Melting Furnace Practice and Benchmarking

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Introduction

In the first Steel Castings Handbook, the choice of steelmaking method employed was determined by the foundry and was related to 1) plant capacity 2) size and intricacy of casting 3) type of steel produced 4) type of operation desired (acid or basic) 5) raw materials available and price of these raw materials 6) fuel costs 7) amount of capital available for investment 8) the competition and 9) the labor available[1]. It also listed the percentage of annual production by melting method with the following numbers: Open-heart 65%, Electric Arc 31%, Converter 2%, and Electric Induction 2%. A review of much more recent melting practice standards can be accomplished through the currently published documentation in the Steel Founders' Society of America Wiki. The first comprehensive documentation of melting carbon steels and stainless steels was in the Steel Founders' Society of America "Green Book" published in 1973[2]. Both induction and arc melting practices have benefits and are covered more completely in this document as well as multiple other sources in the SFSA Wiki including T&O papers[3]. One of the better compilations is in the Melting Efficiency Report that was published by the Carbon and Low Alloy Research Committee in 2021[4]. Several of the best sources of information listed in Appendix I of this paper.

While knowing the best method to melt in your foundry, it is no longer enough when looking to compete against domestic and international competition. Regular review of your process while benchmarking and knowing costs is a necessity. This allows testing for potential improvements to be documented accurately and allow decisions to be made with confidence.

Safety Practices

It makes no difference what type of melting unit is used; safety must be the number one concern when working with molten metal. There have been several documented deaths over the last several years due to unsafe work practices in the melting area. Melting operators should be trained in-depth into the operation of the furnaces. Emergency procedures such as those needed if power is lost should be available at the furnaces with pictures and equipment well labelled to identify with the emergency procedures.

Operators also need to monitor several factors during normal operations for example not limitative:

For induction melting practice:

1. The raw materials that are melted in the heat should be dry and clean. This is important for product quality as well as safety.
2. Regularly observing the ground fault current for changes can indicate potential lining issues. A bouncing ground fault needs immediate investigation. A slowly rising ground fault indicates lining wear with the metal getting closer to the coil.
3. Refractory condition between heats – look for dark areas in the lining. This may be an indication of a thin spot in the lining.
4. Working your charge and trying to see the liquid metal pool. Knowing the time it takes for a charge to drop and feed. If the charge is not dropping, it is an indication of a bridge in the charge and immediate action is needed. This is probably the most dangerous situation as the metal can superheat to temperatures above the ability of the refractory to hold it.
5. Maintenance of the spout so that the metal comes out smoothly. The safety factor is avoid splashing and the potential of molten metal burns on the pouring crew as well as the melter.

6. Keep the melting platform clean without any excessive stuff that can lead to tripping falls or impair quick exit the case need be.

Arc furnaces have a couple of different factors to monitor as well as some that are the same.

1. The raw materials that are melted in the heat should be dry and clean. This is important for product quality as well as safety.
2. All the necessary precaution for Oxygen handling.
3. When blowing oxygen into the metal bath, the exit end of the lance should not be close to the refractory wall. If the blast of oxygen is directed at one spot on the lining, it will burn through the refractory and metal shell.
4. Refractory wear, including the delta section of the roof should be inspected between heats. Thin areas should be patched, and it is much safer and easier to replace a roof and delta if it has not fallen into a molten heat.
5. Maintenance of the spout so that the metal comes out smoothly. The safety factor is avoid splashing and the potential of molten metal burns on the pouring crew as well as the melter.

Melting Basics

Before you even weigh your first charge material, scheduling needs to be determined. Proper scheduling may have a positive impact on melting while poor scheduling will have a large negative impact. It is a rarity if a foundry melts only one alloy. Not only does scheduling affect melting and its efficiency, but it can also do the same to heat treatment. Foundries that schedule based on molding and core making capabilities could potentially save cost by including the elements of melt and heat treatment. In melting, ordering melts by alloy content reduces the possibility of out of specification heats due to chemistry that is affected by previous melts that have not been fully emptied from the furnace. Refractory lining and spout maintenance are critical to prevent this. The same phenomena can occur in ladles. Abruptly changing alloys from low or high values in carbon, chrome, and other elements like melt temperature that can remelt/clean the residual slag from the previous heat can affect spectrometer results. Be cautious of ghost readings that are reflective of the memory of the previous analysis. Those with multiple furnaces that simultaneously melt very different alloys should also be aware of this.

Refractory practice also needs to be determined by the individual foundry. Alloys and products poured will both affect refractory selection. Pouring temperature varies due to alloy and section size. Tap temperature can be affected by ladle size and preheat capabilities. The quantity of molds poured out of a ladle will also affect tap temperature, but ladle size should be selected to minimize overheat, thus saving time, refractory and improving safety conditions. If possible and cost effective, furnaces (and ladles) should be preheated or kept hot to extend refractory life and minimize heat loss from the molten metal. Refractory installation should be completed per manufacturers guidelines. Either a hot or cold sintering practice needs to be properly completed during the first melt out of the newly lined furnace.

Charge building is also a variable in the melting process. How consistent are the charges and the chemistry of the charge materials. The individual element recovery rate should be known for your operation. A least cost charge building program is essential for high volume foundries in today's market to keep charge cost optimal for the desired specifications.. Elements that oxidize easily, carbon, manganese, or silicon, will have lower recovery rates than molybdenum or nickel which do not oxidize readily. (a word on charging order?) The amount of pig material, revert, or scrap buyback material should be used at the maximum amount as it is usually lower cost than virgin material or scrap steels. This will typically be limited by the amount of gas in the metal for induction melting. The carbon boil in arc melting will reduce these gases as can using iron oxide or nickel oxide to induce a small boil in induction furnaces. Boiling in an induction furnace needs to be monitored continuously for safety. It is good practice to have a can of ferro silicon or silicon metal available to kill the boil if it starts to get wild and climb the freeboard in the furnace.

Regardless of the way you melt, it is essential to melt fast and hold at molten metal temperature for a minimum amount of time. To melt fast, ladles, cranes, crew and all molds must be ready to be poured prior to starting the melting process. Molten metal will absorb gasses from the air while molten and absorption of these gases is higher as the metal temperature rises. Increased gas content is detrimental to metal properties and could influence element recovery. If the molds for the next heat are not ready, the furnace should still be charged so that the heat in the furnace lining goes into the charge and not lost even if power is not applied.

For induction melting, densely packed materials are melted more efficiently than light charges. Charge materials should be clean and dry. Carbon or stainless steel melt wrought melt stock should be charged first into the furnace with the non-deoxidized alloys such as Molybdenum and nickel. Ferrochrome should be added at the end of the meltdown period. Easily oxidized additions such as manganese or silicon alloys should be added just prior to taking the initial spectrometer sample. Care should be taken as to not make the late additions onto a surface covered with slag. This slag cover will reduce recovery of the addition.

Heel melting can also be used if the same or similar alloys are scheduled. This is where the induction furnace is not emptied, but a heel of metal is maintained in the furnace and the charge for the following heat is charged into the molten bath. For this to be safe and successful, scrap must be clean and dry prior to charging into the molten bath. The scrap dealer must be trusted to not have any potential bombs such as cans or tubes that have not been punctured in the raw material. The charge on top of the heal should be done as soon as the metal is tapped from the previous heat. This is to avoid a localized attack on the refractory. A study of productivity and electrical consumption should be completed before making this a standard practice.

In arc melting, you want dense charge in at the bottom of the charge and lighter material on top of the charge. This allows the electrodes to bury into the light scrap for higher efficiency and protecting the refractory from the arc while minimizing the possibility of charge collapse breaking an electrode. It is desirable to have a scrap density permitting the entire charge to be loaded prior to striking an arc as this will save time by not having to back charge into a molten bath. Back charging will also release more fugitive emissions to atmosphere.

The comparison of basic or acid practice in arc melting will not be argued here. Both have benefits and selection should be determined by the industry or industries the foundry serves or by cost of operation if all else is equal. A similarity between the two methods is the oxygen blow. This is done to reduce the gas level within the melt. A minimum of 35 points of carbon should be boiled out of the melt. It is somewhat confusing in that you blow a gas into the metal to lower the gas content of that same metal. We are making larger gas bubbles that will join with smaller gas bubbles and float out of the metal. It can be understood if you look at a fish tank pump and filter in operation. The large bubbles float to the surface at a much faster rate than the small bubbles.

AOD refining first came to a steel foundry in 1973. The same year as the green book was published. Because of this, other sources are needed when looking to refine metal through an AOD, vacuum degassing, SPAL, EGAL, or some other method. The SFSA Wiki is a great source of this information. Any type of additional processing to the melt will be at an added cost. It needs to be justified through higher properties achieved or customer requirements.

The most important thing in the metal that comes out of any furnace is the final chemistry. It is poor practice to accept a melt chemistry that is just within the requirement of the specification. The furnace charge should be built to attain a specific target value for each element in an optimized manner. A focus on melt preparation improves overall melt efficiencies by minimizing melt corrections to the heat after the first chemistry sample. Tramp elements are to be limited through the purchase of scrap of known quality. There are several advantages to achieving the same target value for the elements within an alloy. A consistent heat treat practice can be fine-tuned to meet properties and optimize cost. me) Cost is reduced by shorter melt times (electric and refractory savings), reduced metal pigged (trim additions just add weight to a heat that was calculated for the required metal), and lower cost due to less raw material usage. It is good practice to know the statistics within your alloy chemistries. Calculate the standard deviation and Cpk, a statistical metric that measures how well a process can produce products or services that meet quality requirements, of each element within an alloy.

Benchmarking and Knowing Your Costs

Most foundries are aware of the cost of the charge materials for each alloy they pour. Are the furnace trim additions included or are they just all lumped together as a variance from standard at the end of the month? The cost of all additions to each individual heat should be known. Though likely your largest expense in the melting department, knowing your alloy cost is only the beginning.

Figure 1 can show many more items that can be and should be tracked as we move forward with I4.0. It doesn't matter if your business system deals in pounds or tons, all cost items can be associated with melt department costs and should not just be hidden from view and analysis where there is little chance for improvement.

Tracking tap to tap time can gives insight not just into your melting shop but a way to look at shop capacity (if the melt shop is a constraint for pouring). The goal is to have the lowest tap to tap time as possible. Factors that affect this include molds ready to be poured, density of charge material, operator attention to keep furnace full (induction furnaces to optimize power absorption), getting full charge into furnace at initial charge (arc), minimizing trim additions through base heat chemistry control, preheating the furnace prior to the initial heat of the day. If you get 6 heats in a shift and each takes an hour and ten minutes from tap to tap, if you can reduce by 10 minutes, a 14% reduction, you pick up a 7th heat in the same amount of time. This will result in savings on labor and electrical costs every heat.

A sign of chemistry control and careful charge building (weighing each element precisely) is the minimization of trim additions. Minimizing trim addition is precious time savings / productivity improvement. Maintaining a low number is typically an indication of lower alloy costs for the alloy being melted. This also speeds up the melting process, lowering tap to tap time, by eliminating the need to have a second spectrometer sample out of the furnace. This can be done because the heat is typically already in specification and the small addition is to hit a target value within the specification. The reason to do this is that you know the chemical composition of what is going in the furnace if all the internally generated charge material is the same chemistry.

Figure 1: Screenshot of spreadsheet to monitor melting costs.

Melt Shop Costs			Per Pound Shipped	Per Ton Shipped	
			#DIV/0!	#DIV/0!	
Tons Melted			Per Pound Melted	Per Ton Melted	
Pounds Melted	0		#DIV/0!	#DIV/0!	
Tons Shipped					
Pounds Shipped	0				
Average Tap to Tap Time					
	Pounds	% Pig			
Pig Metal (include scrap Heats)		#DIV/0!			
	Pounds	% Trim			
Trim Additions		#DIV/0!			
Actual Yield (%)	#DIV/0!				
Metals Melted	Tons	Pounds	%		
Carbon / Low Alloy Steels		0	#DIV/0!		
Stainless Steels		0	#DIV/0!		
Nickel Base		0	#DIV/0!		
Manganese Steels		0	#DIV/0!		
Chrome Irons		0	#DIV/0!		
Other (Low Temp)		0	#DIV/0!		
Revert Consumption	Tons	Pounds	%		
Gates and Risers		0	#DIV/0!		
Scrap Castings		0	#DIV/0!		
Pig Metal		0	#DIV/0!		
Scrap Buyback		0	#DIV/0!		
Melt Labor Cost ($/Hr.)	Hours	$/Hour	Cost / Lb Melted	Cost / Lb Shipped	
			#DIV/0!	#DIV/0!	
Refractory Costs	Cost	Qty Used	Cost / Lb Melted	Cost / Lb Shipped	
Brick			#DIV/0!	#DIV/0!	
Spout			#DIV/0!	#DIV/0!	
Roof			#DIV/0!	#DIV/0!	
Delta			#DIV/0!	#DIV/0!	
Gunning Material			#DIV/0!	#DIV/0!	
Lining (Dry Vibe)			#DIV/0!	#DIV/0!	
Top Cap			#DIV/0!	#DIV/0!	
Slip Plane			#DIV/0!	#DIV/0!	
Coil Grout			#DIV/0!	#DIV/0!	
Patch Material			#DIV/0!	#DIV/0!	
Other			#DIV/0!	#DIV/0!	
Gases	Cost	Qty Used	Cost / Lb Melted	Cost / Lb Shipped	
Oxygen			#DIV/0!	#DIV/0!	
Argon			#DIV/0!	#DIV/0!	
Other			#DIV/0!	#DIV/0!	
Lances / Tuyeres			#DIV/0!	#DIV/0!	
Porous Plug			#DIV/0!	#DIV/0!	
	Cost	Qty Used	Cost / Lb Melted	Cost / Lb Shipped	
Electrodes			#DIV/0!	#DIV/0!	
	Total KW	Cost / KW	Demand / Transmission Costs	Cost / Lb Melted	Cost / Lb Shipped
Electricity				#DIV/0!	#DIV/0!
				Cost / Ton Melted	Cost / Ton Shipped
				#DIV/0!	#DIV/0!

To find actual yield of your plant, you need to consider everything added to your charge as the denominator in the formula. The numerator is the weight of product shipped. This is not the yield number that your methods engineers try to optimize. This number will consider the methods yield, additives oxidized in the melting process, metal that is spilled during tapping or pouring, metal that is pigged at the end of the pour, metal that is lost due to riser and gate removal, grind losses, and weight lost due to scrap. This number give a general report on the health of the quality of the product being produced. If the number drops, it should be determined what area is causing the decrease. It should be noted that the number can vary from month to month if there is a large difference in metal produced in the melting furnaces. This variance can be due to swings in order intake, plant shutdowns, customer demands, or product quality.

In a jobbing foundry where mix often changes, it is best to track the mix of the different alloys. The different families of alloys tap and pour at different temperatures. This will impact electrical consumption, refractory selection and consumption. The other area that needs to be addressed with alloy mix is scheduling. The alloys need to be scheduled so that they do not create issues with attaining the desired chemistry. Special caution needs to be taken in the selection of refractory material if manganese steels are melted. Copper based alloys create an additional issue where it should be planned to pour these at the end of a refractory campaign or have a designated melting pot for these alloys.

Accounting practice is embedded in the melt shop when tracking the amount of in-house generated melting stock. Scrap buy back is included in this because it was either generated at a foundry, yours or another, and costs less than buying raw materials such as stainless steel or virgin alloys. It will also have gas levels that are in line with what is found in the other forms of revert.

Labor costs can be looked at in a couple of ways. The spreadsheet appears to only include the hourly pay rate in the department. If you are looking to truly capture the full cost of labor, benefits must also be included in the number. The employee responsible for the melt shop becomes more aware of the real cost of labor when all benefits are included in this hourly rate. The benefits that can be included are health insurance, retirement funding, company taxes paid on employees and their benefits, vacation, and portion of workman's comp insurance.

Refractory costs include many different refractories used throughout the campaign. These costs need to be measured at time of use and not rely upon end of month inventory for accuracy. A mistake that can cost a foundry is ordering too large a quantity of certain refractories. They do have a shelf life. Disposal of product if shelf life expired is not just the cost of the product, but also disposal costs. Use of product after expiration may lead to catastrophic failures with much higher costs.

Gasses are often an overlooked cost of the melting department. Beyond the gasses, any tank rental fee and delivery fees should be included in this area. If there are significant costs associated with inspection of tanks, this should be included in this area. Gasses used for preheating furnaces or charges should be included in this area.

Electrical costs should be monitored. You could also include any surcharges paid. There are many ways to try to lower your energy costs in the melt department. Off shift melting and power reduction agreements during high consumption times are two methods of lowering the cost of electricity. The furnaces should have their own metering device for accuracy of measurements. Factors that will affect your overall electrical consumption include refractory thickness, density of charge material, tap to tap time, required tapping temperature, accuracy of melt in chemistry, preheat of charge material, and preheat of furnace lining.

Conclusion

A review of melting practices and the effect of these practices on cost needs to be on-going process in the foundry. Avoidance of injuries in the department is a primary focus as significant or fatal injuries can occur if operators are not diligent.

Fundamental melting practices need to attain the lowest melt time using the cleanest raw materials with the lowest maximum temperature to create the highest quality metal from the spout. Beyond the requirement of a quality metal, there needs to be an understanding of the financial side of the process. Knowing the cumulative cost of melting is more than the alloy contributor. Having a full understanding and documentation of practice costs can make your melt shop more than just a cost center. Knowing your costs in-depth will lead to higher productivity and ability to achieve and document lower costs.

References

1. Steel Founders' Society of America: "Steel Castings Handbook" 1941.
2. Steel Founders' Society of America: "Steel Foundry Melting Practice" 1973.
3. Steel Founders' Society of America Artisans Program – Advanced Melter https://wiki.sfsa.org/index.php/Artisan-Advanced
4. Carbon and Low Alloy Research Committee, D. Poweleit, "Research Report No. 122 Melting Efficiency Improvement" Steel Founders' Society of America, 2021.

Appendix I – Sources of Melting Information

- Steel Founders' Society of America: "Steel Castings Handbook" 1941.
- Steel Founders' Society of America: "Steel Foundry Melting Practice" 1973.
- Steel Founders' Society of America Artisans Program – Melter
- Steel Founders' Society of America Artisans Program – Advanced Melter
- American Foundrymen's Society: "Principles of Induction Melting" 1990.
- P.D Deeley, K.J.A. Kundig, H.R. Spendelow Jr.: "Ferroalloys & Alloying Additives Handbook" Shieldalloy Corporation, 1981.
- W.J. Jackson, "Steelmaking for Steel Founders, Monograph 1, Induction Furnace Practice, SCRATA, Sheffield, England, 1972.
- Carbon and Low Alloy Research Committee, D. Poweleit, "Research Report No. 122 Melting Efficiency Improvement" Steel Founders' Society of America, 2021.
- K.D. Peaslee, S. Lekakh, S. Biswas, J. He, "Steel Foundry Melting Energy Progress" Steel Founders' Society of America T&O, 2012.
- W.J. Jackson, M.W. Hubbard, "Steelmaking for Steelfounders" Steel Castings Research and Trade Association, 1979.
- Harbison-Walker Refractories Company, "Harbison-Walker Handbook of Refractory Practice" 2005.
- Vasile Ionescu, "Control of Oxygen, Nitrogen and Hydrogen in Induction Melted Steels" Steel Founders' Society of America T&O, 2000.