Essential Readings in Light Metals: Cast Shop for Aluminum Production.
Edited by John F. Grandfield and Dmitry G. Eskin.

6. DIRECT-CHILL CASTING

We have included three direct chill (DC) casting overview papers which can provide the basis for developing a good bibliography and overall understanding of DC casting. The industry has put many years of effort into developing improved mould technology. These papers are essential reading for those wishing to make further inroads into mould design. It is crucial to understand the fundamentals of heat and .uid flow (including melt distribution and natural convection) during DC casting as well as water cooling and air gap formation physics in order to produce good quality DC castings.

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RECENT DEVELOPMENTS IN SEMI-CONTINUOUS CASTING OF ALUMINUM ALLOY BILLETS AND SLABS

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Abstract

In spite of the development of several continuous rod and sheet casting processes, the D.C. (direct-chill) short-mold casting process, used on a vertical semi-continuous basis, still accounts for the major part of aluminum alloy production. The process is used primarily to cast round extrusion billets, rectangular rolling slabs, square wirebars and forging stock and special shapes, such as T-ingot. In line with larger output requirements, there is now a trend to larger semi-continuous casting machines of heavy-duty design, offering a greater number of multiple cast strands, longer cast lengths and larger cast cross-sections. Demand for castings to be made at highest production rate, with uniform quality and at lowest cost necessitates the maximum possible use of casting system automation, particularly in the areas of controlling metal temperature, metal flow, cooling water temperature, cooling water flow, casting speed and cast length.

Introduction

During the last 35 years the casting of aluminum alloy billets and slabs has undergone a fundamental change from the general use of static iron molds to the almost universal application of the vertical semi-continuous D.C. (direct-chill) casting process. Thus, today, the D.C. casting machine is truly the "work horse" of the modern cast house, capable of producing the full range of aluminum alloys - from the soft EC grade to the strong 7075 grade - for all applications and in a great variety of shapes, including extrusion billets, rolling slabs, wirebars, forging stock and T-ingots. The size of the equipment varies greatly, from small 2000 lb. drop machines used for scrap remelt by custom extruders to 100,000 lb. drop machines found in large smelters and fabricating plants.

The D.C. casting process has found such complete acceptance in the aluminum industry since it offers a highly reliable and economical production method, involving low capital investment, simple operating features, low manpower requirement and great product flexibility. It turns out an ingot ideally suited for extrusion, rolling or forging operations, with such major properties as (a) uniform chemical composition; (b) fine grain structure; (c) high metal density; (d) freedom from porosity; (e) absence of non-metallic inclusions; and (f) clean and smooth surface.

Historical Background

The beginning of the D.C. semi-continuous casting process for light metals and alloys goes back to the thirties, with the fundamental development work of Ennor at Alcoa in Massena, New York, resulting in his basic U.S. Patent 2,301,027 issued in 1942. By coincidence, the quite similar semi-continuous "Wasserguss" or water-casting process was developed independently at virtually the same time by the Vereinigte Leichtmetall-Werke (VLW) in Germany.

The large demand for defense products made of light alloys during World War II and the obvious advantages of the new process greatly helped to bring about a rapid changeover from casting in conventional static molds to D.C. casting, both in North America and in Europe. This trend has continued, and today virtually all aluminum alloy billets and slabs are produced by the D.C. process.

Process Features

While there have been many detail improvements and engineering refinements, the basic D.C. casting process still follows the Ennor concept. The casting machine is normally placed within a deep floor excavation, with either a steel tank or concrete pit providing a water reservoir (Fig. 1).* In the United States, fuel-fired furnaces are generally used for both melting and holding purposes, while in Europe there is a preference for electric induction melting and resist-

* References are slides to be displayed during presentation.

ance holding furnace equipment. Metal flows from the holding furnace along an open launder through a fiberglass filter into the distributor and then into the open-ended, short, thin-walled, water-cooled mold, made of aluminum or copper. To obtain quiet, non-turbulent "under-pouring", the metal is fed into the mold through a downspout tube immersed below the liquid metal level within the mold. To control metal flow and maintain constant metal level in the mold, an automatic float or gate device is employed.

Before starting the casting process, a stool or bottom block, carried by the platen fixed to the hydraulic cylinder, is raised into the mold. When the metal flowing into the mold has reached the proper level, the cylinder begins its downward travel. The rate of flow of the molten metal and the descent of the cylinder ram are matched, to maintain constant metal level in the mold.

Most semi-continuous D.C. casting systems employ three cooling devices: (1) The PRIMARY water jacket or water sprays surrounding the actual mold sleeve; (2) the SECONDARY water spray system designed to impinge on to the casting below the mold; (3) the TERTIARY water tank or pit with adjustable water level, located below the water spray area.

The water flow control system of the casting machine allows the cooling water flow to be channeled to these three respective areas in accordance with the characteristics of the particular alloy being cast.

Unlike continuous steel casting practice, which involves a deep liquid pipe, the non-ferrous billet or slab is generally cast under such cooling conditions that full solidification of the cross-section is obtained within a short distance of the mold. In the direct-chill casting of aluminum alloys the short molds used and the intense water sprays on to the casting result in a very pronounced longitudinal solidification.

While this method results in a desirable shallow liquid metal pool, with minimum inverse segregation, its very drastic cooling unfortunately can lead to the formation of large internal stresses, which may cause cracking in the sensitive strong alloys. In such cases, it is important to lower the casting speed or to delay the impingement of the sprays, so that the casting is solidified over the whole of its cross-section by the time the direct cooling zone is reached.

When the cylinder ram has reached its lowest position, pouring is stopped, the mold carriage is removed and the castings are lifted out of the pit or tank. After raising the platen, the casting process can begin again.

Instrumentation and Controls

To obtain highly automated operation of a D.C. casting installation and the greatest possible quality of cast product, today's advanced semi-continuous casting system should be designed to control the following parameters (Fig. 2): (a) casting speed; (b) cast length; (c) cooling water conditions; (d) metal temperature; (e) metal flow; and (f) mold lubrication.

Casting Speed

Casting speed is set within the usual 1 to 12 in./min. range by means of a pressure and temperature compensated flow control valve. It offers stepless adjustment and maintains a given setting within ± 1/2% accuracy. Adjustment of the valve on the control pulpit is either manually or by a rotary actuator on the valve equipped with a remote push button control and readout instrument.

Casting speed is indicated by a special liquid flowmeter working in conjunction with a solid-state signal generator and indicator system. As the hydraulic fluid is displaced by the piston during the casting stroke of the hydraulic cylinder, it is fed through the flowmeter and actuates the signal generator. The signal is directly proportional to the rate of fluid displacement in the cylinder, so that the indicating meter can be calibrated to read casting speed directly in inches per minute.

Cast Length

A reliable casting operation requires an accurate indication of cast length at any stage of the cycle. Furthermore, a machine can be stopped automatically once the pre-set cast length has been reached.

Early machines used a mechanical length measuring system, based on a cable connected to the moving platen and a gear-driven clock on the pulpit indicating cast length. Due to lack of accuracy and maintenance problems this system has now been replaced by the same flowmeter signal generator system described under "Casting Speed" above. In this case, however, amount of hydraulic fluid displaced by the main cylinder is equated to ram travel, which is indicated in inches on the pulpit. The readout device is either a circular clock dial instrument or a four-digit counter panel having a range from 0 to 999.9 in.

Cooling Water

The maximum flow of cooling water through the casting machine is determined by the heat extraction in B.T.U. required to solidify and cool the maximum volume of metal to be produced on the equipment. On large casting installations, water flow rates as high as 2000 g.p.m. are required.

To maintain constant casting conditions in the mold area, three parameters must be closely indicated and controlled: (1) water temperature; (2) water flow; and (3) water pressure. The normal cooling water circuit comprises a circulating sump pump, equipped with automatic water level control, mounted in the casting pit. The pump feeds the pit water back into the machine circuit, to the mold area.

Water temperature entering the molds is adjustable within a range of 60 to 80°F and is controlled at any given temperature within ± 3°F tolerance. This control is obtained by automatic blending of the warm pit water with cold makeup water in a three-way butterfly valve under thermostat control. Excess water in the system is discharged to an overflow sump.

Water flow requirements to the molds may vary over a wide range, from 100% to 10% of maximum flow capacity. Flow is controlled within an accuracy range of ± 3% by a power-operated valve.

Water pressure is normally based on 50 p.s.i. in the cooling water supply line. It is dropped by passage through a pressure-reducing valve to obtain a mold water pressure in the vicinity of 20 to 30 p.s.i.

Metal Temperature

In general, it is desirable to cast at the lowest possible metal temperature, without causing freeze-up in the distributor system. For control purposes, a chromel-alumel thermocouple assembly is inserted in the launder connecting the holding furnace with the casting machine distributor.

A temperature recorder-indicator instrument is mounted in the casting machine control pulpit providing the operator with an indication of metal pouring temperature. Based on the known temperature drop between the holding furnace bath and the mold, the holding furnace burner system can then be controlled to obtain a maximum temperature variation of ± 15°F for the metal entering the molds.

Metal Flow

In a modern casting system, the operator's control of metal flow into the molds by manual manipulation of stopper rods or plugs is impractical. Similarly, a free-falling stream of metal into the molds is unsatisfactory. Instead, most current D.C. casting machines employ a fully automatic, self-regulating metal flow control system feeding liquid metal into the molds in a turbulence-free manner through under-pouring downspout tubes.

The liquid metal level in the casting machine distributor trough is kept constant through proper furnace flow control, either by automatic tilting or tap-out hole adjustment. The individual downspout tubes extending from the distributor into the molds are supplied with an orifice matching the desired metal flow rate to correspond to the casting speed selected for a given ingot. A float rests on the liquid metal surface within each mold, directly below the downspout tube. The float moves up and down with slight variations of metal level in the mold, thus adjusting metal flowing from the orifice of the downspout tube. The control system is so responsive that any variations in mold metal level are virtually not noticeable to the naked eye.

Mold Lubrication

To obtain proper ingot quality, it is most important to apply a thin film of rape seed or castor oil lubricant to the metal/mold wall interface. With the relatively shorter casting lengths in the past it was normal practice to apply the lubricant to the mold manually.

In more sophisticated recent casting machines of great stroke lengths mold lubrication has been automated. A supply of lubricant is maintained in a tank and is fed through a tube manifold to the individual molds of the casting machine. Application points are spaced along the mold perimeter, each bringing the lubricant through the mold liner to a wick inserted between the mold liner top and a hold-down plate. The wick is positioned about 1 in. above the metal level in the mold and causes the lubricant to drain down along the mold wall.

Equipment Growth

Current requirements for large cast sections and high output capacity have led to the installation of extremely large, heavy-duty semi-continuous casting machines. The operation of several extrusion presses in the United States of 14,000 tons capacity calls for billet diameters of up to 32 in. New rolling mills are coming on stream with unprecedented slab width and thickness capacities. In this respect, it is of interest to note that typical cast slab weights have tripled every ten years - from about 1 ton in 1940 to the 30 ton weight of a 25 in. x 80 in. x 25 ft. slab in 1970 (Fig. 3)!

A representative 100,000 lb. per drop, 300 in. cast length machine averages six drops per 24-hour day, or 25,000 lb. per hour output. Such large casting equipment is built to extremely rugged, heavy mill-type standards. The platen is 11 ft. wide, 14 ft. long and 7 ft. deep. The hydraulic cylinder is a 12 in. double-acting unit built to operate at a working pressure of 1500 p.s.i. Platen travel is guided by teflon-lined shoes contacting two heavy rectangular columns, comprising stainless steel ways on three faces. The columns are attached to steel structures embedded within the pit walls. Water lubrication is applied to the teflon/stainless steel contact area.

Casting speed ranges from 1 to 12 in./min. and lifting speed from 15 to 120 in./min. The hydraulic system is powered by a 40 h.p. drive. The machine requires a water supply of 2000 g.p.m.

The mold table is of the tilting rather than the sliding type, offering the advantages of compact machine layout, improved alignment between molds and bottom blocks, and permanently connected water feed to the mold table through the pivot shaft.

Equipment Range

The wide range of D.C. casting equipment available today is illustrated by the following four examples:

A) A scrap remelt operation at a custom extruder's plant, the Kawneer Company, Niles, Michigan (Fig. 4). The tank-type machine is designed to cast 8 logs of 7 in. diameter x 139 in. length, equivalent to a cast weight of 4000 lb. per drop.

B) A considerably larger billet casting operation at the extrusion plant of a window and door manufacturer, the Lupton Manufacturing Company, City of Industry, California (Fig. 5). This tank-type machine is designed to cast 24 logs of 6-1/8 in. diameter x 226 in. length, equivalent to a cast weight of 16,000 lb. per drop.

C) A medium-sized slab casting operation at the aluminum sheet rolling mill of the Howmet Corporation, Lancaster, Pennsylvania (Fig. 6). The pit-type machine is designed to cast 3 strands of 16 in. x 51 in. x 144 in. length slab, equivalent to a cast weight of 36,000 lb. per drop.

D) A large-sized slab casting operation at the rolling mill of the Alcan Aluminum Corporation, Oswego, New York (Fig. 7). This pit-type machine is designed to cast 5, 7 or 9 slabs at a time, of 18 in. thickness, 86 in. maximum width and 200 in. maximum length, equivalent to a cast weight per drop ranging from 75,000 lb. to 100,000 lb.

Fully Continuous Casting

While today virtually all vertical D.C. casting installations operate on the semi-continuous principle, there was an initial period when certain plants showed a preference for fully continuous billet and slab casting machines, equipped with pinch rolls to advance the solidified castings and with flying saws for cut-off purposes. Classic examples of this approach were the Junghans machines at the Wieland-Werke in Germany and the Rossi machines at the Extruded Metals Corporation, Grand Rapids, Michigan, and at James Booth and I.C.I. in Great Britain. Another fully continuous machine, capable of casting three strands of 9 in. diameter billet and slabs up to 10 in. x 42 in. size, was installed by Alcoa at Massena, New York, in 1949 (Fig. 8).

The semi-continuous casting system is now the preferred method in the aluminum industry since the installations are simple in operation, less expensive, more flexible in setup and can handle a far greater output tonnage, based on large number of strands being cast simultaneously. In the case of strong aluminum alloys such as 7075 and 2024, it may even be impossible to saw the billet or slab "on the fly" immediately after solidification, due to the high internal stresses set up within the cast section. To avoid splitting, such castings have to be stress relieved prior to the sawing operation.

Horizontal Casting

The concept of horizontal D.C. casting originated at the Ugine Company's Venthon plant in Albertville, France, and has found application in producing both round billets and rectangular slabs. Such installations have been made both fully continuous, with flying saw cut-off, and semi-continuous, with long runout tables. The horizontal casting approach has the obvious advantage of greatly reduced installation cost, since there is no need to build a pit-type foundation for the machine.

In the United States, the Reynolds Metals Company has developed an interesting horizontal continuous casting process, covered by U.S. Patent 3,076,241. It employs a graphite rather than a metal mold and was used originally to produce EC grade bus bar in 2-1/4 in. x 12 in. and 2 in. x 10 in. section. Several horizontal machines are now casting 6000 series aluminum alloy extrusion billet at the Patterson plant of Reynolds in Arkadelphia, Arkansas, producing up to 8 in. diameter x 90 ft. long logs on an 8-strand setup (Fig. 9). Certain quality problems have been encountered with larger billets and harder alloys, which are therefore still better cast on vertical machines.

Hollow Billet Casting

An interesting development is the use of the D.C. casting process in the production of hollow billets and similar cored shapes. This is of particular importance to extruders and forgers who can eliminate the complicated and costly billet drilling and boring operations formerly required.

A tapered, internally water-cooled mandrel, about as long as the mold itself, is used in conjunction with an annular bottom block (Fig. 10). A closely machined spider mounting assures maintaining very tight concentricity tolerances. The water flowing through the mandrel exits at the bottom through spray slots, to cool the inside surface of the billet.

Tandem Casting

Extremely high output can be obtained from a large melting facility by using the tandem system of casting. In a tandem installation, two standard semi-continuous casting machines are arranged so that they may alternately be supplied with liquid metal from one and the same holding furnace. The launder is fixed to a swivel joint at its furnace end, to allow its front end to be swung from one to the other casting machine (Fig. 11).

During the casting operation, the liquid metal is fed to the molds of the first casting machine. Once the castings have reached their full length, the metal flow is switched from the first to the second casting machine in a matter of seconds, and casting is continued on the second machine. In the meantime, the cast logs are removed from the first machine, and it is prepared for the next cast. Thus, virtually uninterrupted continuous casting is obtained from two semi-continuous machines.

T-Ingot Casting

The growing use of T-ingot instead of pig ingot in the aluminum industry has led to a need to cast such shapes at reduction plants on D.C. equipment. An interesting development in this field is the short-stroke D.C. casting machine designed to produce a large number of strands of T-ingot in lengths up to 60 in. A typical 34 in. x 12 in. T-ingot size has a 2000 lb. weight in 60 in. length. It is thus possible to cast the required 2000 lb. T-ingots on a multi-strand basis in a form ready to ship after casting, without requiring the use of an expensive slab saw normally needed to subdivide the much longer logs cast on standard D.C. machines.

A short-stroke T-ingot casting machine recently went into operation at the Eastalco Aluminum Company, Frederick, Maryland, producing 60 in. long ingots on an 8-strand basis (Fig. 12).

Automated Handling

An interesting labor-saving development in semi-continuous casting installations is the introduction of automated handling devices to facilitate the transfer of billets and slabs out of the casting machine pit into the storage conveyor of the sub-dividing saw, without the use of an overhead crane.

Such a system was recently applied to a new 16-strand billet casting installation at the Wieland-Werke in West Germany (Fig. 13). During the casting operation, the billets are lowered vertically by the machine cylinder. At the end of the casting cycle their bottom ends rest on the bottom blocks of the casting machine and their top ends have cleared the bottom of the mold system water box. At this point, a push-off device advances and causes the billets to be severed from the bottom blocks and to be gently transferred into a slightly inclined position within the removal cradle. Subsequently, the upward travel of the casting machine cylinder causes the removal cradle to travel in a path determined by a linkage system, resulting in the tilting of the billets from the vertical to the horizontal. As soon as the removal cradle reaches the horizontal position, the billets are automatically transferred sideways onto a storage table ahead of the sub-dividing saw, which cuts the logs into extrusion lengths. The removal cradle is thus cleared, and the casting machine is again ready to commence its next casting cycle.

Grain Refining

The addition of master alloys to molten aluminum for grain refining purposes is now accepted practice in D.C. casting operations. An important innovation in this area is the development by Kawecki Berylco Industries, New York, of the required aluminum-base master alloys in extruded wire rod form. This wire configuration facilitates the "continuous innoculation" of aluminum alloys, thus automating this phase of the casting operation (Fig. 14).

In their traditional slab form, master alloys previously were introduced into the holding furnace prior to casting. In the new wire form, they can be introduced after the holding furnace, into the metal launder or distributor, thus assuring greater effectiveness of the master alloy and better quality in the cast product.

The wire form makes automated operation possible by permitting a link-up of the feeding mechanism with automatic monitoring of the flow and alloy content of the metal. The wire configuration has the additional advantage of being more easily added to the hot metal just before it enters the casting molds, thus assuring optimum mixing.

The wire-type master alloys are now available in 3/8 in. diameter size in 500 lb. coils. The most effective aluminum-base master alloy for grain refining is a 5% titanium, 1% boron grade. Other grades include 5% titanium, 0.6% boron; 5% titanium, 0.1% boron; and 6% titanium.

Summary

As the market for fabricated aluminum goods has grown, the size of production units has increased aiming to gain productivity through the economies of scale.

The most obvious benefit of scale-up is lower labor cost. It takes no more people to operate a big casting machine than it takes to run a smaller unit. But industrial scale-up is not simply a matter of increasing the size of equipment. A larger casting installation tends to justify a higher degree of labor-saving automation that would be difficult to amortize on smaller machines.

Thus, future D.C. casting facilities in the aluminum industry are likely to be of increasing size and utilizing maximum possible application of automatic process controls and mechanized handling systems.