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Abstract

Theoretical Investigation of the Impact of Impurities in Recycled Silicon Used for the Production of Ferrosilicon †

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1. Introduction

Ferrosilicon (FeSi) is produced using a carbothermal process, usually in closed submerged electric arc furnaces. Quartzites are used as the silicon source in the production of FeSi, while coke (coal or wood chips) is the primary source of carbon reductant [1,2]. Steel scrap is the primary source of iron (called iron chips) [3]. The iron lowers the partial pressure of silica (SiO_2) required for reduction and forms FeSi solutions that reduce the activity of Si. Hence, the process could be carried out at lower temperatures than those employed for the production of silicon. This also results in higher Si yield (less of SiO_2) and lower energy consumption per ton of metal [4]. Approximate charge composition, energy demand and silicon yield for ferrosilicon smelting in a closed furnace for each ton of FeSi produced is shown in Table 1 [4].

Table 1. Typical materials and energy demand for smelting of FeSi in closed furnaces (for 1 ton of alloy) [4].

FeSi Alloy	FeSi20	FeSi25	FeSi45	FeSi65	FeSi75Al
Quartzite, kg	370	552	931	1568	1930
Iron chips, kg	810	780	658	343	250
Coke, kg	200	280	438	720	845
Electrode paste, kg	10	8	16	43.3	54
Electricity, MWh/t	2.1	2.7	4.8	7.4	8.8
Silicon yield, %	94–95	97–98.5	98–99	92–94	91–93

The carbothermic reduction of the silicon process releases huge amounts of greenhouse gases, which also leads to energy loss. To combat climate change, it is imperative to limit the amount of greenhouse gasses emitted during the production process. This could be performed by using recycled silicon recovered from different electronic waste sources. Recycling the metal-contaminated silicon, destined for landfills, in manufacturing FeS using only electricity as the source of energy, could potentially lead to reduced carbon footprint. There are several uses of FeSi in the metallurgy industry. It is used as a deoxidizer, as a carrier of silicon to produce alloys such as silicon steel, and as a carrier for other alloying agents. Therefore, the composition of the FeSi is crucial for the quality of the final product [4]. In recent years, there has been growing interest in the use of recycled material for the production of ferrosilicon [5–10]. Recently, the use of silicon from electronic waste (e-waste) was suggested as a silicon source for the production of FeSi [10]. The recycled

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silicon recovered from e-waste can have several other metal impurities in small quantities, such as silver, copper, aluminum, tin, and lead [11]. It would be helpful to understand the role of the impurities in the FeSi manufacturing process and the impact on the final availability of the Si for the desired process.

2. Aim and Approach

In this work, we investigate the impact of the major impurities found in recycled silicon on the production of FeSi. The formation of FeSi under equilibrium conditions is investigated with the help of FACTSAGE 8.3 software, while varying the impurities present in the recycled Si. The approximate composition of different metals (in percent) mixed with the Si recovered from electronic waste is shown in Table 2. Here, two assumptions are considered: (a) the plastic and other non-metallic components were removed by simple physical processes [11,12], and (b) scrap steel with extremely low carbon content (<0.2%) was treated as a solvent. Therefore, carbon was not included as a component in the analysis. The percentages of metal mixed with silicon in e-waste were used as the basis for the design of hypothetical systems. The Si/Fe ratio in each alloy system and the total weight of the alloy system is kept constant while the percentages of impurities in Table 2 was used to calculate the amount of individual impurities.

Table 2. Approximate content (in percentage) of impurities commonly found in silicon recovered from e-waste [11–15].

No	Material	Percentage in e-Waste [%]
1	Copper (Cu)	1–3%
2	Aluminum (Al)	3–5%
3	Silver (Ag)	1–3%
4	Tin (Sn)	0.5–1%
5	Lead (Pb)	0.5–1%
6	Silicon (Si)	Remaining

The composition of different systems studied in this work are presented in Table 3. A system containing only Fe and Si is taken as the reference system (S-0). The differences with respect to the different phases formed, crystallization temperature, and phase transition temperature are evaluated. The systems are simulated from a temperature of 1500 °C to 100 °C. Phase diagrams for some interesting transformations are also presented. The impact of the phases on the usability and availability of silicon is discussed. This work shows what impurities are critical and should be removed before using recycled silicon for the production of FeSi.

Table 3. Approximate composition (in kg) of the hypothetical furnace charge for FeSi production, where Si is sourced from e-waste while scrap steel is used as a source of Fe.

Alloy Systems	Fe [kg]	Si [kg]	Ag [kg]	Al [kg]	Cu [kg]	Sn [kg]	Pb [kg]	Total [kg]
S-0	55	45						100
S-1	54.7	44.8	0.5					100
S-2	53.9	44.2	0.5	1.4				100
S-3	53.6	44.0	0.5	1.4	0.5			100
S-4	53.5	43.9	0.5	1.4	0.5	0.2		100
S-5	53.4	43.8	0.5	1.4	0.5	0.2	0.2	100

3. Preliminary Results and Discussion

The different alloy systems exhibit different behaviors in terms of number and amount of phases present throughout the cooling process. For example, in system S-1, where Ag is the only metal impurity, no further phase transformation occurs below 800 °C, when the entire system solidifies. In this system, the Ag does not form any alloys with either Fe or Si, and solidifies as a pure phase. The final phases present in such a system would be Ag and a mixture of FeSi and $FeSi_2$. Hence, in such a system, it is expected that Ag crystals would be found distributed throughout the microstructure comprising FeSi and $FeSi_2$. However, when the system contains Al along with Ag, a silver rich alloy with Al, Fe, and Si is formed. In this case, the entire system solidifies at 666 °C and no new phases emerge upon further cooling. At 100 °C, the system comprises three distinct mixtures. A Fe rich phase comprising $FeSi_2$ and $FeAl_2$ is obtained in the maximum quantity. Another solid phase consisting of a mixture of FeSi and $FeSiAl_2$ is also found to be present in smaller quantities. The third mixture comprises a Ag rich alloy consisting mostly of Al and an almost negligible quantity of Fe and Si. Hence, it can be hypothesized that the presence of Ag alone would not cause any difference to the availability of Si in the finally obtained FeSi; however, any additional impurity such as Al, Sn, Cu, or Pb may form alloys with Fe and Si and affect the quantity and the quality of the Si available in the final FeSi obtained. Figure 1 shows the phase diagram of the S-2 system computed with the help of FactSage 8.3 with composition as mentioned in Table 3. Further results will be shown in the conference.

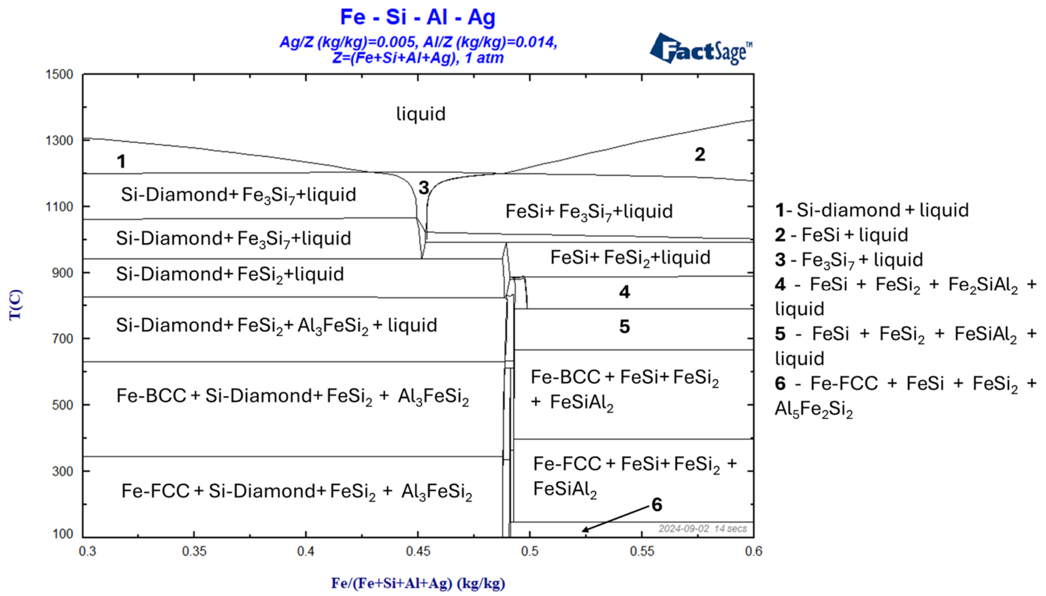

Figure 1. Phase diagram of the Fe-Si-Al-Ag system as computed with FactSage 8.3.

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