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Alloy Recovery and Control in Steel Melting

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Abstract

Alloy recovery plays an important role in steel melting economics because the cost of alloying additives such as ferroalloys and pure non-ferrous metals is significantly higher than the cost of steel scrap. Recovery of alloying additives also influences the reproducibility of steel properties from heat to heat. This paper reviews alloy recovery and final chemistry distributions at seven steel foundries and preliminary laboratory studies of alloy dissolution in ladles. Melting and alloy practices were observed for several plant trial heats in each of the foundries. Alloying and chemistry data were collected for an additional 20 - 155 heats at each plant. The recovery of alloying additives depends on the type of furnace and individual foundry practices. EAF operations had greater variations in final chemistry performance than induction furnace operations. Laboratory experiments showed that there is a potential for increased alloy recovery and control through argon stirring with a porous plug. Argon stirring decreased mixing time by 50% and decreased the local variation in steel composition.

Introduction

One of the highest costs in a melting operation is alloy additions. Therefore, if a foundry can have a better understanding of the factors that determine alloy recovery and improve control of the final chemistry, significant costs can be saved while producing more consistent quality steel castings. Alloy control implies that a foundry has the ability to meet the chemistry requirements for a given grade consistently. As illustrated in Figure 1, the typical foundry practice is to aim well above the minimum alloy requirement, usually at or just slightly above the mid-specification range, avoiding off-specification castings. As control is improved, alloy savings can be realized by targeting a much tighter internal chemistry specification at the lower end of the alloy requirement (see Figure 1). Both alloy recovery and melt practice play key roles in foundries being able to utilize alloy control.

Recovery of alloying additives is important not only from an economical standpoint but also from the standpoint of making high quality products with highly reproducible mechanical properties. In spite of smaller absolute amount of additives, in many cases the total relative expenses can be significant because frequently used elements like *Cr*, *Ni* and *Mo* can cost tens to hundreds of times more than steel scrap. Recovery of additives depends on a vast spectrum of parameters, summarized in three groups:

1. Type of additives (concentration of the alloying elements and their chemical activity, in particular, affinity to oxygen, density, size and shape of particles, concentration of impurities);
2. Methods of alloying (in furnace or ladle, special injection methods, such as wire injection, in stream or in the mold treatments, intensifiers of dissolution by mixing);
3. Melting techniques (type and size of melting furnaces, slag composition, condition, and quantity, temperature of melt, melting period).

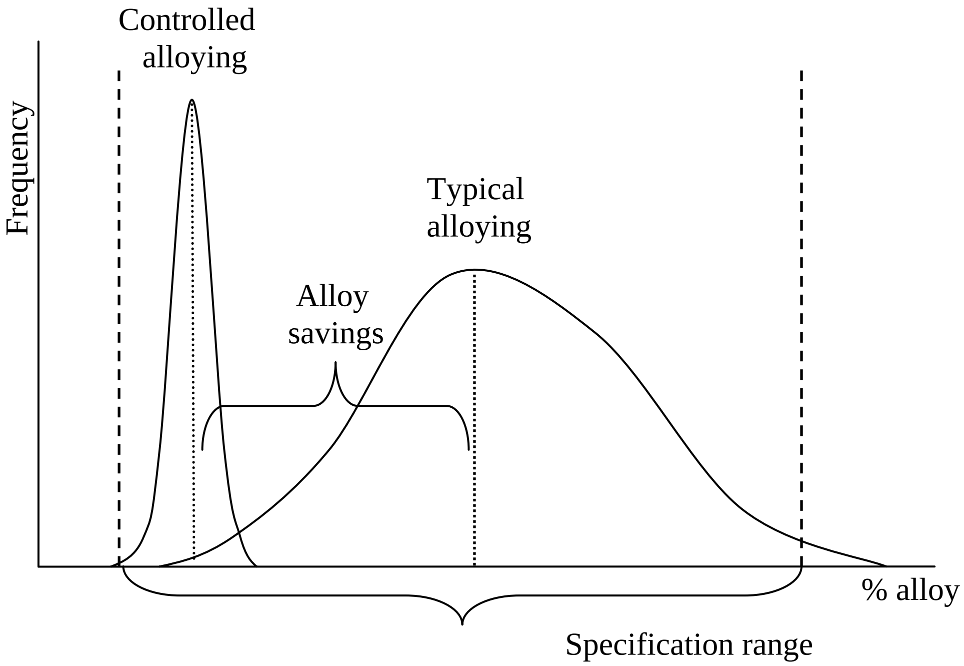

Figure 1. Savings from controlled alloying in place of the typical alloying practice of many foundries

Alloy recovery in industrial operations is affected by many factors. Oxidation of the alloy is usually the primary cause of poor or erratic recovery. Research suggests that ferroalloy recovery is a function of the dissolution rate of the alloy, density of the alloy, and dissolved oxygen in the liquid steel (for nitride–forming alloys, dissolved nitrogen must also be included).[1] It was found that increasing the dissolved oxygen in the steel lowered the alloy recovery and decreased the dissolution rate of alloys with melting points greater than steel. The reduction in dissolution rate was attributed to the possible formation of a refractory oxide on the alloy surface. Important sources of oxygen are furnace slag and air contact (slag carryover and air entrainment during tapping).[2] Other sources of oxygen include slag remaining in the furnace (or ladle) from previous heats, oxygen dissolved in the metal, air carried into the melt by alloy additions, and from refractory-metal interactions.

In order to transfer alloying elements to the molten steel bath, it is first necessary to immerse the ferroalloy into the metal. Upon addition, a steel shell is frozen on the surface of the alloy. Heat transferred from the molten bath remelts this shell back to the original alloy surface.

Convective heat transfer, which is a function of bath stirring and superheat, governs shell melting. Several physical and chemical properties of alloy additions affect how the element is incorporated into the steel melt. Melting point is the primary factor in dissolution rate, while other important properties include density, thermal conductivity, specific heat, and enthalpy of mixing. Density determines whether the addition will float (ferrosilicon), sink (ferromanganese) or be entrained within the melt (ferrochromium). Thermal conductivity, along with specific heat and density, determines the thickness of the steel shell, which forms on the cold addition. Finally, a strong exothermic reaction between the alloy and steel (enthalpy of mixing) can substantially reduce the assimilation time (75% ferrosilicon).

Minimizing alloy size improves dissolution rate, which is contrary to historical practice where large lumpy ferroalloys were employed to aid in penetrating the slag layer. Unfortunately, small size means more surface area on which to transport undesirable gases and moisture, plus, small alloy size increases dust losses and incurs handling difficulties. Lee et al. determined that the optimum size for bulk materials is between 3 and 20 mm in diameter.[3] Wire and powder injection are both means of overcoming limitations imposed by fine alloy size.

Efficient steelmaking processes rely on the motion of molten steel to: dissolve alloys, float inclusions, and eliminate chemical and temperature inhomogeneities. Natural forces can induce steel motion, e.g. convection due to temperature gradient or energy of the falling stream during tap. Natural convection is relatively slow; while tap induced motion is time limited. In contrast, external forces, like induction stirring in induction furnaces, or gas injection through a lance, plug, or tuyere can create significantly more intense motion. Gas injection via lances and porous plugs is the predominant method of stirring used in wrought steel production.

Wrought steel producers typically do not add alloys to the melting furnace and make sixty to ninety percent of bulk alloy additions to the ladle during tapping of the steel. However, there is a trend in the wrought industry towards making more additions at the ladle metallurgy station/ladle furnace or even at the tundish using specialty wire products[4,5]. By, moving chemical correction from the melting furnace to the ladle, the modern steel mini-mill practice of minimizing time and energy consumption in the EAF has been achieved.

Of course, the effectiveness of the above described alloying methods depends on ladle volume. Thus, not all of these techniques can be effectively used in foundries which operate with multiple smaller ladles. Additional research will be necessary for adaptation of these methods to foundry practice. The main aims of this research were to evaluate the recovery of alloying additives in foundry practices and investigate controlled alloying by argon stirring in small-scale ladle.

Methodology

Melting observation and statistical data were used for analysis of alloying additive recovery and steel chemistry distribution in industrial practices. Seven foundries equipped with induction furnaces (IF) and electric arc furnaces (EAF) were observed. All foundries are designated by a letter from A to G to identify the facility while maintaining confidentiality. In addition, lab experiments were performed to determine the effects of ladle stirring on alloy dissolution.

Steel foundry observations. Three to five trial heats were melted and observed in each foundry and the following data was recorded:

- Melting procedure and power-on time
- Weight and composition of charge materials
- Weight, composition of additives, and alloying procedure
- Steel chemistry before and after alloying.

All of the foundries weighed charge materials and tested the chemistry analysis before and after the alloy additions. However, some foundries weighed additives more precisely than others.

Statistical data. At each foundry, an additional 20 to 155 heats were studied by recording the charge weight and compositions, preliminary and final steel chemistry, and the weight of additives from statistical data available at the plant (charge sheets, heat logs, cast logs, computer databases, etc.).

Experimental procedure. Laboratory experiments are being conducted at UMR to examine the role of gas stirring in alloy dissolution. One hundred pound heats of steel are induction melted and poured into a ladle where a bulk alloy addition is made. Consecutive timed samples are then taken for chemical analysis. The ladle is equipped with a porous plug in the bottom for the introduction of argon gas for stirring. This paper will discuss some of the initial tests.

Steel Foundry Melting Study

Induction furnaces (IF)

Four steel foundries with different capacity induction furnaces are included in this study. All of the furnaces had medium frequency power supplies and were lined with alumina based (alumina spinel) refractory. Heats were batch melted and often utilized a liquid heel resulting from excess steel being returned from the previous heat instead of pigging. Foundries A, B, and F typically melt 8 to 12 hours per day with the furnaces setting idle (and cold) during the off-shifts. Foundry G melts by induction furnace occasionally and on those days typically melts only one heat per day in a furnace. The variety in melting schedules resulted in wide differences in the percentage of heats melted in furnaces with hot linings (ranged from 0% to greater than 80%). Table 1 compares the furnace capacity and transformers at each of the plants.

The following summarizes the alloy recovery findings at each of the induction furnace melting facilities.

Table 1. Inductions furnace capacity and characteristics

Foundry	Capacity, lb	Power supply, KW	Lining	Steel
A	2500	500	Alumina spinel	Carbon, alloy
B	9500	4500	Alumina spinel	Carbon, alloy
F	900 1800	250 500	Alumina spinel Alumina spinel	Carbon, alloy, Stainless
G	2000	450	Alumina spinel	Carbon, alloy

Foundry A. Melting and alloying of three heats of low carbon steel were observed. The typical melting practice was to charge some carbon with the scrap. Typically, ferrosilicon (75% *Si*) and electrolytic manganese were added to the furnace at 2800-2900°F after taking the preliminary chemistry test. Because the surface was not deslagged prior to adding the alloys, some of the addition went into the metal and some was lost to the slag. Additional carbon was typically added on a clean melt surface at higher temperatures after deslagging with the assistance of slag coagulant. Aluminum and other deoxidizers were added directly in ladle during tapping. All additives were weighed. The range of recoveries for the various alloying elements in the trial heats and from statistical data for 155 previous heats are provided in Table 2. Recoveries were lower for elements when added to the charge because of the greater potential for oxidation during the melting process. The recovery values for *Mn* and *Si* in the melt were lower during the historical heats (155 heats) than during the observation period most likely because of additional oxidation from the surface slag.

Table 2. Recovery (%) of alloying elements in IF Foundry A

Method of alloying	***C***	***Mn***	***Si***
In Charge	70…85	75…80	70…75
In Melt	90…100	85…90	85…90
In melt (statistics of 155 heats)	94.6	62.65	63.61

Table 3 compares the chemistry change in the slag during one of the trial heats. The large *MnO* increase in the slag after alloying indicates the losses of alloy directly to the slag during the alloying process. As expected, the ladle slag had higher levels of aluminum and titanium oxides.

Table 3. Slag compositions, weight % (Foundry A)

Slag	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	Cr_2O_3
IF-primary	41.5	35	6.59	.51	.79	.2	.04	.74	12.55	.218
IF-after alloying	30.07	38.95	3.2	.73	1.8	.17	.06	.99	24.06	.115
Ladle-after Al+FeTi	24.1	54.65	4.65	.08	.32	.2	.24	2.76	9.85	2.135

Statistical variations in the final *Mn* and *Si* contents in low carbon steel were evaluated by calculating the difference between the final chemistry (C_f) and aim chemistry (C_{aim}). Final chemistry distributions are shown in Figure 2 and the statistical parameters (median - M and standard deviation -SD) for the data are displayed in Table 4. Although the specification range (SR) for alloying elements in steel castings is typically different for each plant and only an aim range, the ratio of SR/SD provides an indication of the capability each plant has to control alloy levels with present practices. From a statistical point of view, a SR/SD ratio of 4.0 indicates that 95,5% of the heats would be within the specification range based upon a normal data distribution. Statistically, the *C* is in control (SR/SD=5) but the *Si* and *Mn* show much greater variation with the *Si* skewed under the aim and *Mn* with a bimodal distribution.

Table 4. Final steel chemistry (wt%) for 155 heats produced in IF (Foundry A)

Parameters	***C***	***Si***	***Mn***
Aim	0.23	0.55	0.55
Median (M)	0.23	0.46	0.73
Standard deviation (SD)	0.01	0.059	0.093
Specification Range (SR)	0.2 - 0.25	0.4 – 0.6	0.4 - 0.6
SR/SD	5	3.4	2.1

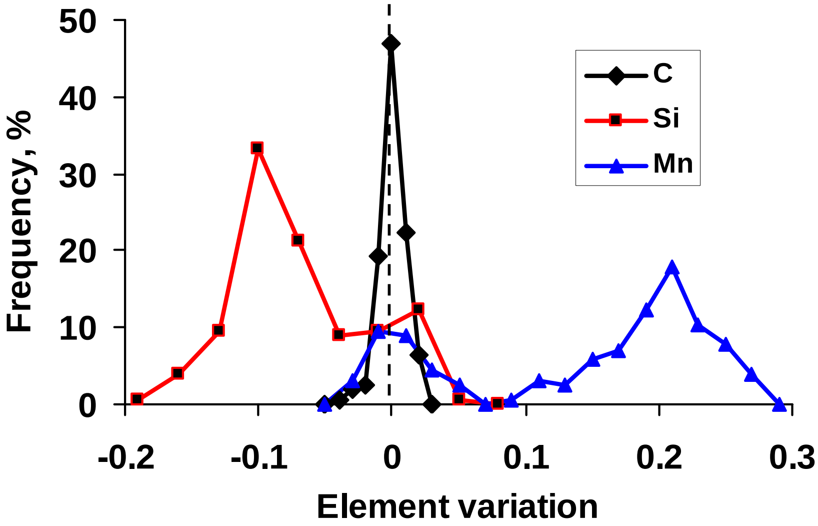

Figure 2. Variations of steel final concentration (IF, Foundry A)

Foundry B. The melt shop at Foundry B operated two 9500 lb capacity induction furnaces simultaneously from one 4500 KW energy supply unit. The high specific value of energy input (near 1000 KW/ton) gave short melting times and intensive stirring of the liquid steel. Once the charge was completely melted, a preliminary chemical analysis sample was taken and the primary slag removed with assistance of coagulant. Alloys were added to a clean melt surface at 2900-2950°F under full power. Statistical values of recovery of *Mn* from ferromanganese, *Cr* from low carbon ferrochrome, *Mo* from ferromolybdenum, and pure *Ni* are given in Table 5.

Table 5. Recovery (%) of alloying elements in 24 IF heats at Foundry B

	Mn	*Cr*	*Mo*	*Ni*
Recovery in melt	78	98	100	100

Final chemistry distributions and the statistical parameters for 24 IF alloy heats are illustrated in Figure 3 and Table 6. Note that this foundry is capable of tighter chemistry controls with present melting practices.

Table 6. Statistics of final steel chemistry (wt%) produced in IF for 24 heats (Foundry B)

	Mn	*Cr*	*Ni*	*Mo*
Aim	1.0	2.94	0.80	0.80
M	1.0	2.94	0.79	.0.81
SD	0.03697	0.07828	0.015937	0.0138
Specification Range	0.7 – 1.0	-	-	-
SR/SD	8.1	-	-	-

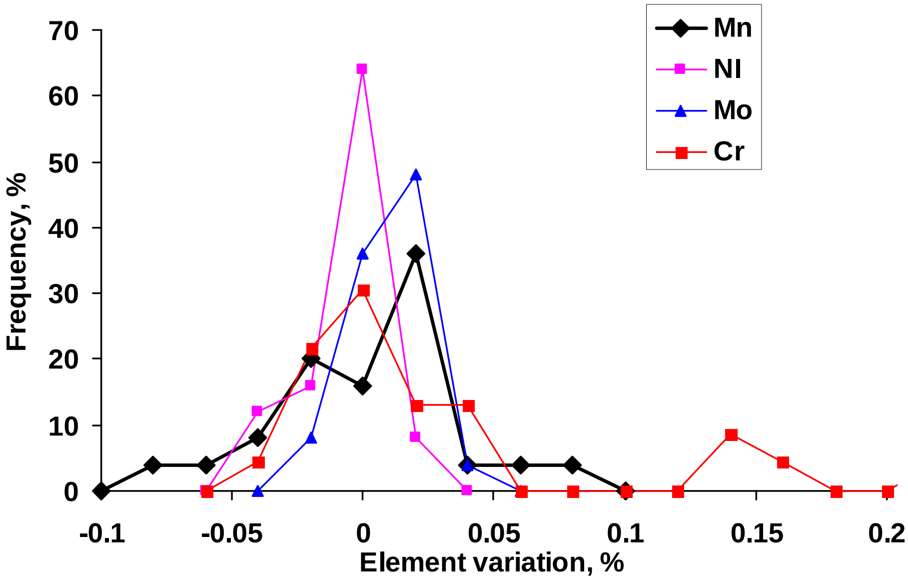

Figure 3. Variations of steel final concentration (IF, Foundry B)

Foundry F. Foundry F melted highly alloyed stainless steels in induction furnaces during the period of observation. Alloy scrap and revert were charged in the furnace along with a part of the low carbon ferrochromium. After melting the charge and taking a preliminary chemical analysis, the primary slag was removed with coagulant and the metal heated to 2850°F. Low carbon ferrochromium, nickel, and electrolytic manganese were weighed and added to the open melt surface under full power. The range of variation in the *Cr*, *Ni*, *Mn*, and *Mo* recovery during the four observed heats are summarized in Table 7.

Table 7. Recovery of alloying elements in four IF heats (stainless steel at Foundry F), %

Method of alloying	*Mn*	*Cr*	*Mo*	*Ni*
In Melt	74…94	60…92	99…100	99…100

Electric Arc Furnaces (EAF)

Four foundries equipped with EAFs having capacities ranging from 2.5 to 15 ton were observed to study alloy additive recovery and control. These foundries used both acid and basic melting practices and linings (see Table 8). Although some of the foundries had AODs, only non-AOD heats were analyzed in this paper.

Table 8. EAF furnaces observed in plant trials

Foundry	#EAF	Typical heat, lb	Lining	Steel
C	1	19000	Magnesia	Carbon, alloy, stainless
D	1, 2	11000	Silica	Carbon, low alloy
E	1, 2, 3	6500, 8500, 9400	Silica	Carbon, low alloy
G	2,4	20000, 8500	Magnesia	Carbon, low alloy

Foundry C. Three heats of low and medium carbon steel were studied with different melting practices including one heat with a cold lining, one heat with a heel and hot lining, and one heat with a pour-back on solid charge and hot lining. During these heats, 75 lb of carbon and 50-120 lb of ferrosilicon (75% Si) were added to the furnace with the scrap charge. After melting, oxygen boiling, preliminary chemical testing, and a $CaCO_3$ addition, chemistry correction was accomplished by adding ferromanganese and ferrosilicon. The recovery from this addition may have been affected by the significant amount of slag in the furnace. Carbon correction was made by a combination of pig iron and 1-3 minutes of dipping the graphite electrodes. Typical changes in the steel composition during the heat are summarized in Table 9.

Table 9. Changing chemistry (wt %) during melting steel in EAF

Operation	***C***	***Mn***	***Si***	***P***	***S***
Melt-in preliminary test	0.45	0.29	0.12	0.013	0.025
After oxygen blow	0.08	0.145	0.01	0.007	0.020
After $CaCO_3$, FeSi, FeMn, and C additions	0.23	0.79	0.53	0.013	0.011

Statistical variations of carbon, silicon, and manganese final concentrations are summarized in Figure 4 and Table 10. This foundry will require some change in practice to improve alloy control based on the relatively low SR/SD values. However, the *Mn* is skewed to the high side and the aim could be lowered to save alloy costs.

Table 10. Statistics for final steel chemistry (wt %) produced in 59 EAF heats (Foundry C)

	C	***Mn***	***Si***
Aim	0.22	0.65	0.45
M	0.22	0.725	0.451
SD	0.015	0.116	0.079
Specification Range	0.2 -0.25	0.5 -1.0	0.45 – 0.6
SR/SD	3.3	4.3	3.1

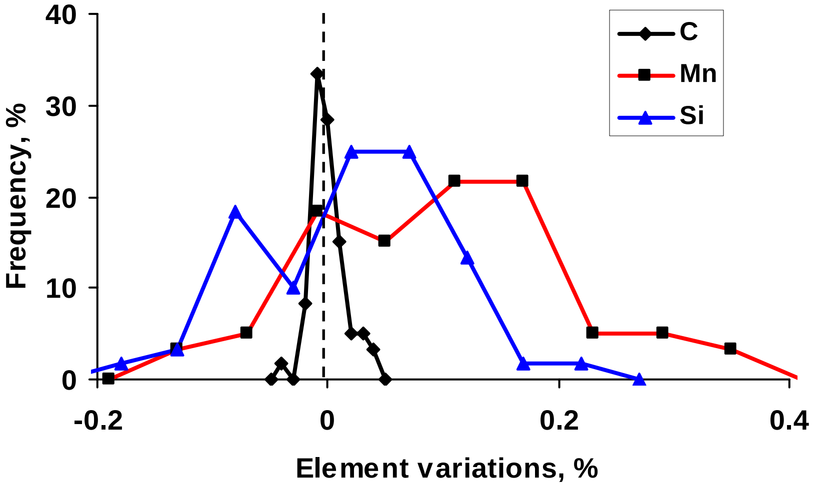

Figure 4. Variations of steel final concentration (EAF, Foundry C)

Foundry D. Four EAF trial heats were observed for this study. All were melted in a silica lined furnace with an acid slag practice. All materials were weighed before charging with no ferroalloys placed in the charge. Once the scrap is melted, a chemical sample is taken and the bath blown with oxygen for five to ten minutes. The ferroalloys are added once the temperature is at 2850-2900°F. The recovery of *Mn* and *Si*, as well as the statistical study of 21 heats is summarized in Table 11 and Figure 5. Both the Mn and Si curves are skewed to the high side of the range. There are opportunities to save alloys through alloy practice changes.

Table 11. Statistics of final steel chemistry produced in EAF for 21 heats (Foundry D)

	Mn	***Si***
Recovery, %	83	89
Aim	.75	.40
M	0.815	0.439
SD	0.091	0.049
Specification Range	0.6 – 0.9	0.30 – 0.50
SR/SD	3.2	4.1

Foundry E. This foundry operates three EAFs with silica lining. EAF #1 and #2 used oxy-fuel burners for accelerated preheating and melting of the solid charge with total heat times of less than 60 minutes. Statistical data for Si and Mn recovery for manganese and silicon additions in the EAF are summarized in Table 12. Distributions of alloying element compositions in the final melt for Furnace #3 were closest to the aim of the three furnaces and showed the least amount of variation as illustrated in Figure 6. Statistical parameters for the three furnaces are summarized in Table 13.

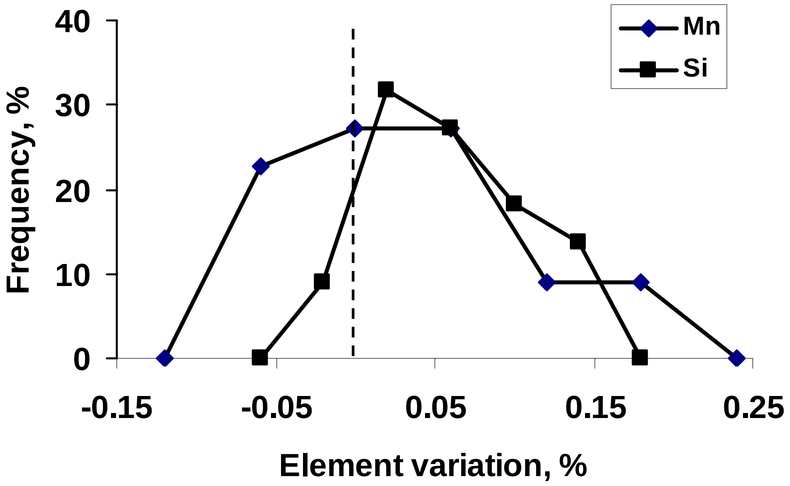

Figure 5. Variations of steel final concentration (EAF, Foundry D)

Table 12. Statistics of Mn and Si recovery (%) in EAF for 150 heats (Foundry E)

Furnace	Practice	***Si***	***Mn***
#1	FeMn & FeSi in EAF	81	69
#2	FeMn & FeSi in EAF	82	80
#3	FeMn & FeSi in EAF + FeSiBa in ladle	87	73

Table 13. Statistics of final steel chemistry (wt %) produced in 150 EAF heats (Foundry E)

	Mn			***Si***		
	EAF #1	EAR#2	EAF #3	EAF #1	EAF#2	EAF #3
Aim	0.80	0.80	0.80	0.45	0.45	0.45
M	0.87	0.89	0.82	0.43	0.38	0.42
SD	0.172	0.093	0.056	0.086	0.046	0.047
Specification Range	0.6 – 1.0	0.6 - 1.0	0.6 – 1.0	0.3 – 0.6	0.3 – 0.6	0.3 – 0.6
SR/SD	2.3	4.3	7.1	3.5	6.5	6.3

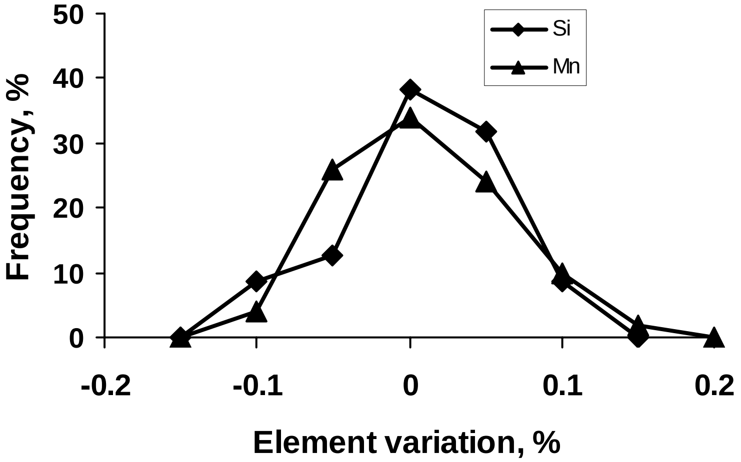

Figure 6. Variations of steel final concentration (EAF #3, Foundry E)

Foundry G. Statistical data distribution for the final *Mn* and *Si* compositions in 37 heats melted in #2 EAF are summarized in Table 14. This furnace used a magnesia furnace and basic melt practice.

Table 14. Statistics of final steel chemistry (wt %) produced in 37 EAF heats (Foundry G)

	Mn	***Si***
M	0.59	0.45
SD	0.107	0.144
Specification Range	0.5 -0.9	0.3 – 0.6
SR/SD	3.7	2.1

Preliminary Dissolution and Stirring Work

Work has started at UMR to examine the factors that affect dissolution rate. Results from some of the preliminary melts are plotted in Figure 8. In this series of experiments, a single addition of low carbon ferromanganese (raise Mn by 0.30%) was added to 100 lbs of 0.80% C steel in a special ladle with a porous plug mounted in the bottom. Two factors were varied in this series: ferroalloy size (0.79 inch diameter versus 1.18 inch diameter) and argon flow rate. Preliminary results suggest that alloy particle size is a more critical factor in dissolution rate than argon stirring. Future research will determine the factors that are most important to alloy control for foundries.

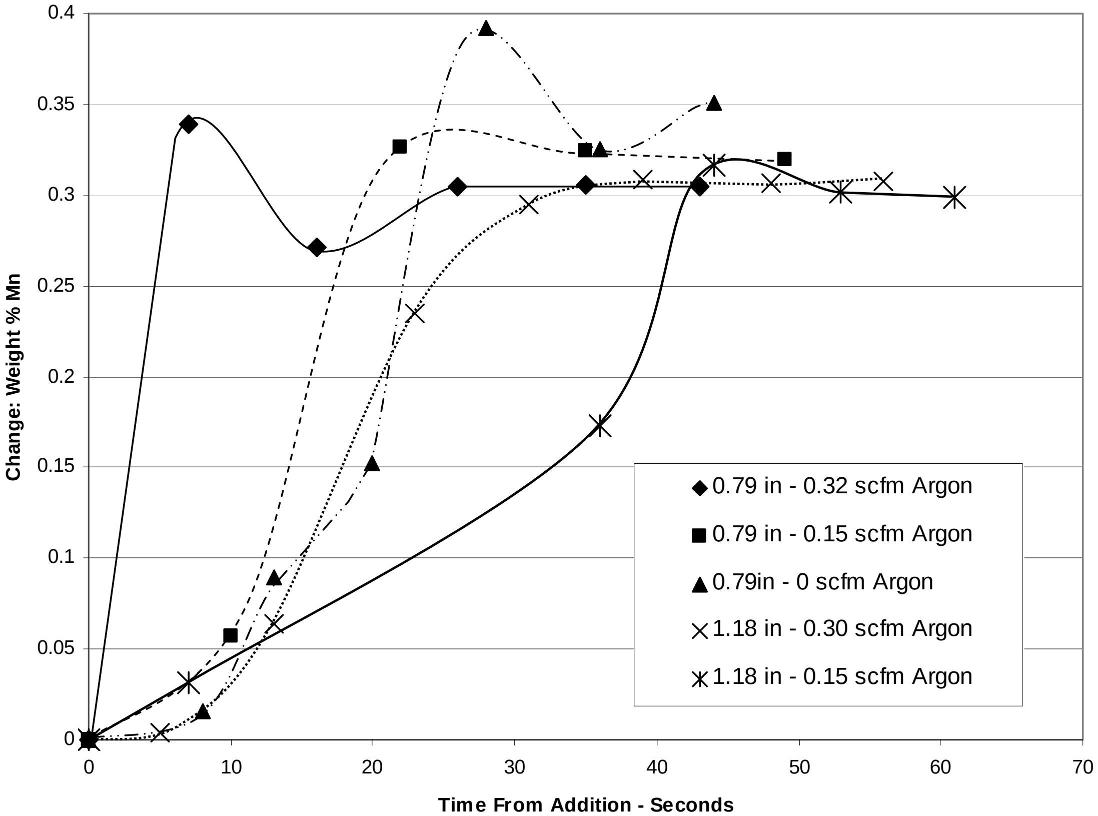

Figure 7. Change in Manganese Weight Percent with Time

Summary

This study of seven steel foundries showed that there is a vast variety of factors which influence the recovery of ferroalloys and the ability to tightly control final chemical composition. Table 15 shows the wide variation in Mn recoveries and alloy control capabilities between six of the foundries studied in this paper, induction furnace studies at UMR, and UMR trials at a LMF in a mini-mill. The intensive mixing in induction furnaces provides better homogeneity of alloying elements in final melt. The best industrial results were achieved in Foundry B, where recoveries of *Mn*, *Cr*, *Ni,* and *Mo* were high and the chemistry control was tighter. The laboratory results at UMR were slightly better than industrial operations due to the improved recovery in the ladle. Some of the factors observed in this study that affected alloy recovery and control (negative and positive) in induction furnaces included:

- Oxidizing conditions (melting in air, additives with charge, and slag on surface during alloying)
- Induction stirring after alloy addition
- Time of addition (charge, in furnace, or in ladle)
- Accuracy of weights and additions

Alloying in EAF furnaces was generally less accurate than in induction furnaces resulting in chemistry distributions with more scatter (see Figure 8). Figure 8 shows the improvement in recovery and control that can occur when alloys are added in the ladle. Some of the factors observed in this study that affected alloy recovery and control (negative and positive) in EAFs included:

- Lack of intense stirring resulting in less homogeneous chemistry
- More slag
- Time of addition (with charge-low recovery, in furnace, or in ladle-high recovery)
- Accuracy of weights and additions
- Dipping electrodes is extremely expensive method of adding carbon

Figure 8 shows the wide variation in chemistry control that occurs in foundries today. There are many opportunities for improvements that will save alloying costs as well as providing customers with steel castings that are more consistent in properties.

Table 15. Recovery and variation of Mn in different melting practices

%	IF			EAF				
	A	B	UMR	C	E	D	G	LMF
Recovery	65	78	92	-	69-80	83	-	95
SD	0.093	0.037	0.023	0.116	0.06-0.17	0.091	0.107	.052
SD/M	0.127	0.037	0.035	0.160	0.069-0.198	0.121	0.181	0.043
SR/SD	2.1	8.1	NA	4.3	2.3-7.1	3.2	3.7	9.3

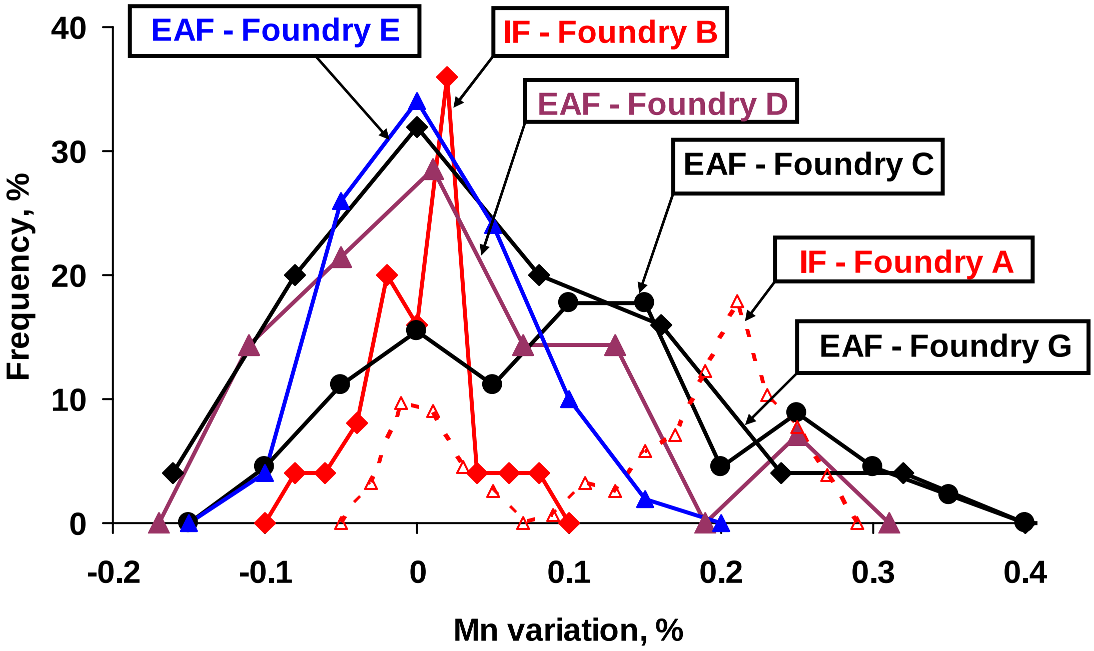

Figure 8. Variation of manganese concentration in steel melting in different foundries.

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