, and stacked into bundles. The shear results in a sharp edge on the end of the ingots. In other respects the ingots are of high quality having low dross levels (there is no cascade into the mold) and excellent dimensional tolerance[23].

Typical ingot size is 9.6 Kg +/- 0.25 kg, 730 +/- 5mm long and 103 mm high, 54 mm wide. Bundle weight variation is generally lower than open mold conveyor bundles at around ±5 kg in a 1035 kg bundle.

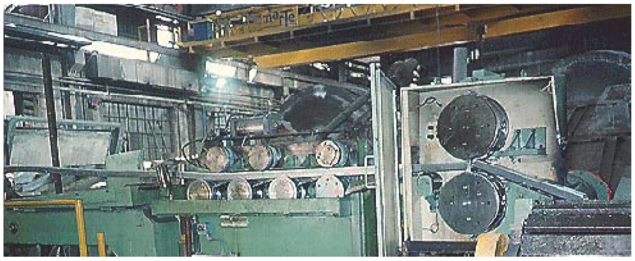

Figure 7 Rotary shear used on Properzi wheel and belt ingot caster [23].

Properzi have delivered at least 7 of the 4.2 m diameter configurations of wheel and belt casters for foundry alloy ingot production.

Figure 8 Properzi ingot bundle.

The maximum line speed increases with the wheel diameter. The production rate of these machines is quite high; purity aluminum can be run at 20 t/hr while the lower thermal conductivity of foundry alloys requires a slower speed of 15 t/hr.

Centreline porosity can occur with wheel and belt casting product if the cooling is not optimized. As with the other casting processes the cooling water needs to be kept from the metal entry point to the mould (wheel) to avoid metal explosions.

Recently, there has been further development by Properzi to enable production of larger ingots using grooved articulated water cooled blocks on a belt rather than a wheel [24]. As with HDC, casting consideration needs to be given to parallel filters in the launder to the caster to enable filter changes so that the filters do not become over loaded during long runs.

Future Innovations

Casting direct from crucible to conveyor casting machine using laser level control and level pour from the crucible into a launder is entirely possible. The benefit of eliminating furnaces in capital and operating costs would be high. Such a system could also be used with an HDC caster.

Process comparison

The casting processes can be compared on the basis of possible products, their quality, and operating economics (Table 1). Optimum choice of casting process comes down to the product mix, customer/marketing requirements, whether the plant is greenfield or brownfield and the tonnage to be produced. If one wishes to make T-bar and has no available capacity on existing VDC machines then HDC casting represents a good choice. For small foundry ingot production conveyor lines, HDC and wheel and belt casters overlap and the choice comes down to product quality versus, technical complexity and production cost.

Table 1 Comparison of processes to produce remelt ingots.

Process	Ingot size (kg)	Dross levels	Dimensional control	Losses	Annual capacity (ktpa)	Conversion cost ($US/t)	Capital cost* ($US million)	Problems
Sow casting	500-1000	high	poor	Splashing, skimming	50-150	10	0.1	Metal splashing
Ingot conveyor	5-25	medium	intermediate	Skimming 0.3%	110-170	20-40	2.5	Mold life, Ingot release
VDC	T-bar	low	good	low	110-150	80-120	6	Hot tearing
HDC	5-15 kg & T-Bar	low	good	Sawing 1%	Small ingot ~50 T-Bar >140	25-50	1.5	Lubrication, worm holes, tube blockages, hot tears
Wheel and belt	5-15 kg	low	good	low	80-100	40-80	2.5	Shrinkage pipes, Wheel and belt life

*Indicative numbers only and n*ot including furnaces.*

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