CAUSE AND PREVENTION OF EXPLOSIONS INVOLVING DC CASTING OF ALUMINUM SHEET INGOT

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Abstract

The casting of aluminum alloy sheet ingot and T-bar presents the potential for some of the most volatile situations that can occur in DC (direct chill) and EMC (Electromagnetic) casting processes. Aluminum Association explosion incident data from over 300 explosions spanning a twenty-year period were reviewed and analyzed looking for common factors and repetitive reasons for explosions. Analysis of explosions occurring during the three stages of sheet ingot casting, 'start of cast', 'steady state' and 'end of cast', were examined and prioritized. Case studies illustrate the need for understanding both technical and non-technical factors contributing to explosions involving molten metal. This paper identifies the major causes of explosions involving DC casting of aluminum alloy sheet ingot and makes recommendations for how to prevent the recurrence of such events and minimize the risk of injury.

Introduction

Molten substances such as aluminum and alloys of aluminum for wrought ingot applications pose potential hazards for worker safety, especially if these hazards are not properly understood or if safe job practices are not strictly followed. Of greatest concern are the hazards that can result in metal and water explosions.

Educating the workforce has been an ongoing effort in the aluminum industry for many years. Through the Aluminum Association, the combined efforts of many companies has fostered a more consolidated approach to safety related research, molten metal incident reporting and information sharing. Through the Aluminum Association's incident (explosion) reporting program, valuable information has been gathered that has helped identify major areas of safety concern in aluminum cast shops. The three major areas are: (1) Melting furnaces, particularly involving scrap charging, (2) Casting, particularly the start-up phase of DC casting and (3) Metal Transfer. Safety guidelines for these three areas are generally addressed in The Aluminum Association publication: "Guidelines for Handling Molten Metal." (1)

DC casting may be divided into two major sectors: (1) open mold technologies, and (2) hot-top technologies. A paper discussing safety concerns involving hot-top technology was presented at TMS in 2003(2). The present paper focuses on the safety concerns of open mold technology, specifically sheet ingot casting and T-bar casting. Please note that references made to sheet ingot casting in this paper usually apply to T-bar casting as well. For reference, Figure 1 shows typical components of an open mold set-up for producing sheet ingot by the DC casting process.

Aluminum Association Data

The Aluminum Association has been collecting data on molten metal explosions for over 20 years. Companies submit reports on a volunteer basis, and all names are withheld to preserve confidentiality. In the period 1980 to 2002, a total of 1,877 reports were received. There were 614 reports pertaining to casting, of which 494 involved DC, HDC and EMC(3).

With the cooperation of the Aluminum Association, the authors were privileged to access the complete data base, including incident descriptions as written by submitters of the reports. Incident data also includes other information related to the explosion including a rating of the force of the explosion(4) (Force 1, Force 2 and Force 3), the number and extent of injuries, the amount of metal involved, the alloy, metal temperature, type of plant (Recycling, Reduction, Rolling or R&D) and month and year. This more complete information enabled us to determine that of the 494 DC/HDC/EMC incidents, 309 involved the production of sheet ingot, including EMC and T-bar (i.e. open mold technology).

From a health and safety perspective, the Aluminum Association data(2) indicates a significantly higher injury rate and number of injuries for all types of casting incidents compared to melting and transferring incidents. Figure 2 shows that between 1980 and 2002 there were 417 injuries reported in casting related incidents, including 17 fatalities. This highlights the importance of understanding the nature of the hazards associated with the casting process before proposing solutions.

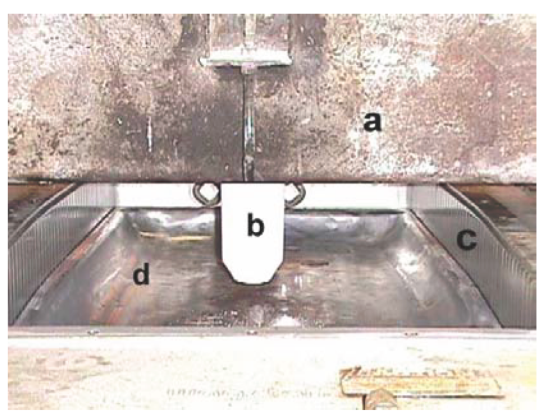


Figure 1. DC Open mold set-up: (a) launder, (b) down-spout, (c) mold wall, (d) bottom block

Analysis of the Data

Using the written descriptions of the incidents, root cause or primary and secondary causes were assigned for each incident. Based upon this incident analysis, the data was analyzed through various Pareto and statistical methods including mosaic plots, contingency tables and contingency analysis, which are shown in Figures 3 through 8.

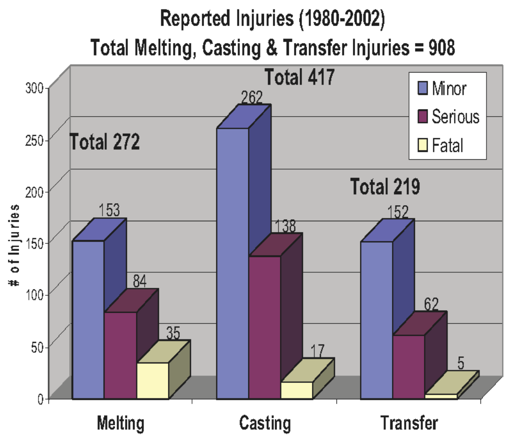


Figure 2. Injuries by Molten Metal Operation

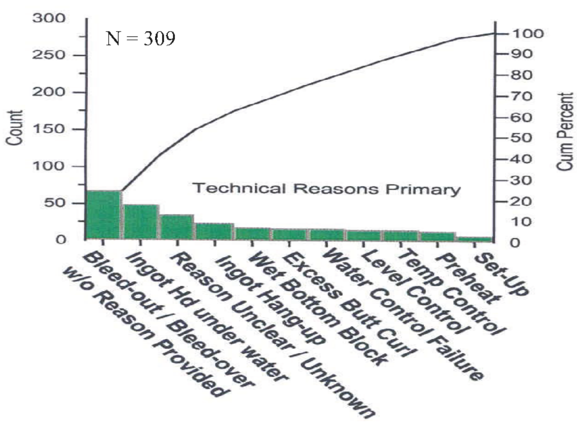


Figure 3. Reasons for Explosions – All Cast Stages

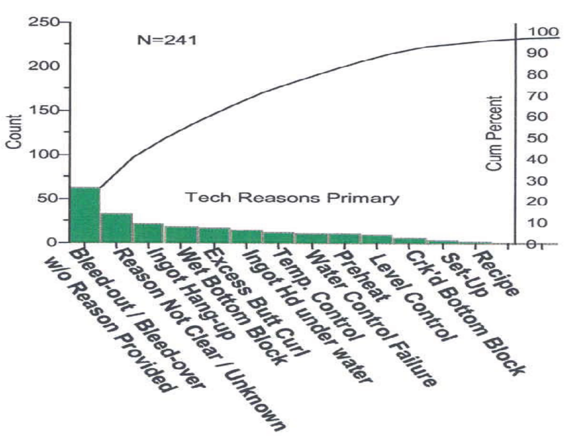


Figure 4. Reasons for Explosions – Cast Start-up

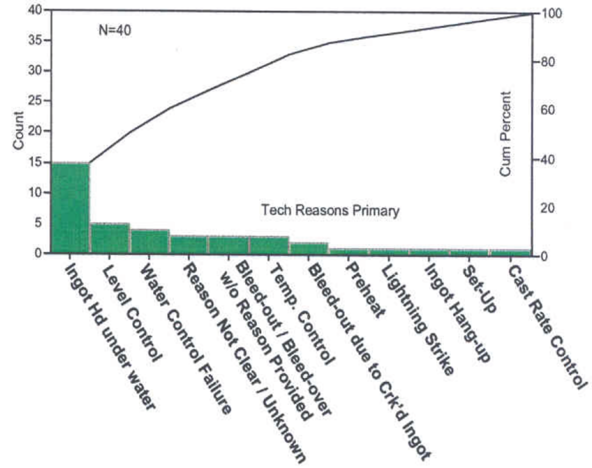


Figure 5. Reasons for Explosions – Steady-State

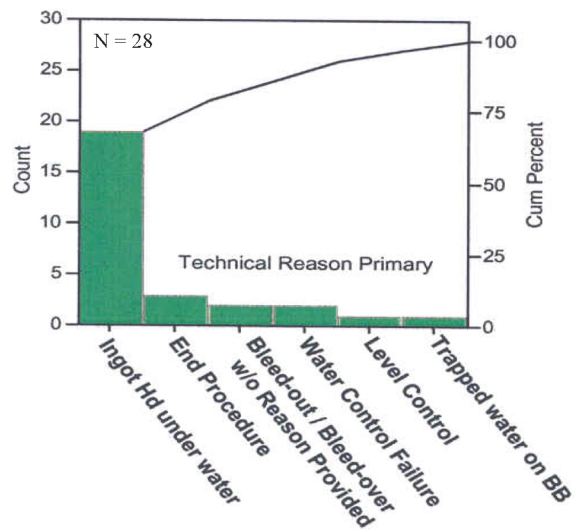


Figure 6. Reasons for Explosions – Termination

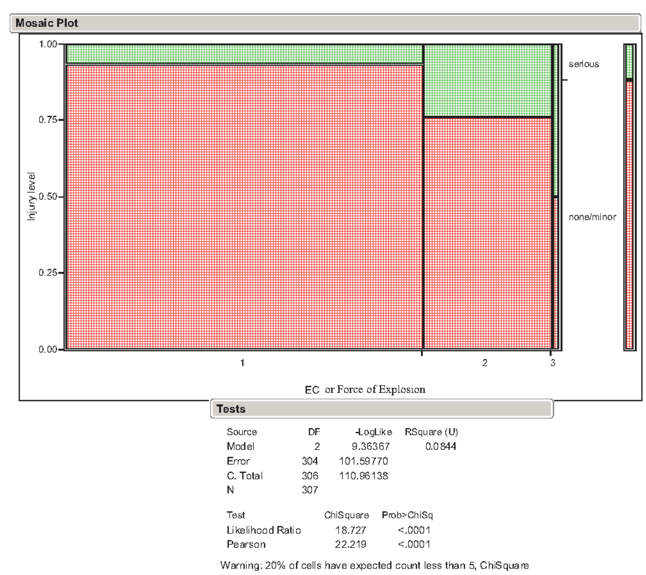
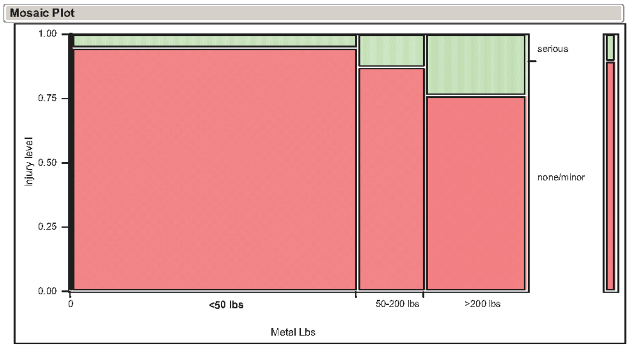


Figure 7. Injury Level vs. Force of Explosion



Tests

Source	DF	-LogLike	RSquare (U)
Model	3	5.788745	0.0823
Error	205	64.538869	
C. Total	208	70.327613	
N	209		

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	11.577	0.0090
Pearson	12.792	0.0051

Warning: 20% of cells have expected count less than 5, ChiSquare suspect

Figure 8. Injury Levels vs. Metal Lbs

From the analysis of these and other Pareto diagrams, mosaic plots and contingency tables, the following observations can be made:

1. Of the 309 incidents involving DC casting of sheet ingot and T-bar, 240 or 78% occurred during the start-up phase. The remaining 13% and 9% occurred during steady state and termination, respectively.

2. Of the 241 incidents occurring during the start-up phase, 60 were due to bleed-outs with no reason provided. An additional 22 had no defined reason at all. These 82 incidents resulted in 35 injuries, 10 of which were serious.

3. Ingots hanging up in the mold and excessive butt-curl accounted for an additional 54 incidents and caused 32 injuries including 7 serious and one fatality.

4. Equipment set-up, inadequate pre-heating, and wet bottom blocks were connected with 39 incidents during start-up and resulted in 33 injuries, 10 of which were serious.

5. Of the total 309 incidents, 72 could be considered to be related to equipment issues, but not strictly related to malfunctioning equipment. These accounted for 42 injuries including 14 serious. The major failures were evenly divided between temperature control, water control, and metal level control. It is noteworthy that several of the water control related incidents pertained to malfunctioning or improperly adjusted butt curl reduction technology.

6. The single largest reason reported for explosions during steady state and termination was running the molten ingot heads under the water. Total number of occurrences of this was 48, 15 of which occurred during steady state, and 19 of which occurred during cast termination. Twenty-three injuries resulted.

7. Out of the total 309 incidents, 105 were judged to have multiple or contributing causes. Three principal contributing (or secondary) causes ("trapped water on block", "ingot head under water", and "temperature control") accounted for 79% of these.

8. A single event, a lightning strike, accounted for 25 serious injuries and 4 fatalities.

9. For all three casting phases, a comparison of primary reasons for Force 1 vs. Force 2 explosions did not show a significant difference.

10. Figures 7 and 8 show that the potential for more serious injury increases with the force of the explosion (EC1, EC2 and EC3 is equivalent to Force 1, Force 2 and Force 3 in Figure 7) and the amount of metal involved with the explosion.

11. Comparison of the primary reasons for explosions through the twenty years of data indicate that there are now less explosions for level control and water control failures; however, ingot hang-up and ingot head under water continue to be prominent reasons for explosions.

12. It is important to note that no explosions were judged to be the result of inadequate protective coating of the casting pit or steelwork and only one steady-state incident was the result of low water level in the casting pit.

These observations suggest several areas that need attention if explosions and injuries are to be abated.

Safe Start-Up Guidelines

Safe casting is contingent on a successful start-up. With 78% of all incidents related to this part of the cast, it is critical that all essential elements are in place to make this happen. The following are general guidelines to assist with achieving a safe start-up; however, specific details and additional requirements will need to be determined by each casting location based upon their own equipment, alloys and sizes being cast.

- Equipment must be designed by professionals who understand the hazards of DC casting and are familiar with Aluminum Association guidelines for the same.
- Maintenance on casting equipment must be performed by qualified personnel.
- Casting pit water levels and protective coatings of the casting pit walls and metal support equipment such as bottom block bases and platen covers need to be properly maintained.
- Extreme care must be exercised when welding on molds or bottom blocks to ensure no cracks or pores remain that could trap moisture.
- Mold walls and bottom blocks should be free from cracks and gouges.
- Bottom blocks must be blow dried with compressed air and preferably oiled.
- Molds must be free from tow-in.
- Mold skirts must be coherent (no missing segments from bleed-outs or mechanical damage).
- Lubrication should be uniform around the mold bore through-out the length of the cast.
- Molds and bottom blocks must be bolted in place.
- Hoses for cooling water must be properly connected.

- Water patterns should be uniform. A standard bucket test should be deployed to verify variations in flow within a mold and from mold to mold. Normally, no more than 10% variation in flow can be tolerated for a successful start-up. More critical applications require 5% or less variation in flow.
- Butt curl reduction technology equipment must be properly calibrated.
- Molds and bottom blocks must be level and centered (properly aligned). This is crucial for preventing hang-ups and bleeding between the mold and bottom block.
- Bottom block temperatures should be consistent from cast to cast.
- Pins (flow control rods), spouts, and floats, must be properly preheated and positioned.
- Combo bags (channel bags) must be free from defects and properly positioned.
- Casting hydraulic cylinder must be free from drift.
- Chemical composition of the alloy to be cast must be within limits.
- Thermocouples must be calibrated and in good repair.
- The metal temperatures in the holding furnace and in-line metal treatment units as well as refractory temperatures need to be controlled with the intent of achieving consistent metal temperatures to the ingot head with minimal variation within a cast and from cast to cast.
- The correct casting recipe must be loaded into the casting PLC or computer.
- All dams must be in place.
- Drain tubs must be empty, free of trash and debris that could contain moisture, pre-heated and in the proper position.
- PPE (personal protective equipment) is worn by all personnel at or near the casting station.
- Emergency equipment (shower, E-stop, etc.) are in working condition.
- Personnel have a demonstrated knowledge of how to handle casting related emergencies.
- Water chemistry and temperature needs to be consistent from cast to cast.
- A back-up water supply system is available with a proper alarm and control system.

Quality Reporting

It was astounding to discover that a full third (82) of all reports dealing with the start-up phase lacked sufficient detail to determine a root cause. This may be due to any of the following:

- Root cause of the incident was not ascertained by the investigator or was unknown to the person submitting the report.
- Written descriptions are not subject to scrutiny or clarification.
- The incident reporting form does not require the submitter to determine a root cause.

Controlling Butt-Curl and Ingot Hang-Ups

Excessive butt-curl or rate of butt curl generally becomes a problem for large sheet ingot casting where ingot widths exceed 1.5 meters (59 inches) and when aspect ratios (width to thickness) exceed 3:1. In very wide ingots, it is necessary to establish and stabilize a steam film on the rolling faces of the ingots between 0 and 0.2 to 0.3 meters (8 to 12 inches) of cast length. This is most easily achieved by using butt-curl reduction technology.

Butt curl and ingot hang-up problems can occur when the butt curl technology is not controlled or working properly or when excessive cooling rates occur during the start-up phase of the cast. Most start-up phase butt-curl reduction technology targets to develop a steam film across the rolling face of the ingot and excessive butt curl occurs when this film boiling is not properly established or does not change to nucleate boiling at the proper rate. The consequence of this may be that the ingot hangs up in the mold or that the ends bleed over, thereby trapping water with molten metal on the bottom block. 53 of the 241 start-up incidents were attributed to excessive butt curl or ingot hang-ups. We suspect that this number would have been much higher if the previously discussed 82 incidents from undetermined causes had been better reported.

Additionally, 'trapped water on bottom block' was a secondary cause 41 of 87 times (39%) when secondary reasons were attributed to start-up incidents. It is also evident from observations in various cast houses that explosions do not result every time metal bleed-outs on to the bottom block from an ingot hang-up or excessive butt curl. In fact, an explosion occurring under these circumstances may be considered to occur at a low frequency; however, they can be serious to personnel and equipment when an explosion does result.

Some injuries associated with ingot hang-ups relate to personnel attempting to free an ingot. This is ineffective and dangerous. It is an established fact that impacts can trigger aluminum/water explosions. Sometimes the ingot butt will melt through and trap water on the bottom block, such as related in the following incident:

"At start of DC cast, metal hung up in mold. Operator pounded on mold with hammer, but metal melted thru ingot butt and contacted wet starting block. Explosion threw metal about 30'. No injury or damage."

The only safe course of action to take if an ingot hangs up in the mold is to abort the cast and leave the area. Eventually the ingot butt will cool sufficiently to drop out of the mold. It is not easy to predict when this will happen. No-one should be in the proximity of the ingot butt when it drops out of the mold.

The following conditions can lead to excessive butt curl:

- Too much cooling water at start-up.
- Malfunctioning butt-curl reduction technology.
- Metal level too low, or mold filling too slowly.
- Metal temperature out of range (too cold).
- Incorrect amount of bottom block fill and start-down at wrong time.
- Initial casting speed too slow.
- Hot metal not directed sufficiently to the ends of the ingot (problems with ingot head metal distribution).

Wet Equipment Hazards

Improper equipment set-up in several instances resulted in water getting onto the bottom block, as exemplified in this account:

"Within a minute after dough-ball pin was released and metal was flowing, crew heard hissing and saw molten metal and water swirling on bottom block. Crew started to run when explosion occurred; they were badly burned. Bottom block set too low in mold."

Improper set-up, inadequate blow drying and oiling of bottom blocks and inadequate pre-heating of equipment such as floats, spouts and pins accounts for 33 injuries and reflects a failure in one or more of the following areas:

- Personnel have not been sufficiently trained in the hazards of the workplace or in plant practices.
- Communication regarding equipment readiness has been lacking.
- Verification of equipment readiness by operators and supervisors has been lacking.
- Safe job practices (SJP) have not been in place or have not been enforced.

Steady-State and Termination

The major area of incidents during steady state and termination was running the ingot heads under water. This accounted for 15 out of 41 steady state incidents and 19 out of 28 termination incidents. It should be noted that there were also 14 of these incidents recorded during a start-up. Altogether, this area accounted for 48 of the 309 incidents, second only to "bleed-outs without reason provided."

Other causes such as "loss of level control", "loss of water control", and "loss of temperature control" constituted the other significant areas associated with steady-state incidents. Problems in these areas can occur anytime during casting.

The Hazard of Submerged Ingot Heads

Running ingot heads under water creates explosions because it can trap water underneath the molten metal crater or inside the shrinkage cavity. This occurs for a variety of reasons:

- Hydraulic cylinder drifted.
- Failure to stop platen descent at end of cast.
- Operator believed the ingot was completely solidified.
- Operator did not abort cast after plugging off one or more casting positions.
- Problems with metal level control equipment.
- Operator did not understand the hazards involved.

An incident showing the need to better educate personnel on this hazard follows:

"Operator decided to lower ingot heads to help solidification but hit fast down rather than slow down with cooling water still running. Two explosions occurred when ingots were below molds. Molten metal hit roof 30' away. No injury."

Of all the incidents related to DC casting, this is perhaps the easiest problem to remedy. If this is to be achieved, we must do a better job educating the work force about this significant hazard.

The Need for Training

As mentioned previously, we need to do a better job of educating the workforce about the hazards related to handling molten aluminum. Unsafe practices result when operators are either not trained adequately or are not properly supervised. The following example shows how a practice of continuing a cast resulted in an explosion:

"About 2 minutes after a drop of 5 ingots had started, ends of 2 ingots bled out. Operators plugged these 2 ingots and resumed casting at reduced speed. After 4-5 minutes, explosion occurred on top of an ingot. Metal splashed out and steam burned 2 operators."

It is equally important that each company ensures that supervisors and staff understand molten metal hazards as well. A significant number of reports reflected not only a lack of understanding of the true cause of molten aluminum explosions, but actually revealed that significant misunderstandings exist. Here is one example:

"Drop was terminated after 7" into cast due to control rod freezing in pouring spout. Explosion occurred in ingot sump; ingot butt had severe crack. Water got into crack and triggered explosion when it reached the ingot sump. Metal thrown 40'; no injuries."

It may be that the above report leaves out other relevant information. If the 'ingot butt crack' that is referenced is actually the 'shrinkage cavity', the description would be correct. Otherwise, the description sounds incorrect. Explosions in DC casting occur from water turning to steam and expanding 1,000 fold because of being trapped by molten metal. This includes Force 1 and 2 explosions as defined by the Aluminum Association. Force 3 explosions in DC casting also start as aluminum-water explosions which progress to a chemical reaction between aluminum and oxygen. We leave discussion of lithium containing alloys to others.

Conclusions and Recommendations

1. Equipment maintenance, set-up, and preparation are critical factors to safe cast execution.

2. Control of critical casting parameters including metal temperature, cooling water (including butt curl reduction technology), metal fill, and casting speed are all essential to avoid excessive butt curl, hang-ups, and bleed-outs.

3. Personnel need to be trained in the potential hazards that exist in DC sheet ingot casting. This need is illustrated by the high number of incidents caused from running ingot heads under the water.

4. The quality of information obtained from the data base can be no better than the quality of information going into it. Lack of detail in 1/3 of the incident reports reduced their potential value. A comprehensive review of the reporting format should be evaluated by industry experts to improve the quality of the information. Better reporting will enable

the industry to make more informed decisions for investing in safety related studies and programs for the future.

5. Although many of the incidents did not identify root causes or reasons for bleed-outs, it is noteworthy that explosions were not identified to be associated with lack of protective paints and only one was due to low water levels in the casting pit. It is possible that this can be the result of the extensive communication in the aluminum industry regarding the benefits of protective paints and maintaining sufficiently high casting pit water levels. This communication extends back to the 1950's and continued into the 1990's with testing of new protective paints.

6. Further research is needed to better understand the explosions that occur when there is trapped water on the bottom block for various reasons. If this was better understood there may methods developed to eliminate or minimize these explosions, as we have done by using coatings on casting pit walls and the exposed steel of bottom block bases.

7. Additional analysis should be performed of this Aluminum Association data involving casting explosion incidents to determine if other insights and direction can be provided to the aluminum casting industry. Additionally, it would be worthwhile to perform more detailed analysis of the explosion incidents involving melting, metal transfer and round ingot casting to increase our knowledge and methods to prevent explosions and reduce injuries in these areas as well.

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