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Cause and Prevention of Explosions Involving Hot-Top Casting of Aluminum Extrusion Ingot

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Abstract

Production of aluminum alloy process ingot for extrusion and forging applications is commonly performed by means of a hot-top casting technology. Explosions involving hot-top casting operations are preventable. This paper identifies the hazards of hot-top casting. The impact of equipment design, process control and quality of workmanship are examined in the context of preventing explosions.

Introduction

Semi-continuous vertical DC (direct chill) casting technology for the production of Aluminum process ingot has been in commercial use for over half a century. The genesis of DC casting involved open molds with metal being transferred through a down-spout from a launder positioned above the mold. This has sometimes been referred to as open-mold casting because the mold top is at all times visible to the observer (see Figure 1). This type of casting technology is still in wide use today, especially for the production of rolling slab or sheet ingot.

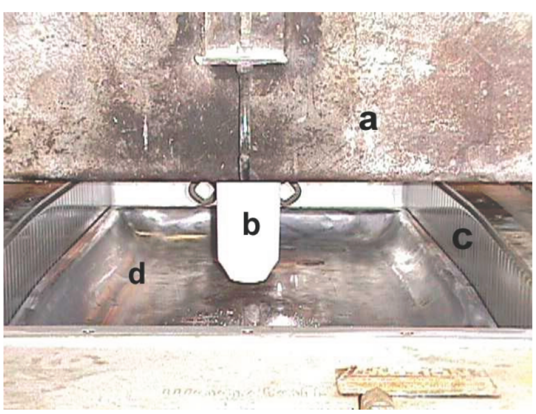

Figure 1 – DC open mold set-up: (a) launder, (b) down-spout, (c) mold wall, (d) bottom block.

Another form of DC casting technology, called "hot-top", developed in the 1960's, is so named because a molten metal reservoir (or hot top) is fastened directly to the top of the mold (see Figure 2). The hot-top is conjoined with the launder and constitutes the terminal of the launder system at each mold location (see Figure 3). Since the hot-top is attached directly to the top of the mold, no down-spout is needed. Hot-top is sometimes referred to as level-pour, because the metal level in the launder and the hot-top are one and the same. Hot-top mold technology has found its home principally in the production of round ingot (or billet) for extrusion and forging applications.

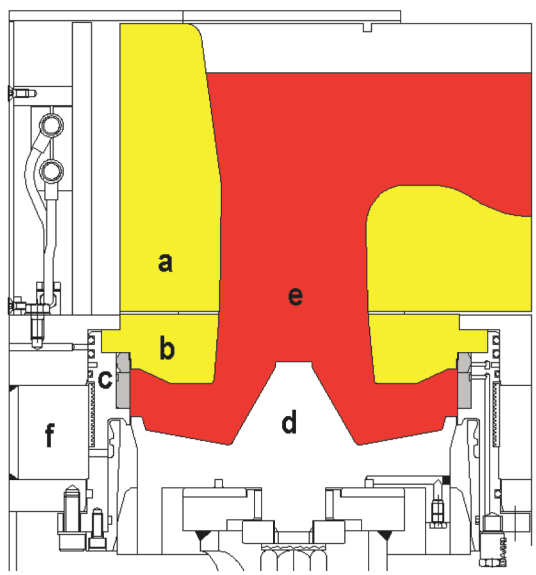

Figure 2 – Bottom-mounted hot top mold cross-section: (a/b) launder/hot-top, (c) mold wall, (d) stool-cap (bottom block), (e) molten metal, (f) water chamber.

The appeal of hot-top casting technology for making round ingot stock lies in several factors including product quality, operational ease, and safety. However, specifics of equipment design, process control and quality of workmanship can have a significant impact on how safe hot-top equipment really is to operate.

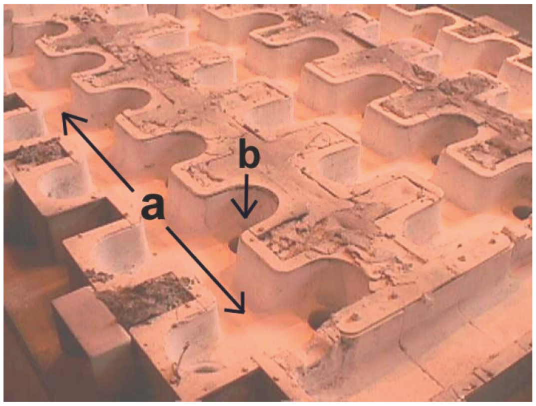

Figure 3 – Hot-top casting tabletop: (a) launder, (b) hot-top above mold (launder terminal).

The Hazard

Proportions of ingot size have lead some to the conclusion that the smaller dimensions of extrusion ingot are safer to cast than the larger dimensions of sheet ingot. This seeming advantage is offset by the fact that extrusion ingot casting systems usually contain many times more casting positions than can be accommodated for sheet ingot casting. Hence, the total volume of molten metal involved in a billet casting system may be as great as for a sheet ingot casting system.

Analysis of 1,544 incidents (or explosions) reported through the Aluminum Association's Molten Metal Incident Reporting Program for the years 1980 through 2000 shows that while DC casting accounts for only 15% of the most serious explosions (Force 3 type), DC casting accounts for 30% of the fatalities.[1] This stems from the proximate location of casting operators to the casting table during the highest risk phase of the process, namely, the start-up. Though we do not know from the reported data what percentage of these incidents involved hot-top casting, it is known that hot-top equipment was involved in a number of instances.

One case in 1983 resulted in the death of five persons and serious injury to five others when a hot-top casting station exploded. Molten metal was sent forty feet to the ceiling and showered around the cast house. Burning clothing ignited by molten metal caused severe burns to afflicted personnel. In 1997, seven persons were killed when a hot-top casting system exploded. The operator had failed to turn on the water prior to starting the drop. When the water was turned on, an explosion occurred.

Cause of Explosions

The most common cause of explosions in DC ingot casting processes is the entrapment of water by molten aluminum. This was the case with the 1983 incident cited above. When trapped by molten metal, water rapidly turns into steam and expands 1,000 fold. This change of state releases tremendous energy and physically throws the molten metal out and away. Because this energy release is so rapid, molten metal can be hurled at high velocity up to fifty feet from its source. The Aluminum Association has designated these type of explosions as either Force 1 or Force 2 depending on how far molten metal is dispersed.

Force 3 explosions are much more serious than Force 2 and involve a rapid chemical reaction between aluminum and oxygen. This releases terrific energy as aluminum oxide is formed. Per unit mass, aluminum packs three times the explosive force of TNT. Considerable effort has been expended to understand the cause of such explosions. Although a complete understanding has yet to be attained, it is significant that in DC casting processes, Force 3 explosions have occurred under similar conditions to Force 1 and 2 explosions, that is, entrapment of water by molten metal.

It has also been found that shock (or a pressure pulse) significantly increases the likelihood that a Force 3 explosion will occur. For additional details on aluminum explosions, please referred to Guidelines for Handling Molten Aluminum, Third Edition, published by the Aluminum Association.[2]

Efforts to prevent explosions in aluminum casting processes should have the dual focus of (1) reducing the risk for bleed-outs to occur and (2) eliminating the opportunity for water to become entrapped by molten metal. While the entrapment of water by molten metal constitutes a major hazard, the mere mixing of molten metal in water does not necessarily produce an explosion. As long as the evolving steam has an unrestrained escape path, no explosion occurs. Although this may be oversimplifying the problem, in the vast majority of cases, if water was not entrapped by molten metal, an explosion did not result. Exceptions to this rule are Al-Li alloys which react explosively when introduced in the molten state into water.

Problems Unique to Hot-Top

A summary of safety related concerns specific to hot-top casting systems are as follows:

- Hot-top molds are often shorter than conventional DC molds.
- Stool cap-to-mold engagement is often at a minimum (as little as 3-5 mm).
- Molds are not visible during casting.
- Limited visibility of stool caps (or starting blocks) prior to tapping furnace.
- Mold seals for water, metal, gas and oil are critical to successful operation.
- Water seals on bottom-mounted molds are especially critical from a safety standpoint.
- As-cast surface defects and bleed-outs may only be detected by looking underneath the casting table.
- Surface defects and bleed-outs may occur any time during casting.
- High-multiple casting systems may make it difficult to plug off some casting positions.
- Large numbers of molds makes it challenging to keep all molds in good working order.

Equipment Design

General design considerations for explosion prevention common to all DC casting systems include:

- All surfaces in the casting pit should be painted with a company approved organic coating.
- All stool bases (not stool caps) should be painted with a company approved organic coating.
- Stool bases should have an A-framed top or open lattice framework so that water and molten metal will shed freely into the casting pit in the event of a molten metal bleed-out.
- Minimum clearance between the stool base and pit wall of 75 mm (3 inches) should be maintained.
- A molten metal dispersion grid to break up and cool molten metal bleed-outs.
- Freestanding water depth in the pit should be 3 meters (10 feet) minimum at all times.
- No protruding shelves or other areas along pit walls where molten metal and water can collect.
- Shields to prevent water from splashing onto the floor.
- Fail-safe emergency cooling water system with at least five minutes of emergency water flow available.
- Fail-safe hydraulic controls that assure platen movement will continue even if electricity is lost.
- Accurate casting rate indication and control equipment.
- Accurate metal temperature monitoring and control equipment.
- Accurate water flow measurement and control equipment.
- A water supply or treatment program that assures freedom from scaling, corrosion, microbiological growth, undesirable chemicals, and oils.
- Self-cleaning filters and screens to ensure that the casting water supply is free from debris.
- Consistent water temperature monitoring and control.
- Easily accessible cast abort button.
- Emergency-down valve for manually lowering furnaces.
- Emergency start/stop valves for the casting cylinder.
- Emergency shut-off for casting pit water.
- Sufficient drain pan capacity for handling all molten metal in troughs and tabletops.
- Internally guided main casting cylinder to prevent guide shoes from binding up.
- Casting cylinder free from drift.
- Adequate pre-heating equipment for troughs and tabletops.

Design considerations specific to hot-top casting equipment include the following items:

- Properly engineered alignment systems that facilitate tooling set change-outs.
- Self-centering stool caps to ensure easy set-up and to avoid equipment damage.
- Steel stool caps to prevent early failure from thermo-mechanical fatigue (see Figure 4).

Figure 4 – Deformed center cone on stool cap made from aluminum.

- Grip or clinch on stool caps to assure ingot stability and to prevent hang-ups. On larger diameter ingots, molten metal can melt through the bottom of a hung ingot and trap water on the stool cap and cause an explosion (see Figure 5).

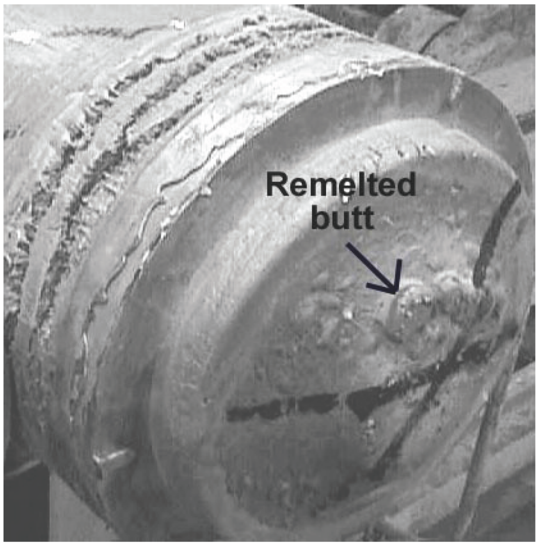

Figure 5 – Bottom of hung ingot with partially remelted butt.

- Water drains on stool caps, or easy inspection for water on stool caps.
- Absence of screws or welds on top of the stool cap - Fasteners and welds present potential hazards for trapping moisture.
- Stool caps designed so that water does not bounce on top of the stool caps before metal enters the molds – Water on stool caps have caused explosions.
- Primary and secondary water seals for bottom mounted molds – These seals keep water from entering the refractory hot-top. Secondary seals serve as a back-up in the event the primary seals are damaged.
- Refractory hot-top components that prevent metal leaking and sticking – This includes strategically located relief angles and absence of stress risers. It also includes material characteristics such as chemical inertness to aluminum, low shrinkage, good resistance to thermal shock, and good mechanical strength. Moldable refractory fillers ideally possess these same qualities.
- Mold design that ensures all process fluids are properly contained. This includes water seals, lubricant seals, gas seals, and molten metal seals.
- Mold design that minimizes chances of plugging up water passages. Broken water patterns can cause bleed-outs.
- Mold design that ensures adequate stool cap-to-mold engagement and a simple way to verify it.
- Robust mold design that requires minimal maintenance between casts.
- Casting table design that minimizes the risk of warping. Residual heat in the casting table refractory must be dissipated or the table may warp. This is especially dangerous when hot-top molds are very short and have limited stool cap engagement. A warped table can result in some stool caps being positioned below the mold, flooding with water and causing an explosion.

Process Control

Process control plays a vital role in preventing explosions in hot-top casting processes. For this reason it is imperative that the following items are in place:

- Qualified process engineering support - A wrong decision on how to adjust casting process parameters can have catastrophic consequences. For example, too slow a casting speed can cause severe cold-folding, moisture entrapment inside the mold cavity with a resulting explosion.
- Accurate control of metal temperature in all vessels prior to tapping furnace – Metal that is either too cold or too hot can create freeze-ups, hang-ups, or bleed-outs. Suggested temperature limits are +/- 5^o C (+/- 10^o F). Temperature displays should be verified against hand-held thermocouples regularly.
- Adequate pre-heating of all troughs and transfer systems - Insufficient pre-heating can lead to cold starts, hang-ups, and bleed-outs.
- Cooling water system with adequate cooling capability and water treatment.
- Automated filling of molds with metal at cast start - This removes the operator from the immediate vicinity of the casting table thereby reducing exposure to molten metal.
- Automated metal level detection and furnace tilt rate control – This ensures that the casting table will neither overflow or be starved for metal. If the metal level falls below the hot-top, water can get on top of the ingot head and cause an explosion if the metal flow is subsequently restored. Loss of metal level control should signal an abort.
- Simplified, optimized casting practices – Casting practices (or recipes) should be no more complex than necessary to produce a quality ingot safely. This is especially important if casting variables are manually controlled. Even casting recipes executed by a PLC should not

contain more complexity than needed. Unduly complex casting recipes can make troubleshooting more difficult.

- ❑ Automated control of all critical casting parameters: water flow, casting speed, casting gas, and casting lubricant – When these functions are executed by the PLC, the operator is free to observe the cast. For example, when casting with hot-top casting systems, especially gas cushion molds, it is important to observe underneath the casting table during the first several inches of the cast to make sure that all casting positions started out properly. Visual inspections under the table at approximately one meter intervals is highly recommended for early discovery of any developing problems.
- ❑ Automatic abort function under special circumstances such as loss of water, out of control casting speed, and out of control metal level – If the cast is out of control in these important elements, aborting the cast is the only safe course. In such cases, it should not be necessary to burden the operator with this decision. When these conditions have been properly defined and identified, the PLC is an able tool for executing such a function.
- ❑ Safety interlocks to prevent equipment damage and personnel injury – To design such controls properly requires competent process engineering support. Such interlocks might include (1) not being able to tilt the holding furnace before casting water has been turned on, (2) not being able to start the platen moving until metal dams have been raised and sufficient time has elapsed to permit filling of all molds with metal, (3) not being able to shut off the casting water or stop the casting cylinder while the cast is in automatic, etc.
- ❑ Anti-drift control for casting cylinder – Even relatively new hydraulic cylinders can have a small amount of drift. For this reason, after the casting equipment has been prepared for a new cast, the PLC should continuously monitor and correct the position of the casting cylinder as needed to ensure that the stool caps are at all times inside the molds. Otherwise water could get on top of the stool caps and explosions could occur as metal enters the mold cavities.

Quality of Workmanship

The following items pertain to quality of workmanship as it impacts safety in the production of hot-top extrusion ingot:

- ❑ Visual quality standards (pictures or samples of both good and defective product) – Operators must know the difference between acceptable and unacceptable product quality. Unacceptable as-cast surface quality is usually one step away from a serious defect or a possible bleed-out (see Figure 6). Knowing what to look for will keep operators more alert to problems as they develop, thereby enabling corrective action to be taken before a problem becomes serious or dangerous.

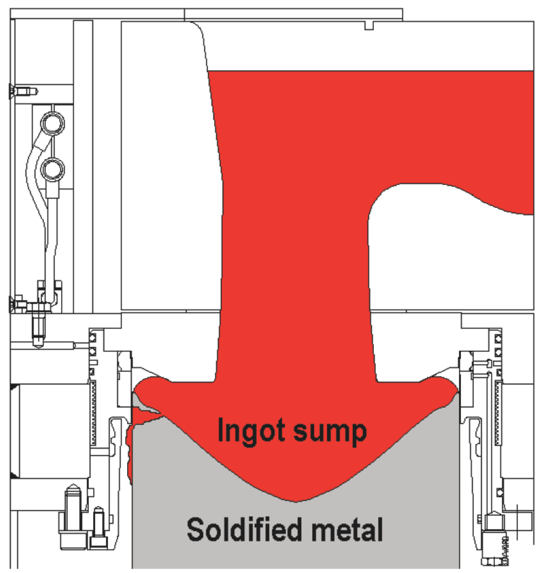

Figure 6 – Bleed-out: A tear in the newly formed ingot shell causes molten metal to spill from the ingot sump.

- ❑ Corrective action for scrap prevention – Corrective action when a small problem first appears can often prevent the generation of scrap or a safety problem from developing. For example, surface defects such as drags or zippers ordinarily start small and grow larger. If preventive action is taken early, scrap generation can be avoided and no safety problem will develop.
- ❑ Established work routines (operator checklists, maintenance logs, mold tagging procedures, etc.) - Some suggested routines and rules that impact safe operation of casting equipment include:
  - o Calibrate casting speed and water flow rate periodically.
  - o Inspect thermocouples regularly.

- Verify fixed temperature displays with portable hand-held thermocouples.
- Check and correct defective mold water patterns.
- Make sure stool-caps are centered over the molds (not all systems are self-centering).
- Confirm that self-centering stool caps move freely.
- Verify stool caps are engaged into the molds at all four corners of the casting table.
- Verify refractory hot-top components are in good repair.
- Make very certain that joints between refractory hot-tops and molds are in good repair. Failure of such joints can result in ingot hang-ups and bleed-outs.
- Make sure mold seals are in good repair. Failure of gas seals and molten metal seals in some types of gas cushion casting systems can cause extreme surface defects and bleed-outs (see Figure 7).

Figure 7 – Surface defect: Tears and bleed-outs.

- Make sure casting lubricant and gas systems are calibrated and functioning properly.
- Repair or replace damaged molds and stool-caps. Replace cracked stool-caps. Do not weld on stool caps or molds.
- Blow moisture off stool caps; oil lightly.
- Verify that metal temperatures are correct.
- Verify correct casting practice is loaded into the PLC.
- Make sure casting water is on before tapping furnace.
- Check for water on stool caps before tapping furnace.
- Wear personal protective equipment properly and in good repair.
- Stand behind protective shielding when filling molds with metal and during the start of the cast.
- Check underneath the casting table at start of cast for hang-ups and bleed-outs. NEVER attempt to free an ingot that has hung up! An explosion may occur.
- Plug bleed-outs and hang-ups immediately or abort the drop.
- Once inserted, NEVER remove a metal plug-off dam (or cone) until the cast has ended. Disrupting the flow of metal to the mold will cause water to enter the mold cavity. If metal enters the mold after this happens, an explosion can happen.
- Do not stand or walk on top of the casting table while casting is in progress.
- Do not leave the casting area unattended during the cast.
- Be alert to possible problems.
- Periodically look underneath the casting table for defects and bleed-outs.
- Observe problems with individual casting positions. Take corrective action before scrap is generated.
- Between casts, perform in-pit maintenance as prescribed.
- Measure finished ingot length against indicated length. This can reveal problems with casting rate control equipment.

- ❑ Standards for equipment and tool replacement – Poor tools produce poor results with respect to quality and safety. For example, a brush with damaged or dried bristles cannot be reliably used to repair a molten metal seal inside a mold. Using such a tool increases the likelihood of a casting defect or bleed-out on subsequent casts.
- ❑ Personal protective equipment (PPE) - If it is not properly worn or if it is in poor repair, PPE will not afford the level of protection it is designed for.
- ❑ Housekeeping – Good housekeeping prevents injury from tripping and also creates a positive working climate for all. Good housekeeping stands as a seal of quality and safety. The converse of this is also true. Poor housekeeping reflects

poor attitudes towards quality and safety. Tools are hard to find and tripping hazards and spills present daily hazards, not just in emergencies.

- Maintenance – Neglected maintenance erodes employee confidence in safety and quality. Deferred maintenance is like deferred housekeeping. It affects attitudes and work habits. Prompt attention to maintenance, especially safety related maintenance, demonstrates to employees that management takes safety seriously.
- Training, involvement, empowerment - Properly trained employees not only perform the job correctly, but also understand why it is important to perform the job in a certain manner. Employee involvement in safety programs breeds ownership and commitment.[3]
- Established safety culture – Commitment and consistency on the part of management and supervisors towards matters of safety fosters a culture of safety in the workforce. If this commitment is lacking in the management ranks, a safety culture will not evolve.[4]
- Supervision and follow-up – Supervisors who consistently follow-up on safety related matters are key to solving quality of workmanship issues.
- Intolerance for offenders – Although most employees are interested in performing their work safely a rare employee may choose to not follow standard practices and thereby jeopardize himself and others. Such behavior must be dealt with swiftly and consistently.[5]
- Performance incentives for safety, quality and productivity – Incentives need not be costly. The key to effective incentives is sincere appreciation and recognition by management for a job well done. Everyone appreciates a sincere compliment, and it costs absolutely nothing.

Summary

Explosions involving hot-top casting equipment for producing round extrusion billet and forging stock typically involves the entrapment of water by molten metal. Such explosions can be devastating both with respect to human suffering and loss of property. By focusing on equipment design, process control and quality of workmanship, conditions leading to such explosions can be eliminated. To be achieved, this goal will require commitment and resources, but its attainment is worth the price.

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