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Decreasing Electrical Energy Consumption Through SiC Additions

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ABSTRACT

This paper summarizes results of industrial experiments investigating the introduction of supplemental chemical energy in Electric Arc Furnaces (EAF). Specifically, this research evaluates the effects of adding 0.4-0.6% of the scrap charge weight as *SiC* (10 lbs per scrap ton charged) in the EAF. *SiC* additions increase the available exothermic reactions during oxygen boiling in an attempt to reduce the electrical energy requirements. Results from 180 trial heats at two different steel foundries are highlighted and statistically evaluated. In both cases, the *SiC* additions had a measurable effect on decreasing the electrical energy consumption.

1. INTRODUCTION

Supplemental chemical energy is a promising way for decreasing electrical energy consumption and increasing the efficiency and productivity of melting steel in foundry EAFs. There are many technologies that are possible for introducing supplemental chemical energy into the EAF steel melting process including:

- preheating the charge
- oxy-fuel burners for heating cold regions of the solid charge during melt down
- post-combustion of CO produced in the furnace to CO_2
- exothermic heat from oxidation reactions within the melt.

Both preheating the charge and oxy-fuel burners have the potential of increasing the melting efficiency of the solid scrap charge. Figure 1a illustrates the energy balance during the melting period. During the scrap melting period, electrical energy is input at a fixed rate determined by the electrical transformer settings. Heat losses occur through the furnace sidewalls and roof with some additional losses through sensible heat in the off gas. The addition of chemical energy through the introduction of an oxy-fuel burner can significantly decrease melting time by eliminating “cold” spots such as the area near the charge door which melt slower than the rest of bath. The reduction in melting time results in a reduction in electrical energy. The overall energy efficiency improves because the reduction in melt time results in less convection and radiation heat losses through the walls and roof.

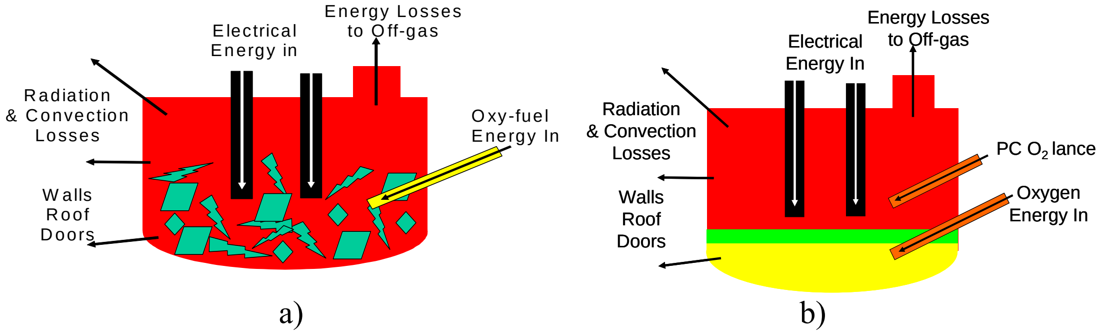


Figure 1. Energy use and losses (a) during scrap melting and (b) during flat bath periods

The second two supplementary chemical energy methods, post-combustion of *CO* in the furnace to CO_2 and exothermic heat from oxidation reactions to the melt, could both increase energy efficiency during the flat bath period (see Figure 1b). Opportunities to increase the energy efficiency are greatest during this period because the electrical energy efficiency drops significantly when heating liquid steel with an open arc in air. A significant portion of the arc energy is reflected from the arc and bath surface to the sidewalls and roof where the energy is lost in heating (and often melting) refractory rather than steel. In addition to using chemical energy, there is a future potential of increasing arc efficiency by utilizing more energy efficient long arcs (higher voltage and lower current) with a foamy slag to decrease the heat losses by blanketing the arc.

Scrap preheating systems, oxy-fuel burners and post-combustion of *CO* require additional capital investment. By comparison, the addition of a material such as *SiC* which produces exothermic reactions during the oxygen blow does not require any capital investment. Figure 2 illustrates the advantage of using *SiC* as a source of chemical energy. Because the heat is generated within the liquid steel, heat transfer efficiency from the exothermic reactions should be nearly 100%, much higher than the typical 40% efficiency for post-combustion of *CO* above the bath.

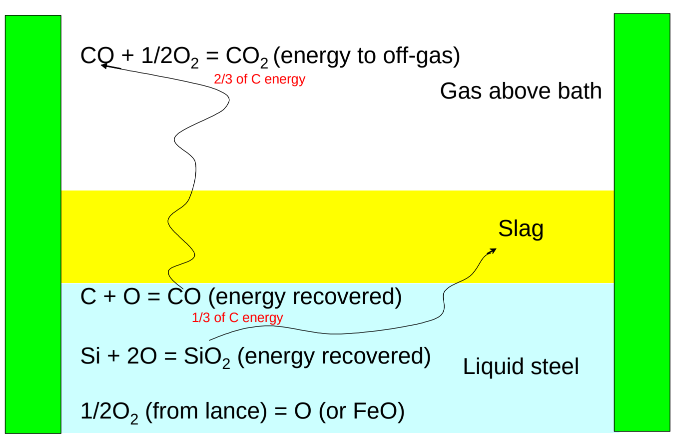


Figure 2. Chemical energy in the steel, slag and above the bath of the EAF

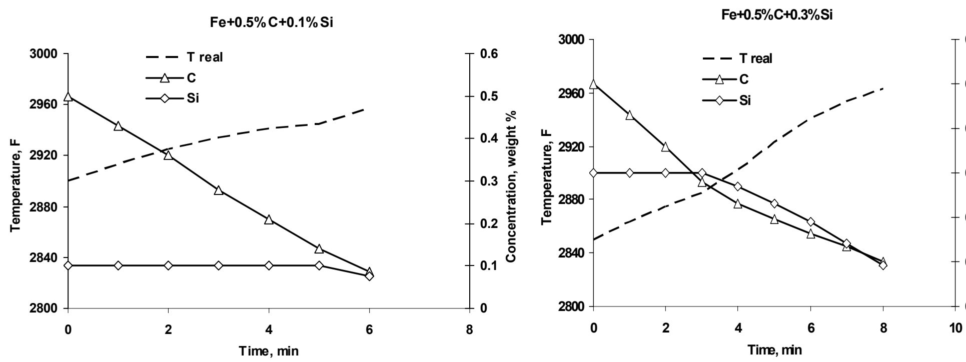
In this research work, the amount of exothermic heat generated during oxygen boiling was increased by adding *SiC* with the solid charge. The purpose of this investigation was to evaluate the energy and operational effects of adding enough *SiC* with the scrap charge to represent 0.4-0.6% of the charge weight in two foundries. The first foundry, Foundry A, uses 20 ton EAFs with no oxy-fuel burner, and the second foundry, Foundry B, uses 5 ton EAFs with oxy-fuel burners. This paper summarizes thermodynamic calculations, industrial measurements, heat balances and statistics of the industrial data.

2. EXOTHERMIC ENERGY DURING OXYGEN BOILING OF STEEL

Calculations with FactSage, a commercial thermodynamic software, combined with statistical analysis from 80 industrial heats from the 20 ton EAF's at Foundry A were used as a baseline evaluation of the exothermic reactions during oxygen boiling for a normal melting practice (no *SiC* addition).

2.1 *FactSage calculations.* During the oxygen boil, oxygen reacts with dissolved carbon, silicon and manganese in the steel melt. FactSage, a commercial software database and free energy minimization program, was used to compute the expected amounts of reactants remaining in the liquid steel and the resulting energy generated during the oxygen boiling process. The model considered the possible reactions of *C* with O_2 to form *CO*, *Si* with O_2 to form SiO_2 and *Mn* with O_2 to form *MnO* in the steel melt, the cooling effect of the oxygen gas (initial temperature at 80°F) and the heat losses from the melt during boiling as an enthalpy sink. The rate of heat loss was calculated on the basis of experimental measurements of the rate of temperature drop during holding of liquid steel in an EAF with the power-off.

Two examples comparing the effects of steel melt down compositions on the amount of energy generated during oxygen blow are shown in Figure 3. Figure 3a shows the computed change of melt composition and temperature for a typical heat melting in with 0.5% *C* and 0.10% *Si*. Figure 3b shows the difference in the temperature of the liquid steel in a heat where the carbon is the same (0.5% C) but the *Si* is elevated to 0.3% *Si*. During the oxygen blow, the reactions of oxygen with carbon and/or silicon and manganese depend on the steel chemistry and temperature. Increasing the silicon content in the melt from 0.1 to 0.3% doubles the amount of available chemical energy when blowing the carbon down from 0.5%*C* to 0.1%*C* (see Figure 4). These calculations show that *SiC* additions allow the possibility of blowing oxygen sooner in the bath (lower initial temperature) and result in higher temperatures at the end of the oxygen blow. The higher steel temperature after the oxygen blow could provide enough energy to compensate for the heat losses during the alloying and killing of the steel with cold ferroalloys (*FeSi*, *FeSiMn* and *FeMn*) as well as for a period of final chemistry corrections.



a) 0.5%C and 0.1%Si before oxygen blow b) 0.5%C and 0.3%Si before oxygen blow

Figure 3. Influence of melt *Si* content on steel composition and temperature during oxygen blow

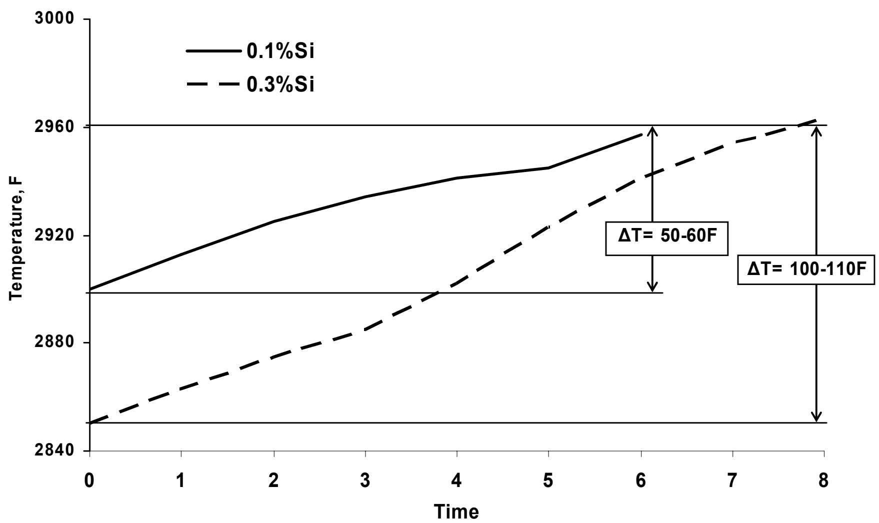


Figure 4. The potential melt temperature increase from higher Si during oxygen blow

2.2 ***Statistics of chemical energy usage during oxygen blow in Foundry A (no SiC).*** Actual changes in the melt temperature during the oxygen blow were studied by evaluating 80 heats produced using the normal melting practice (no *SiC* additions). The results were tabulated and statistically analyzed. The change in the melt temperature during the oxygen blow varied from slightly less than zero to 150 °F increase with an average increase of 57 °F (Figure 5a). The efficiency of chemical energy usage during the oxygen blow was calculated as a ratio between the actual temperature increase and the theoretically possible value based on the chemistry change. The average value of chemical energy efficiency for carbon and silicon oxidation during the oxygen blow was 39% based on the actual temperature increase (see Figure 5b). Multiple regression analysis (Equation 1) showed that silicon oxidized during the oxygen blowing (Δ*Si* weight %) was more effective in raising the temperature than oxidizing carbon (Δ*C*, weight %).

$$\Delta T(°F) = 103.5 * (\Delta C,\ \text{weight}\ \%) + 132.1 * (\Delta Si\ \text{weight}\ \%) \qquad (1)$$

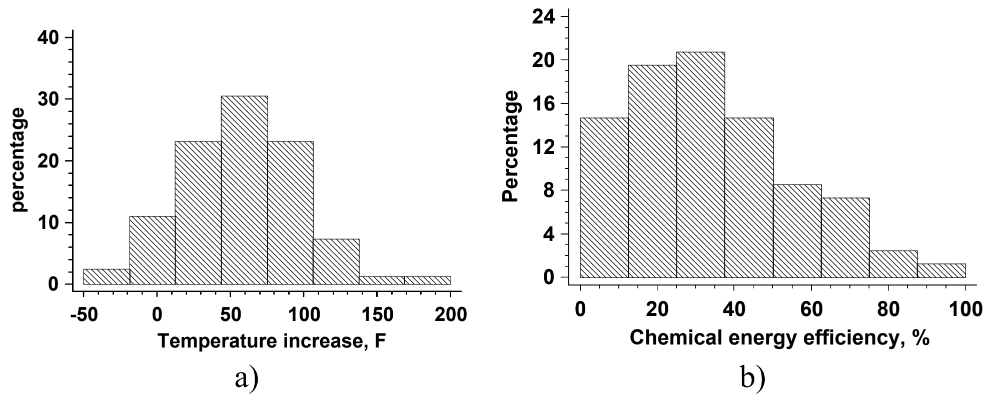


Figure 5. Statistics of a) melt temperature change and b) chemical energy efficiency during oxygen blow for normal melt practice at Foundry A (no SiC addition)

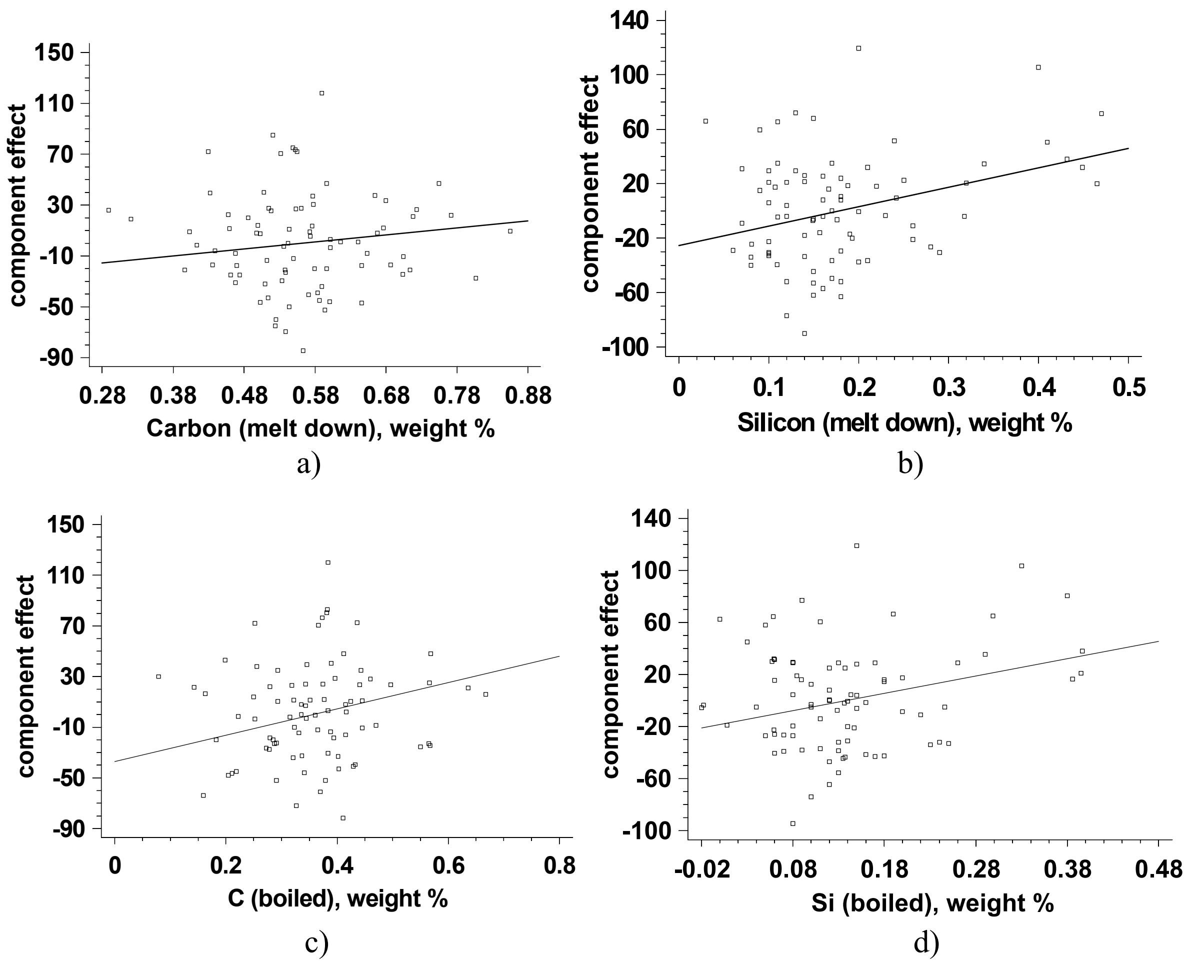


Figure 6. Influence of *C* and *Si* in melt down (a and b) and amount removed during oxygen blow (c and d) on melt temperature using at Foundry A (no SiC addition)

Statistics for the temperature increase versus melt down *C* and *Si* chemistry as well as oxidized *C* and *Si* are shown in Figure 6. Both thermodynamic calculations and foundry statistics show that higher silicon content decreases the need for electrical energy during the flat bath (correction) period.

3. INDUSTRIAL TRIAL RESULTS AT FOUNDRY A

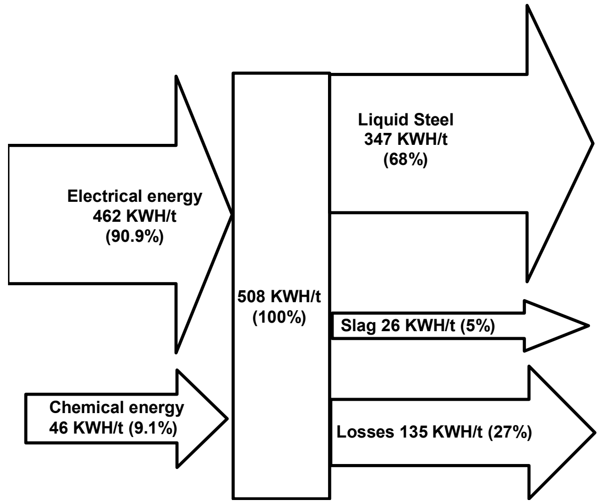
3.1 Observed heats with SiC. In the industrial trials, 200 lbs of *SiC* (material is 90 weight % *SiC*) were added with the 40,000 lb scrap charge. Carbon additions in the charge, pig iron and/or charge carbon (82 weight % *C*), were decreased in these heats to compensate for the additional carbon content in the *SiC* (28 weight % *C*). Results from the observed trial heats are summarized in Table 1. An energy balance comparing a heat containing 200 lbs. of *SiC* with the regular melting practice from a previous UMR trial is given in Figure 7. With *SiC*, the available chemical energy was nearly double (17% versus 9.1%) that a of normal heat. Total and operational energy efficiencies for three heats from the trials with *SiC* are compared with three heats using the regular melting practice (no *SiC*) in Figure 8. Introduction of *SiC* increased the energy efficiency during the flat bath (correction) period and the total energy efficiency by 5 to 10%.

Table 1. Results of observed heats with *SiC* additions in charge

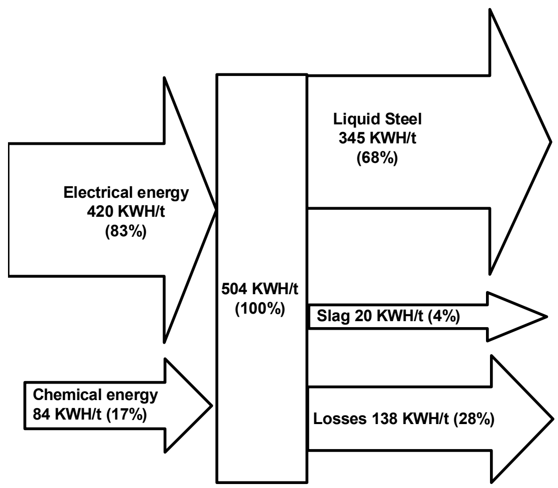
#Heat	EAF	Charge, lb.				Heat time, min	KWH/ton
		SiC	C	Pig iron	Dust		
E1036	4	200	150			169	455
E1037	4	200	150	1000		155	420
E1038	4	200	275			212 (20 min delay)	454
E1042	4	200	75	1000		151	456
E1043	4	200	225	1020		147	438
E1044	4	200	100	1090		174 (20 min delay)	443
V1032	3	200	150			168	417
V1033	3	200	275	1000	1000	205 (cold lining)	488
V1038	3	200	275	1000	1000	217 (cold lining)	462
V1039	3	200	100	800	1000	180	430

3.2. Statistical comparison of industrial heats. In addition to the three trial heats illustrated, 120 test heats were made using 200 lbs of *SiC* in the solid charge. Data from these heats were statistically compared to 120 heats without *SiC* additions. Data from EAF #3 (brick roof) was separately analyzed from EAF #4 (water cooled roof) data because previous statistical analysis showed that there were substantial differences in the energy consumption in these two furnaces.

a) Energy consumption statistics for EAF #3 (brick roof). Statistical data from a 60 heat set with *SiC* was compared to a 60 heat set without *SiC* in Table 2 and Figure 9. The introduction of *SiC* resulted in an average decrease of 33 KWH/ton in the electrical energy consumption. There is a statistically significant difference between the means of the two sets of heats at the 95.0% confidence level.



a)



b)

Figure 7. Heat balances (modified Sankey diagram) heats a) without and b) with SiC

During the melting of the 60 heat trial containing *SiC*, other melting factors were varied which also affected energy consumption. The analyzed factors included variations in weight and composition of the scrap charge and differences in the heat time. In 18 of the trial heats, 800 – 1000 lbs. of EAF baghouse dust was recycled with the scrap charge. Because the iron in this material is primarily iron oxide, any iron recovered by the bath is a result of the iron oxide in the dust being reduced through oxidation of silicon, carbon or manganese in the bath. This could also have an influence on the effectiveness of *SiC* and the recovery of alloying elements. Therefore, data was analyzed separately for heats with and without EAF dust in charge (Table 3 through Table 5). These tables also compare the operating results for the 60 heats without *SiC* with the 60 heats with *SiC*.

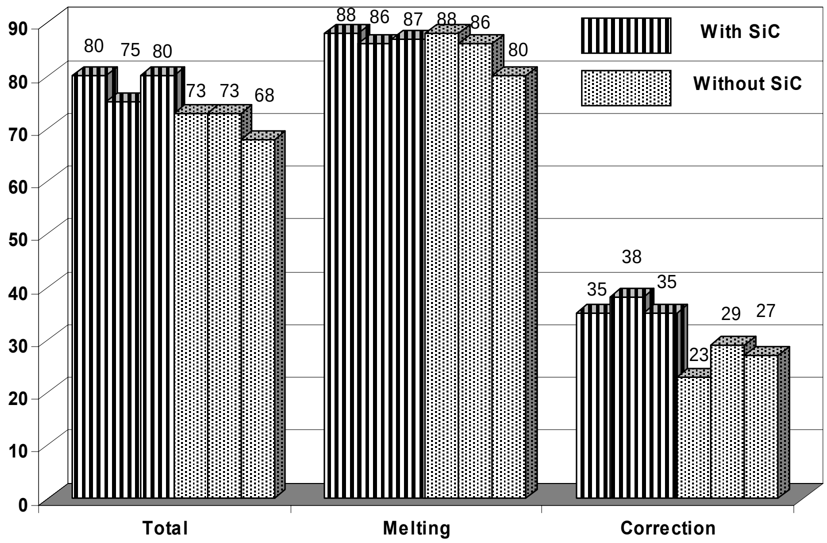


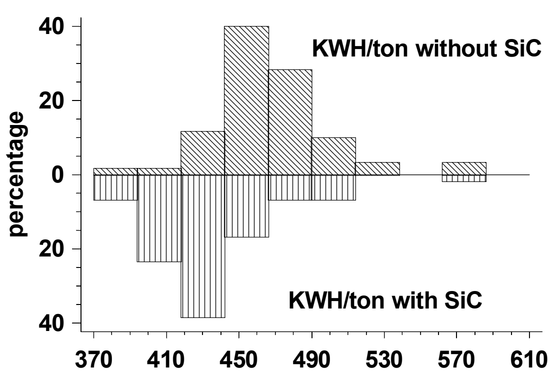
Figure 8. Comparison of total and operational energy efficiency for heats with and without *SiC*

Table 2. Comparison of energy consumption for melting steel in EAF#3

Parameter	Before	With SiC
Average	467.3	434.1
Standard deviation	32.4	34.3
95.0% confidence interval for mean	458.9 - 475.6	425.2 - 442.9

Table 3. Effect of *SiC* additions and melting practice on energy consumption and productivity for EAF #3

Heats	Electrical energy consumption		EAF productivity	
	KWH/ton	Decrease, %	Ton/hour	Increase, %
Without *SiC*	467.3	-	6.22	-
With *SiC*:				
- all 60 heats	434.1	7.1	6.54	4.8
- 18 heats with EAF dust	441.1	5.6	6.47	4.0
- 42 heats without EAF dust	430.7	7.8	6.57	5.6



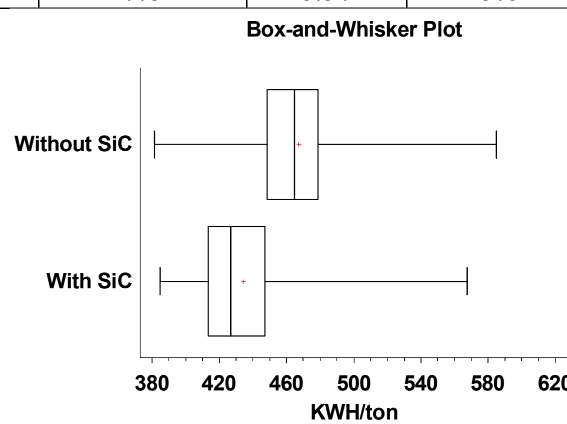


Figure 9. Comparison of energy consumption for melting steel (EAF #3)

Table 4. Influence of *SiC* and dust on changing melt down steel composition in EAF #3

Average concentration in melt down, weight %	Without *SiC*	With *SiC*
Carbon	0.560	0.556
Silicon:		
- all 60 heats	0.13	0.25
- 18 heats with EAF dust		0.18
- 42 heats without EAF dust		0.27
Manganese:		
- all 60 heats	0.31	0.36
- 18 heats with EAF dust		0.29
- 42 heats without EAF dust		0.38

Table 5. Influence of *SiC* and dust on changing heat time in EAF #3

Average time	Without *SiC*, min	With *SiC*, min
Melting of charge:		
- all 60 heats	146	140
- 18 heats with EAF dust		144
- 42 heats without EAF dust		138
Flat bath (correction period):		
- all 60 heats	55	52
- 18 heats with EAF dust		53
- 42 heats without EAF dust		51
Heat time (from power on to tap):		
- all 60 heats	201	192
- 18 heats with EAF dust		197
- 42 heats without EAF dust		189
Tap to tap time:		
- all 60 heats	290	265
- 18 heats with EAF dust		279
- 42 heats without EAF dust		258

In examining Table 5, the heat time and tap to tap time decreased between 5 and 10% in heats with *SiC* when compared to similar heats without *SiC*. In addition to the added chemical energy reducing the "power-on" time, delays due to an overactive bath were eliminated resulting in more consistent and controlled melting. The results of the multiple regression analysis of energy consumption for 60 heats with *SiC* additions are given in Figure 10 and the equation of the fitted model (Equation 2) is:

$$\begin{aligned} KWH/t = {} & 620 - 12.5*(\text{Charge weight, t}) \\ & + 14*(1 \text{ - for heats with dust, } 0 \text{ - for heats without dust}) \\ & + 0.38*(\text{Charge melt, min}) \\ & + 0.17*(\text{Flat bath, min}) \\ & + 0.10*(\text{Time between heats, min}) \end{aligned} \qquad (2)$$

The R-Squared statistics indicates that the model as fitted explains 59.5% of the variability in KWH/ton. From this data, increasing the charge weight or shortening of the tap-to-tap time in either the melting, flat bath (correction) period as well as the time between heats decreases the electrical energy consumption.

The increase in the silicon based on the addition of 200 lbs of *SiC* also resulted in additional oxygen requirements to provide the chemical energy during the oxygen blow for the silicon to silica reaction. The actual amount of oxygen used was fit to the following Equation 3, based on readings from the meter placed on the furnace panel:

$$O_2\text{, lbs} = 440*(\text{weight \% of } C_{\text{boiled}}) + 413*(\text{weight \% of } Si_{\text{melt down}}) \quad (3)$$

The temperature change during the oxygen blowing was fitted to Equation 4 and *C* and *Si* component effects are plotted in Figure 11:

$$\Delta T,\ ^{\circ}F = 85*(\text{weight \% of } C_{\text{boiled}}) + 128*(\text{weight \% of } Si_{\text{boiled}}) \quad (4)$$

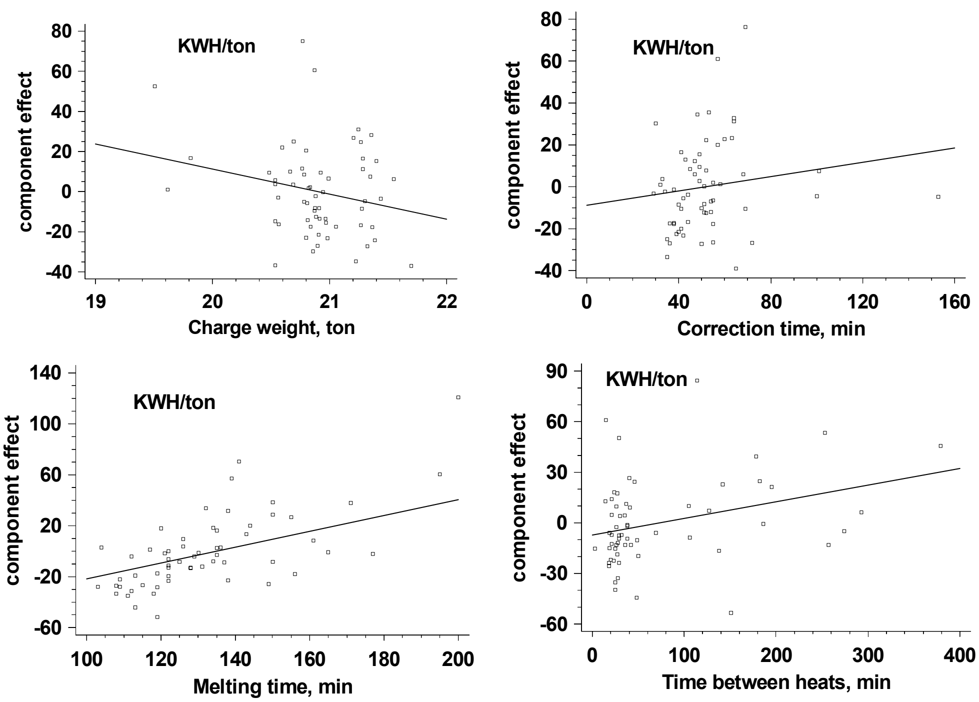


Figure 10. Multiple linear regression model of energy consumption for melting steel in EAF #3 with 200 lbs of SiC in charge

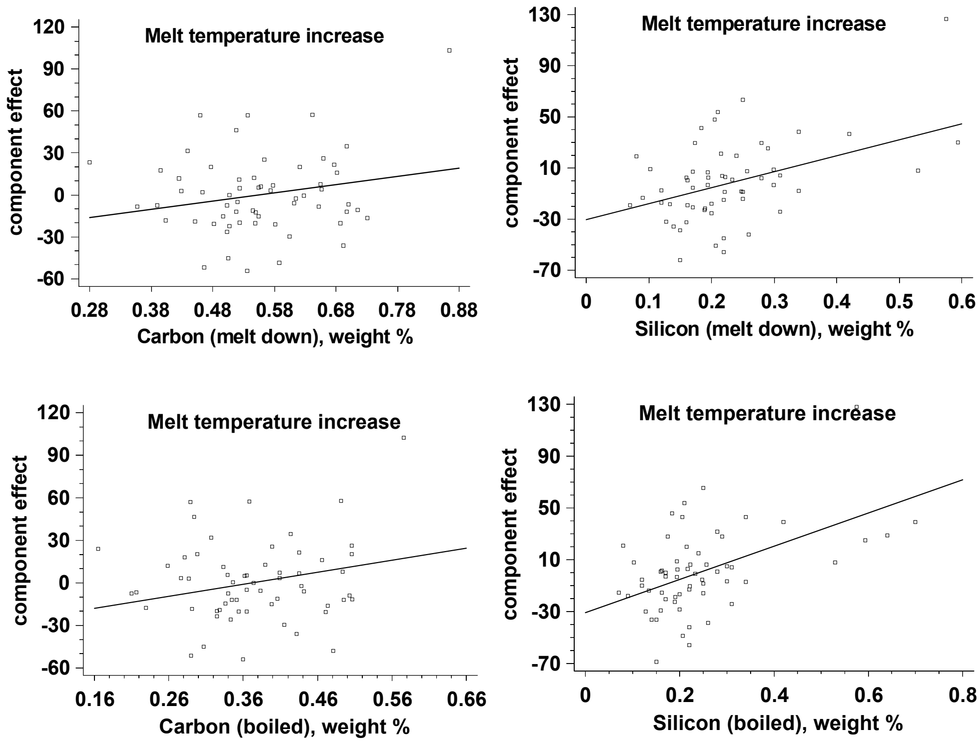


Figure 11. Influence of *C* and *Si* in melt down on increasing melt temperature during oxygen boiling in EAF #3 with 200 lbs of *SiC* in charge

b) EAF #4 (with water cooled roof) – energy consumption statistics. The data from EAF #4 was considered separately because it utilizes a water-cooled roof resulting in much different heat transfer and electrical usage. Similar to EAF #3, 60 heats with 200 lbs of SiC were compared with 60 heats using the traditional melting practice immediately prior to the trial. The summary of statistics of energy consumption is in Table 6. In this case, none of the heats contained EAF baghouse dust and energy consumptions were compared for "cold start" heats and heats produced on a "hot lining". There were statistically significant differences between each data sets at 95% confidential level.

Table 6. Comparison of average electrical energy consumption (KWH/ton) for heats in EAF #4

	Without *SiC*	With *SiC*	Decrease
Electrical energy consumption:			
- average for all 60 heats	484	463	21
- for heats with "cold start"	496	491	5
- for heats with "hot lining"	481	458	23

3.3. Evaluation of energy efficiency of SiC additions in charge. The average energy efficiency of the silicon and carbon contained in the *SiC* additions was calculated as a ratio of the experimentally measured temperature change to the theoretically possible temperature increase based on the silicon and carbon oxidation during the oxygen blowing. Theoretically, the oxidation of 0.10% *Si* provides 7.77 KWH/ton of steel. As a result, the addition of 200 lbs of *SiC* (product contained 90% *SiC* which is 70% *Si* by weight) to a 40 000 lb charge adds 0.31% *Si* to the bath at melt-in. This quantity of *Si* would theoretically add 24 KWH/t of chemical energy. This number is less than the electrical energy saved during experimental measurements in EAF #3 (33 KWH/ton) and very close to the actual energy saved in EAF #4 (21 KWH/ton). The 40% increase above the theoretical experienced in EAF #3 was a result of dramatic melting practice improvements in the heats containing *SiC*. The *SiC* addition not only decreased the electrical energy required by replacing electrical energy with chemical energy, but the recovery of the chemical energy from the carbon increased because of the much less violent bath reactions from carbon boiling.

4. INDUSTRIAL TRIAL RESULTS AT FOUNDRY B

The purpose of this investigation was to statistically evaluate the energy and operational effects of using *SiC* additions in the charge of the electric arc furnaces (EAF#3 at Foundry B). 60 lbs SiC was used in a 5 to 6 ton charge of EAF#3 which was approximately 0.5-0.6% of the metallic charge. This furnace is equipped with an oxy-fuel burner and PLC controls.

4.1. Energy consumption statistics. The melting results of 30 heats produced with a 60 lb addition of *SiC* were compared with the results of 30 heats produced without *SiC*. Heat log data of the base practice and practice with *SiC* were compared and statistically analyzed using the following parameters:

- charge weight, lbs
- electrical energy consumption, KWH/heat and KWH/t
- power on time, min
- tap-to-tap time, min
- EAF productivity calculated as a ratio: (charge weight, t)/(tap-to-tap time, hour)
- EAF melting productivity calculated as a ratio (charge weight, t)/(power on time, hour).

Table 7. Comparison of average data for two melting practices at Foundry B (with and without *SiC*)

	# Heat	kWh/t	EAF productivity, t/hour	Melting productivity, t/hour	Power-on time, min	Tap-to-tap time, min
With SiC: -all heats -hot lining -cold lining	 33 30 3	 420.9 410.6 523.3	3.04	3.63	82	98
Base practice: -all heats -hot lining -cold lining	 33 30 3	 440.6 432.3 524.1	2.97	3.63	80	99

A comparison of the two melting practices is summarized in Table 7. The heats were separated by heats melted on a hot lining and heats melted on a cold lining. The summary of the electrical energy consumption statistics for the heats produced on a hot lining with both practices is in Table 8. Based on the t-test comparison, there was a statistically significant difference between the means of the two sample cases (base practice and *SiC*) at the 99.0% confidence level. A statistical distribution of the electrical energy consumption for the two melting practices for heats on a hot lining are shown in Figure 12.

Table 8. Summary of statistics for electrical energy consumption at Foundry B KWH/t (heats with hot lining)

Parameters	With SiC additions	Base practice
Heats #	30	30
Average	410.6	432.3
Standard deviation	24.8	25.1
Minimum	367	381
Maximum	489	501
99.0% confidence interval for mean	398.1 – 423.1	419.7 - 444.9
P-value	0.00138731	
t-value	-3.359	

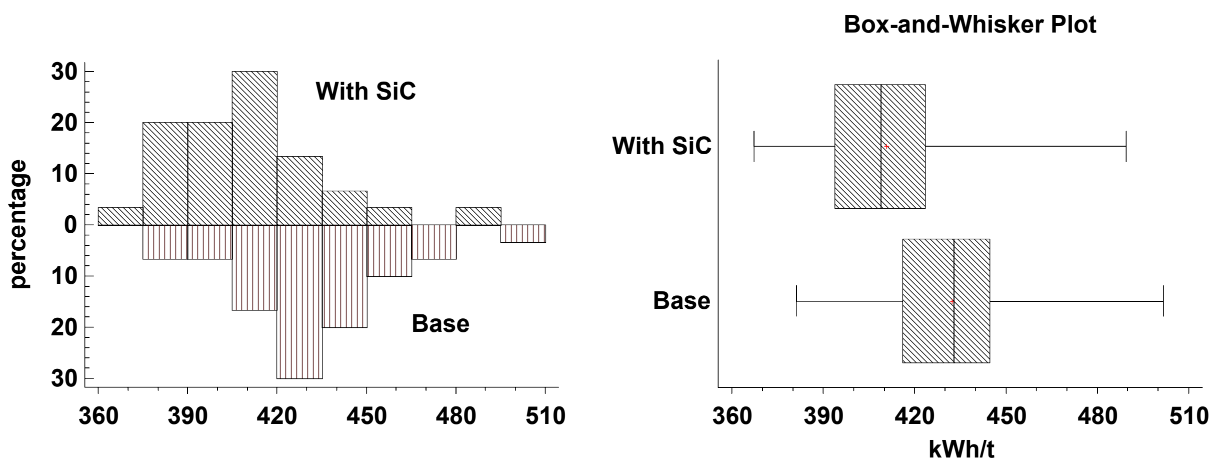


Figure 12. Statistics of electrical energy consumption for melting steel at Foundry B with and without *SiC* on a hot lining

4.2. Multiple regression analysis. Multiple regression analysis showed (Figure13) that two factors had statistical influence on electrical energy consumption for melting practices with and without *SiC* additions (based on heats melted with a hot lining). These factors were tap-to-tap time and EAF productivity. Not surprisingly, increasing productivity and decreasing tap-to-tap time (or power-on time) decreased the electrical energy consumption for melting on a per-ton-of-steel basis. In comparing the two linear regression lines, the KWh/t line for heats with *SiC* is approximately 20 KWH/t lower than heat without *SiC*, in agreement with the overall average. In both cases, the addition of chemical energy reduced the energy consumption.

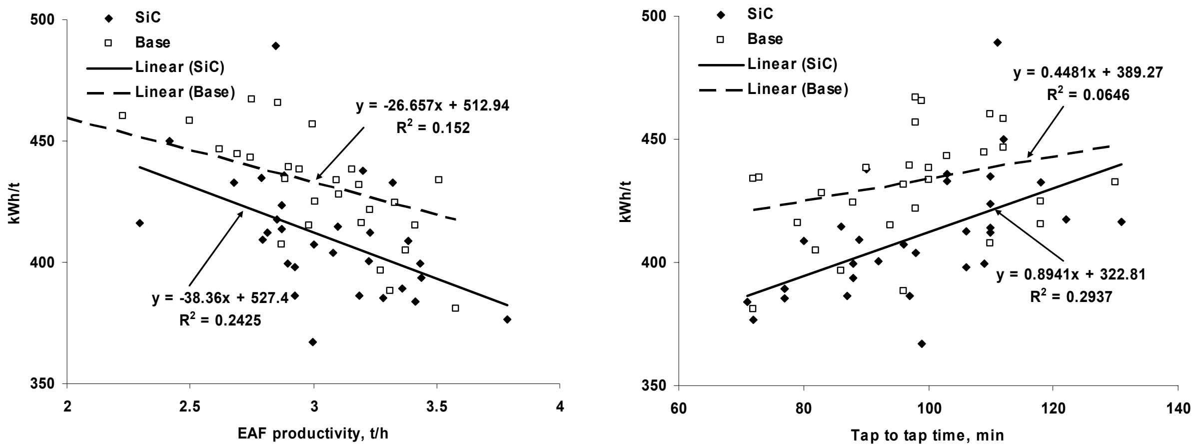


Figure 13. Electrical energy consumption versus EAF productivity and tap-to-tap time for different melting practices at Foundry B

5. CONCLUSIONS

1. ***Foundry A***. The addition of 200 lbs of *SiC* in a 20 ton EAF charge had a measurable effect on decreasing the electrical energy consumption and increasing the productivity of the melt shop:

- 33 KHW/ton decrease in the average electrical energy consumption in EAF #3 (with brick roof) from 467 kWh/ton to 434 kWh/ton
- 21 KWH/ton decrease in the average electrical energy consumption in EAF #4 (with water cooled roof) from 484 KWH/ton to 463 kWh/ton
- 5% to 10% increase in the average EAF productivity.

2. ***Foundry B***. The addition of 60 lbs of *SiC* in a 5 - 6 ton EAF charge decreased the electrical energy consumption by an average of 22 kWh/t (from 432 kWh/t to 410 kWh/t), a 5% reduction. Although electrical energy was saved, there was no statistically significant improvement in the EAF productivity because this foundry is utilizing oxy-fuel burners and maximizing the power-on time. Power-on time averaged 80% of the total tap-to-tap time, one of the highest (if not the highest) percentages in the U.S. foundry. Previous studies have shown that the U.S. steel foundry average power-on percentage is 50-60%.

3. There were other melting improvements as a direct result of the *SiC* addition including a lowering of the start temperature for oxygen boiling, decrease in the lining erosion, increase in the lifetime of refractory roofs, and safer (less violent) oxygen boiling. The addition of 0.4-0.6% of *SiC* in the charge decreased electrical energy consumption by an average of 22 -33 kWh/t or 5% for both foundries.