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A Technical Perspective on Molten Aluminum Processing

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Abstract

In today's context of global competitiveness, all factors related to molten metal treatment which directly or indirectly affect product quality, the environment and processing costs must be optimized. In this regard, technology and innovation play a decisive role for the development and implementation of the most appropriate molten metal treatment processes and practices. The following discussion will review the most recent significant developments in the field of molten aluminum processing and outline potential areas for improvement.

Introduction

In order to meet the continually increasing product performance requirements of the world market place, molten metal quality is a major preoccupation of the cast house. In the context of this discussion, metal quality refers to the degree to which an aluminum alloy is free of the following contaminants: alkalis (sodium, calcium, and lithium), non-metallic inclusions, and dissolved hydrogen. Improvements in metal quality have been achieved with the development and implementation of molten metal treatment technologies during the last 20 years. Advances, particularly during the last decade, are significant and reflect an improved comprehension of the underlying principles governing molten metal treatment.

However, notwithstanding recent advances in metal quality, the cast house metallurgist still faces significant challenges. Metal processing and monitoring costs are significant – available resources must be used judiciously. Pressure to increase productivity and metal throughput are incessant, while at the same time, metal quality variation is unacceptable. Environment issues must be taken seriously and can limit the metal processing options that are available.

Recent progress made in the field of molten metal treatment technologies is summarized and future challenges are suggested.

Overview of Metal Processing Steps

Many different metal treatment technologies and practices are available to the cast house metallurgist. The successful implementation and use of these technologies is accomplished only when an appropriate balance is achieved between metal quality, productivity, cost and the environment. The general sequence of molten metal processing steps is shown in Figure 1 and consists of crucible pre-treatment upstream of the furnace, furnace processing, and in-line treatment – degassing and filtration. Additionally, the transfer of the liquid metal between each processing step must be given particular attention. It is generally recognized that as the liquid metal advances towards the ingot, metal treatment operations become increasingly "critical".

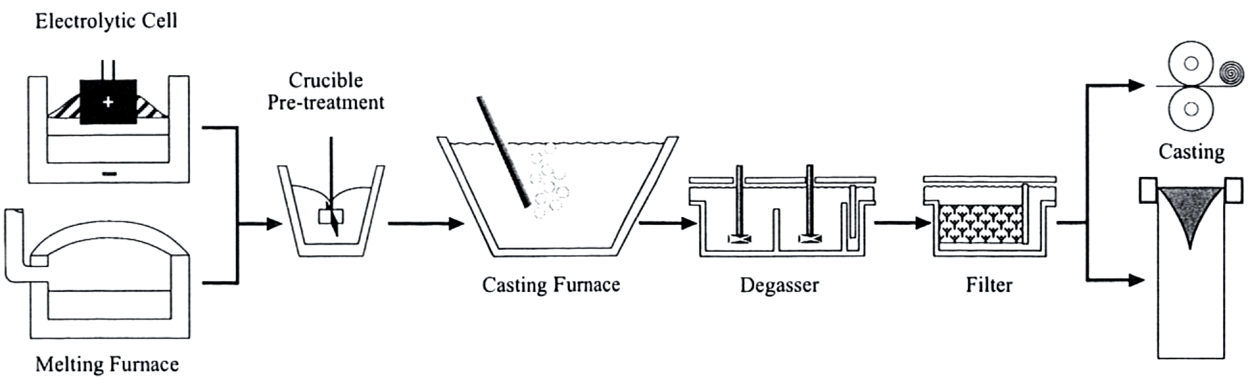

Figure 1: Sequence of Molten Metal Processing Steps.

In the past, process development and optimization efforts focused on individual metal treatment steps. Semi-empirical methods, requiring little knowledge of the underlying metal treatment mechanisms, were used to relate process changes to final product performance. This situation was complicated by the low impurity concentrations that had to be accurately measured and because the available metal quality measurement techniques, at the time, were costly and often laboratory-based - leading to limited acceptance or use by the industry.

Molten Metal Analysis and Control

Impurities

The types and sources of impurities present in liquid aluminum, as well as their detrimental effects on specific products, have been reviewed in detail elsewhere[1]. It is pertinent to note that the molten aluminum supplied to the cast house comes from two distinctly different sources: smelter electrolysis and remelt/recycle operations. The impurities present in the metal supplied from these sources are also different and can affect the metal treatment strategy that is used. Remelted metal is normally associated with higher levels of hydrogen, calcium, and hard oxide inclusions that are formed during high temperature scrap melting processes. On the other hand, smelter metal is associated with higher levels of sodium, aluminum carbide inclusions, as well as non-metallic inclusions generated from the addition of large quantities of alloying elements. Table I summarizes the impurity levels present in the metal supplied to the cast house.

Table I Typical Impurity Levels in Metal from Smelter and Remelt Sources

Characteristic	Smelter	Remelt
Composition	≥ 99.7% Al	Alloyed or close to final composition
Hydrogen	0.1 – 0.3 ppm	0.2 – 0.6 ppm
Alkali Na Ca Li	30 – 150 ppm 2 – 5 ppm 0 – 20 ppm	≤ 10 ppm 5 – 40 ppm < 1 ppm
Inclusions (PoDFA scale)	> 1 mm^2/kg Al_4C_3	$0.5 < mm^2/kg < 5.0$ Al_2O_3, MgO, $MgAl_2O_4$, Al_4C_3, TiB_2

Motivated by cost reduction or simply by a sometimes limited availability of good quality clean scrap metal, today's aluminum recycling plants must have increased flexibility to accept variable scrap quality, and as such, the molten metal treatment system must be increasingly robust to handle a higher and fluctuating impurity load. Similarly, present trends in aluminum smelter operation include efforts to improve current efficiency and to reduce environmental emissions. This has led to increasingly high sodium and/or lithium levels in the primary metal produced. Consequently, improved molten metal treatment performance in the cast house is necessary.

Control Technologies

Quantitative instrumental techniques capable of accurately measuring the extremely low concentrations of the various contaminants are presently used throughout the aluminum industry.

Inclusions – Metal Cleanliness Considered industry standards, the LiMCA and PoDFA metal cleanliness assessment techniques, developed by Alcan, have been previously described in detail[2, 3, 4]. Briefly, LiMCA is based on the resistive pulse principle and generates both an inclusion concentration value and a complete size distribution. PoDFA is based on the filtration of 1-2 kg of metal through a well-calibrated small filtration disk with subsequent metallographic examination of the inclusion concentrate. Information on inclusion species and sizes, as well as a semi-quantitative total inclusion level expressed in mm^2/kg are obtained. LiMCA and PoDFA are complementary technologies in as much as their respective quantitative and qualitative capabilities combine to give essential data required for an informed judgment of metal cleanliness.

However, significant challenges remain to be overcome. The LiMCA instrument is on-line, but complex to operate, and PoDFA analysis requires metallographic expertise/facilities and is thus off-line. An inherent weakness of the LiMCA technique is the inability to distinguish the physical state of the inclusion. Consequently, and unless a deep bed filter is used, reliable LiMCA measurements are difficult to obtain immediately downstream of an in-line degasser[5] due to the complex interactions between the gas/liquid/solid inclusions present. Exploratory development work on an alternative inclusion detection technology focuses on the use of ultra-sound[6]. It remains that a simple, low cost yet quantitatively accurate on-line metal cleanliness assessment tool is needed by the industry.

Hydrogen The AlSCAN™ technology[7, 8] is now in use throughout the industry and is recognized as the standard technique for on-line hydrogen analysis. Due to it's high precision, AlSCAN has made possible the quantification of different phenomena (such as ambient humidity) affecting hydrogen in molten aluminum.

Chemical Composition Optical emission spectroscopy has established itself as the reference analysis technique for the measurement of alloy chemical composition at the level of major constituents, as well as trace elements. A complex calibration and alloy matrix correction procedure is required for the different alloy families, and remains a technical obstacle to overcome.

Control Strategies

Measurement techniques capable of quantifying all aspects of metal quality have been in widespread use for roughly 10 years. With the specific objective of process development, focused campaigns in the cast house involving metal quality measurements, before and after the different stages of metal treatment, have permitted the identification of important process parameters. Combined with heightened efforts in metallurgical process modeling, an improved understanding of the underlying metallurgical principles has been achieved, allowing advances in the development and optimization of metal treatment technologies and practices.

The considerable measurement costs related to these process development activities were easily justified by the performance/quality improvements that were progressively obtained. However, at present, molten metal treatment technologies have reached a state of maturity that no longer requires such a high level of quality measurement support.

The most effective use of metal quality measurement resources is being re-examined. A strategy focusing on product quality control and process capability monitoring is presently emerging. Statistical process control techniques are being exploited to maximize the amount of information extracted from the data. The use of control charts and the establishment of process control limits enable the metallurgist to learn from the process in order to improve it. Finally, process benchmarking and data exchange between different divisions of a company facilitates the establishment of process "best practices". Figure 2 summarizes this metal analysis and control strategy.

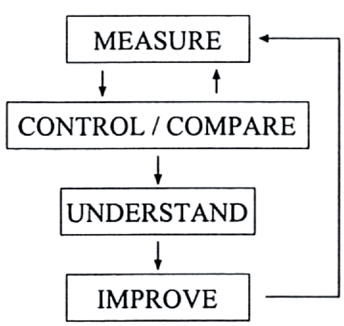

Figure 2: Metal Quality Measurement and Control Strategy.

Molten Metal Processing Technologies

Over the last 10 years, the need to produce higher quality products has encouraged nearly uninterrupted development efforts in the field of metal processing technologies. The clear benefits of these technologies with respect to quality, cost, productivity and the environment, has led to their widespread use throughout the aluminum industry.

To appreciate the overall molten metal processing performance that is now demanded in the cast house, Figure 3 summarizes the low impurity levels that must be achieved for various products. Compared to the incoming impurity levels (Table I), highly efficient impurity removal is required during metal processing.

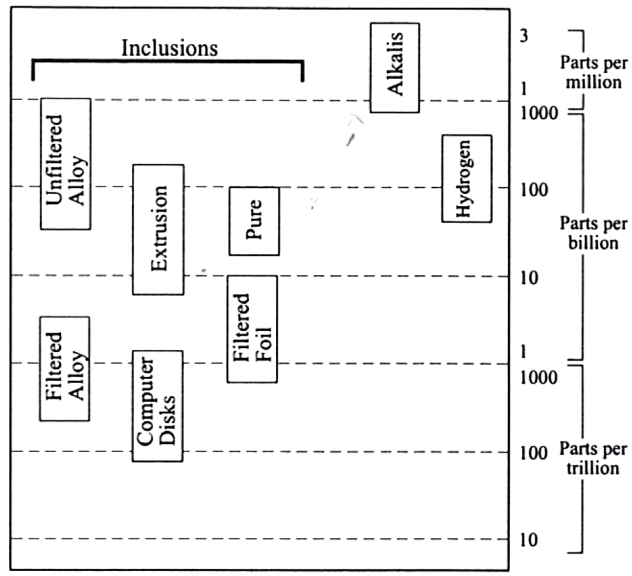

Figure 3: Typical Impurity Concentrations in Some Aluminum Products.

Crucible Pre-treatment

Several crucible-based treatment technologies[9, 10, 11] have been developed with the objective of removing alkalis and inclusions from the metal prior to transfer into the casting furnace. All these technologies are similar in as much as a reactive flux (either chlorine-based or salt-based) is injected into a well-stirred crucible of liquid aluminum. The present consensus favors the chlorine-free technology for both performance and environmental reasons.

Due to the crucible shape (surface/volume ratio), the metal depth and the intensity with which the metal is stirred, crucible pre-treatment is rapid, environmentally sound and significantly reduces the need for subsequent furnace fluxing.

In the past, crucible pre-treatment technology was applied almost exclusively to smelter applications. More recently, and as the performance of subsequent furnace treatment technologies have improved, the need for crucible pre-treatment has been re-questioned with respect to its costs versus its advantages. However, in the present context of increasing alkali impurity levels in primary smelter metal, and the need to accept potentially lower quality scrap in recycling operations, the beneficial impact of crucible pre-treatment can only become more significant for both smelter and recycle-based cast houses. Clearly, the challenge is to readily identify situations where the benefits of crucible pre-treatment can be best exploited. With more widespread use envisioned, molten metal management may also become an issue. Finally, extension of this concept to include alloy preparation has the proven potential[12] for further increasing the value of this metal processing step.

Furnace Treatment

The most common type of casting furnace in current use throughout the aluminum industry is the fossil fuel heated reverberatory design. The reverberatory furnace, containing a relatively shallow melt depth, with a high surface area to volume ratio, is optimized for heat transfer. This melt geometry, combined with the lack of bulk metal circulation, does not promote efficient metallurgical treatment. In addition, the vertical temperature gradient that is generally established through the melt can be greater than 200°C and is responsible for elevated dross formation and reduced heat transfer. These problems are magnified as furnace sizes constantly increase.

Conventional furnace fluxing with static lances is generally accepted as a rather inefficient way to treat molten aluminum, and depending on the metal quality requirement, excessively long treatment periods are necessary. This has a negative impact on both productivity and the environment.

In an effort to overcome reverberatory furnace design limitations, considerable effort has been invested by the aluminum industry to understand the fundamental metallurgical phenomena taking place[13, 14, 15, 16] and to apply this understanding to improve processing technology and practices. During the last decade, two methodologies have been pursued to overcome the inherent inefficiencies of furnace treatment: first, by directly improving the efficiency of furnace treatment itself, and secondly, by reducing the need for furnace treatment and exploiting the more efficient crucible pre-treatment and/or in-line treatment technologies.

Stirring In the past, stirring by lance gas injection was commonplace and suffered from limited effectiveness as well as increased dross generation. Today, advanced subsurface stirring technologies include: pneumatic jet stirring, electromagnetic approaches and rotary devices.

The metallurgical and operational advantages of forced metal circulation have been previously reported in detail[17] and include rapid homogenization of the alloy, reduction of the temperature gradient and the associated metal oxidation, increased uniformity and consistency of metal processing and improvements to furnace control in general. The use of bulk metal circulation systems has grown throughout the industry.

Fluxing Furnace "fluxing" refers to the removal and separation of impurities from liquid metal by direct reaction and dewetting based on the use of a chemically active agent. Until recently, the aluminum industry relied exclusively on the use of chlorine for fluxing.

The complex mechanisms of furnace fluxing with static lances and chlorine have been studied in detail[18] and its effects on metal cleanliness, alkali removal, as well as dross formation, have been quantified for a wide variety of alloys. In the past, limited improvements to lance fluxing were achieved simply by the use of more lances or by the introduction of porous plugs (with the associated operational difficulties).

Recent improvement to furnace treatment effectiveness has been achieved by "process intensification" aimed at increasing metal stirring and fluxing kinetics. Metallurgical modeling has confirmed[19] that the rate limiting step of the furnace fluxing process, assuming the presence of a minimum of bulk metal circulation, is the gas/liquid interfacial contact area generated by the gas purging system.

The rotary gas injection (RGI) furnace fluxing technology,[20, 21, 22] utilizing high shear gas dispersers, has been know for some time. This furnace fluxing technology, and others[23], markedly increases the interfacial contact area between the liquid metal and the fluxing agent. Recent adaptation of this technology by the aluminum industry has resulted in significant gains in the cast house. Increased impurity removal rates have reduced furnace cycle times and improved productivity. The absolute metal quality levels achieved have improved, lessening the load on subsequent in-line metal processing steps. Equally as important, significant reductions in chlorine consumption, made possible by the improved process efficiency, have had a direct and positive impact on atmospheric emissions.

Salt fluxes can be used effectively for the replacement of chlorine during furnace fluxing[24]. Rotary flux injection technologies have also provided the opportunity to replace chlorine with a salt-based flux[25, 26] while reducing environmental emissions and maintaining metallurgical treatment performances comparable to chlorine. Figure 4 shows the impact of these advances on the overall chlorine consumption of a cast house.

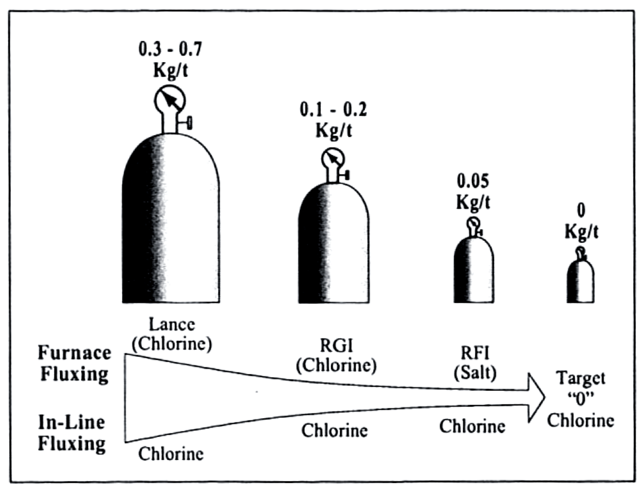

Figure 4: Progressive Reduction of Chlorine Consumption in the Cast House.

However, there remain important challenges to overcome with respect to furnace treatment. The casting furnace is not an efficient chemical reactor. Although present design limitations have been partially overcome by the introduction of improved fluxing technologies, furnace fluxing cannot provide metal that meets the cleanliness requirements of critical products.

Subsequent in-line metal processing is still necessary. There is a general need to reduce metal surface turbulence in the furnace that leads to dross formation and metal loss. The majority of dross is generated during metal transfer into the furnace, with the remaining dross generated during other furnace processing activities, including alloy addition and skimming. Employing the best technologies available today, including siphon metal transfer, a target dross generation rate of approximately 1% is possible. However, siphoning cannot be used in all cast houses, thus underlining the need for continued efforts in the area of furnace design for improved metal transfer. Finally, the trend towards casting furnaces with greatly increased capacities severely limits production flexibility with respect to batch size and alloy change.

In-line Metal Treatment

Due to the inherent inefficiencies of furnace treatment, a growing emphasis has been placed on the utilization of in-line metal processing over the last 20 years. Many in-line treatment processes have been developed with the objective of providing more efficient and consistent metal treatment performance, while reducing treatment time, emissions and metal loss due to dross formation. There are two categories of in-line metal treatment processes namely, degassing/fluxing and filtration.

Degassing The in-line degassing process is now widely accepted and used almost universally throughout the aluminum industry. During the degassing treatment, a gas composed of argon and chlorine is dispersed into the liquid metal using one or more high-speed rotary injectors. The in-line degassing process design is based on the classic multi-stage stirred tank reactor and on recognition of the need to generate small gas bubbles to increase the interfacial gas-metal contact area. Due to their functional similarity, all rotary-type in-line fluxing processes provide roughly equivalent metal treatment performance. It should be noted that although these processes are called "degassers", they function to remove not only hydrogen but inclusions and alkali impurities as well. The physical and chemical factors which influence in-line degassing/fluxing performance have been published in detail elsewhere.[27, 28]

Recent advances in the design of in-line degassers have resulted in more efficient and consistent metallurgical performance. Improved rotary gas dispersers with increased shearing[29] maximize gas-metal contact area – a necessary condition for efficient metal treatment.

The capacity of in-line degassing technologies has been scaled up by the use of multiple staging, in order to meet the demands of increased casting rates. Multiple staging also has the advantage of having "built-in redundancy". The impact of a rotor failure on the metal quality is less severe. Another recent improvement is the operation of in-line degassers in a "sealed" mode,[30] that is to say, with an inert cover gas – essentially free of oxygen – over the liquid metal surface inside the unit. The impact of this development on the removal of impurities has not been fully quantified. However, there are definite advantages in terms of considerably reduced dross generation, easier operation (skimming less frequently) and possibly lower particulate emission rates.

On the other hand, scale-up of the conventional multiple-stage degasser has greatly increased the amount of metal retained inside the unit between casts and the resulting metal loss at alloy change. The large floor area requirement and equipment complexity is also becoming a very important issue for the cast shop.

To address these issues, a recent in-line degassing innovation is the development of a trough-based process[31, 32, 33] targeting multi-alloy cast houses. The trough-based process virtually eliminates metal loss at alloy change and maintains roughly equivalent metal treatment performances and capacities. Development of the Alcan Compact Degasser technology in particular, was based on the use of a hydrogen diffusion model[34] and is a prime example of how a fundamental understanding of the metallurgical principles can lead to process innovation.

The use of high shear rotary injectors with chlorine-containing gas mixtures for the treatment of Al-Mg alloys leads to the formation of minute magnesium chloride inclusions. If an effective metal filtration system is not used, the entrainment of these inclusions downstream of the degassing unit tends to accelerate surface oxidation of the molten metal. Oxide-related production or ingot quality problems can result. This phenomenon can limit the amount of chlorine that can be used during in-line degassing, the consequence of which is poor alkali removal performance. Work has been initiated on separation techniques for the removal of chloride inclusions[35, 36] in an effort to overcome this limitation.

The elimination of chlorine from the cast house is advantageous for safety and environmental reasons, as well as for reduction of maintenance costs. Proven alternatives to the use of chlorine exist for both crucible pre-treatment and furnace fluxing. Using these salt-based alternatives, the overall chlorine consumption in the cast house can be drastically reduced without penalizing metal quality or productivity. The last technical barrier to a truly chlorine-free cast house is the development of a chlorine alternative for in-line degassing. However, no such chlorine alternative presently exists. Today, the only option is to operate the degasser without chlorine while accepting reduced metallurgical performance - albeit at the same time, solving the magnesium chloride entrainment problem. In this context, and keeping in mind the integrated approach to metal treatment, zero chlorine operation for in-line degassing is a potentially viable solution for achieving a chlorine-free cast house. Upstream and downstream processing practices/technologies would have to be altered to maintain the overall metal treatment performance of the system.

Tighter environmental emission limits are issues that must be addressed. Will technological improvements or operational changes be sufficient to meet the environmental regulations of the future? Perhaps a more drastic re-thinking of the in-line degassing process will be required.

Filtration In the aluminum industry, molten metal filtration has been used in one form or another for many years[37]. It is common to use a filter strictly for precautionary reasons, that is to say, as a "safety net" to guard against uncontrolled upstream process variations that result in sporadically high inclusion levels. However, in the context of this discussion, the use of a filter is considered an essential metal processing step. The objective of filtration is to improve the metal quality to the degree required for demanding products/applications.

Unfortunately, a poor scientific understanding of the fundamental mechanisms taking place during aluminum filtration has hampered developments in filter design. Empirical design methods are often used based on trial and error. The filter was considered a "black box" because it was almost impossible to obtain a direct measure of what the filter was doing. At best, physical model analogues (water models) were used as a design guide.

Two technical advances have started to change this situation. First, is the development of inclusion measurement capabilities. For example, the use of LiMCA to quantitatively measure metal cleanliness has resulted in a practical comprehension of filter behavior in terms of operational phenomena such as inclusion release events, maximum filter loading and the impact of metal velocity on filtration efficiency. Secondly, and more recently, is the scientific advancement in fundamental research that has started to elucidate the important mechanisms that are active during aluminum filtration.[38, 39, 40] However, continued effort is required to gain a more complete understanding of depth filtration, the knowledge of which can eventually serve as the basis for more sophisticated filter design techniques.

What is understood today? Filtering techniques employed in the aluminum industry are mostly based on the depth filtration mode which involves the deposition and retention of inclusions throughout the entire depth of the filter. Inclusions are removed from the metal stream by sedimentation and are very weakly retained on the surface of the filter medium. Filtration performance is improved by:

- providing a stable and wetted interfacial contact between the liquid metal and the filter medium;
- reducing pore size;
- increasing filter depth;
- reducing the metal flow velocity.

A major constraint of aluminum filter design is the operational limitation of the very low head loss that can be accepted across the filter[41]. Note that the factors that improve filtration performance (above) all tend to either increase the head loss or increase the filter size – both of which are undesirable. Finally, more work is needed to relate molten metal cleanliness to product properties and performance. In many cases, the real metal cleanliness level that is needed for a particular product is not properly quantified.

Note that cake mode filtration is not presently used in the aluminum industry. Cake filtration involves the deposition of a layer of inclusions at the inlet to the filter medium with little or no penetration of the inclusions into the internal pore structure of the filter. This results in a very rapid metallostatic head build-up and is unacceptable for cost and practical operating reasons.

Single-use filters such as the ceramic foam filter (CFF) are physically small and are changed after every cast. This gives the advantage of low floor space and low metal holdup - facilitating alloy changes. However, because of their relatively small dimensions and the high metal velocity through the filter, metallostatic head loss considerations limit the thickness and the minimum practical filter pore size that can be used. As a consequence, these filters are not highly efficient[42].

On the other hand, deep bed filters are used during multiple casts. They are physically large to contain the amount of filter media necessary to filter hundreds or thousands of tons of metal between media changeover. The large flow area of these filters reduces the metal velocity and greatly improves the filtration efficiency at the expense of a high metal holdup volume and a high floor space requirement. The elevated cost associated with filter media changeover limits the use of multi-cast filters to cast houses having infrequent alloy changes.

Regardless of whether a deep bed filter, a ceramic foam filter (CFF), or a cartridge filter is used, the technical challenge facing metal filtration has always been defining the optimum balance between the required metal cleanliness, the filtration cost, the available head loss and more recently with significantly increased casting rates, the size of the filter.

There is a definite need to develop an efficient, low hold-up filtration process capable of treating high metal flow rates.

Metal Conveying

Particular attention must be given to the metal transfer equipment that connects the elements of an integrated metal treatment system. Metal turbulence and cascading must be avoided. The resulting oxides that are formed can undo much of the metal cleanliness gains that were achieved during upstream processing. In addition, it is recognized that the refractory and patching materials used in troughs (and in-line treatment units) can lead to the formation of heterogeneous inclusions. If this occurs late in the sequence of metal processing, the effects could be highly detrimental on product quality. Even ambient humidity can cause problems and has been shown to cause hydrogen pick-up in liquid metal exposed to air. Under conditions of high ambient humidity, products with strict hydrogen limits can only be cast with great difficulty.

The basic trough design has not changed appreciably for decades. Unlike the magnesium industry, where elimination of the metal free-surface has been accomplished using closed liquid metal conveying systems, the reactive/aggressive nature of liquid aluminum has prevented equivalent developments in this industry. Upon completion of metal processing, there is a need to maintain the liquid metal at its highest quality level for delivery to the casting machine. The present trough design cannot always fulfil this requirement.

Future Implications

The integrated approach to metal treatment that has just been described has gone through a period of process development and optimization. Each element of the treatment sequence is being pushed to its maximum. Although there remain challenges, only step-wise improvements to quality/productivity/capacity are anticipated.

In order to make a "quantum step" change, future technical hurdles may best be overcome by a complete re-thinking of the molten metal treatment strategy in the cast house. It must be recognized that multiple interventions are presently required to remove some impurities. For example, it is necessary to use all the metal processing steps to remove non-metallic inclusions, while alkali removal is done during two or three steps. The future challenge may be to re-think metal treatment technologies, including the casting furnace, starting from a "*carte blanche*" - the premise being that a metal processing step should be done once, but it must be done "right". For example, if inclusion-free metal could be produced in the casting furnace, in-line treatment for inclusion removal would no longer be necessary. Conversely, if a "super" filter could be developed capable of accepting very high inclusion loading, upstream metal processing for inclusion removal would no longer be necessary and significant productivity gains and/or processing cost reductions could be achieved.

Conclusions

There still remain key molten metal treatment challenges in the cast house.

- Molten metal processing must be more robust – capable of accepting poorer quality metal at the input, while producing higher and less variation metal quality at the output.
- There is a need to develop a more selective on-line inclusion detector.
- Further development is needed to optimize furnace design with respect to processing performance and batch size flexibility.
- The last technical barrier to a truly chlorine-free cast house is the development of a chlorine alternative for in-line degassing.
- Continued effort is required to gain a more complete understanding of depth filtration mechanisms.
- More work is needed to relate metal cleanliness requirements to product properties and performance.
- The development of an efficient, low holdup filtration process capable of treating high metal flow rates is needed.
- Improvements are needed for liquid metal conveying systems to prevent dross formation and metal loss.

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