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Energy-Saving Process for Industrial Production of Ferro-Silicon-Magnesium Alloy

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Abstract

Ferro-silicon-magnesium (FeSiMg) is an essential addition currently used in the production of ductile cast iron. FeSiMg is considered an excellent alloy to introduce magnesium into cast iron to modify the form of graphite in matrix from flake-shaped graphite into nodular graphite.

Two-step route is currently the most common technique for producing ferro-silicon-magnesium alloy. In the first step, ferro-silicon alloy is produced in submerged arc furnace (SAF). In the second step, ferro-silicon is re-melted together with steel scrap in induction furnace (IF), and the produced molten metal is poured into ladle containing Mg-ingots, calcium-silicon, and rare earth elements.

Instead of this this energy-intensive technology, one-step energy-saving process is presented in this work to produce ferro-silicon-magnesium alloy containing calcium and rare earth elements. 25 MVA-submerged electric arc furnace was used to produce molten ferrosilicon and the heat content of which was used during tapping to melt the coated magnesium ingots, rare earth elements, calcium-silicon, and steel scrap to produce ferrosilicon-magnesium alloy in one step. Furthermore, an innovative technique was employed to enhance magnesium recovery by applying a protective layer of ferrosilicon fines onto the surface of Mg-ingots.

By applying this technology, magnesium-recovery was found to increase and power consumption decreasing by increasing both tapping rate and surface coated percentage of Mg-ingots. Applying higher tapping rate of 202-268 kg/min and coating of 76-80% of Mg-ingots surface, higher Mg-recovery of 74.2-74.8% and lower power consumption of 6343-6548 kWh/ton FeSiMg were obtained. The produced FeSiMg alloys have 40-50% Si, 7-11.7% Mg, 1.3-2.3% Ca, 0.47-0j.92%Al, 1-1.3%Ce + La, and balance Fe.

Adopting the one-step process instead of the conventional two-step (SAF-IF) route results in an energy savings of 5322 kWh per ton FeSiMg alloy.

Keywords: Energy-saving, industrial process, submerged arc furnace, ferrosilicon, ferro-silicon-magnesium, rare earth elements, calcium silicon, magnesium-recovery.

1. Introduction

Magnesium is essential in the production of ductile cast iron, as it transforms the graphite morphology from flakes to spheroids, enhancing the material's strength, ductility, and toughness. By controlling sulfur content and modifying microstructure, magnesium ensures that ductile iron is suitable for a wide range of engineering applications, including automotive components, pipelines, and heavy machinery [1-9].

However, adding pure magnesium to produce ductile cast iron presents several challenges and problems, including high reactivity creates violent reaction resulting in metal splashing, low solubility in molten iron, vaporization, poor recovery, process control difficulties and potential safety hazards. These issues lead to material waste, increased costs, and defects in the final casting [10]. To overcome these problems, magnesium is typically added in the form of alloys like ferro-silicon-magnesium (FeSiMg) as a carrier alloy moderates the reaction with the result of reducing the metal loss and safety risks. This provides better control, higher efficiency, and improved metallurgical properties in ductile iron production [11].

Calcium was found to help in magnesium stabilization in the alloy by reducing its oxidation and evaporation at higher temperatures with result of reducing magnesium losses beside its ability to produce spheroidal graphite [12]. The introduction of Ca into FeSiMg forms a secondary Mg-containing phase, $CaMgSi_2$, within the structure, leading to a more controlled reaction and ultimately enhancing magnesium recovery.

The term "Rare earth elements (REE)" is used to refer to the lanthanides series elements [13-15]. Rare earth elements (REE), such as cerium (Ce) and lanthanum (La), are often introduced into FeSiMg alloys to refine the nodularization process [12]. By improving nodularity, reducing carbide formation, and enhancing overall casting quality, rare earth elements

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contribute to superior mechanical performance and longevity of ductile iron components used in various industrial applications [16].

The optimal silicon content in ferro-silicon-magnesium alloy ranges from 40% to 50% to facilitate magnesium silicide formation and mitigate reaction intensity [17], while the magnesium content typically falls within the 5% to 10% range. Calcium and rare earth elements contents range 0.5-3% and 0-2%, respectively.

Ferro-silicon-magnesium alloy can be produced by reducing magnesium-containing ores, such as dolomite, using carbon, silicon, or aluminum [18-20]. However, employing carbon as a reducing agent in an electric arc furnace presents significant challenges due to the high operating temperature and magnesium's high vapor pressure. Similarly, using aluminum in the process is costly, and the resulting alloys have high aluminum content, making this approach less favorable. Additionally, when silicon or a combination of silicon and aluminum is used to reduce burnt dolomite ore, the magnesium recovery rate does not exceed 13.8% [18].

Besides reduction processes, a ferro-silicon-magnesium alloy with a low magnesium content of approximately 5.5% could be produced by immersing magnesium ingots in molten ferrosilicon [18]. This immersion method is more cost-effective than the reduction technique for manufacturing FeSiMg alloy. However, it faces technical problems as the reaction between magnesium and molten ferrosilicon generates intense heat, leading to sparks, smoke, and fumes. Additionally, the alloy exhibits low magnesium content and poor magnesium recovery.

Two-step route is currently the most common technique for producing ferro-silicon-magnesium alloy. In the first step, ferro-silicon alloy is produced in submerged arc furnace (SAF). In the second step, ferro-silicon is re-melted together with steel scrap in induction furnace (IF), and the produced molten metal is pouring into ladle containing Mg-ingots, calcium-silicon, and rare earth elements.

In the present study, instead of the two-step energy-intensive technology, one-step energy-saving process has been used to produce ferro-silicon-magnesium alloy containing calcium and rare earth elements. Submerged electric arc furnace was used to produce molten ferrosilicon and the heat content of which was used during tapping to melt the coated magnesium ingots, steel scrap, rare earth elements and calcium-silicon to produce ferrosilicon-magnesium alloy in one step. This process is designed to enhance efficiency, reduce energy consumption, and minimize intermediate steps. Furthermore, an innovative technique was employed to enhance magnesium recovery by applying a protective layer of ferrosilicon fines onto the surface of Mg-ingots.

2. Materials and Methods

Fifteen experimental industrial heats were designed and performed to produce ferro-silicon-magnesium alloys using a 25 MVA-submerged electric arc furnace at the Egyptian Ferroalloys Company (EFACO), Edfo. The raw materials needed for experimental industrial heats have been identified. These materials include quartz, mill scale, carbonaceous reducing agent (poly-char and semi-coke) and electrode paste for producing molten ferrosilicon. Further additions of steel scrap, magnesium ingots, calcium silicon alloy, rare earth elements and FeSi fines were needed for producing FeSiMg alloy. The analysis of different raw materials has been carried out by different methods of spectroscopy, XRF and wet chemical analysis. The analysis results of different materials are given in **Tables 1-4**.

Table 1: Chemical composition of quartz and mill scale, wt.%

	SiO_2	Fe_3O_4	Al_2O_3	P_2O_5	MnO	CaO	NaO	SO_3
Quartz	99.1		0.7	0.05				
Mill scale	0.93	97.48			0.55	0.20	0.19	0.12

Table 2: Chemical composition of carbonaceous materials, wt.%

	Fixed carbon	Volatile materials	Ashes	Sulphur	Moisture
Electrode past	85.20	11.00	3.10	0.19	0.5
Poly-char	82.70	4.94	3.87	0.49	8.0
Semi-coke	77.68	5.40	6.67	0.25	10.0

Table 3: Chemical composition of calcium silicon alloy, FeSi fines and steel scrap, wt.%

	Si	Mn	Al	P	S	Ca	C	Fe
CaSi	61.56		0.44	0.023	0.002	13.63	0.13	20.00
FeSi fines	68.50		1.25	0.021	0.013	0.78	0.70	28.61
Steel scrap	0.24	0.88	0.002	0.025	0.026		0.25	98.49

Table 4: Chemical composition of rare earth elements, wt.%

(Rare earth elements)	Ce	La	Si	Ca	Al	Mn	Ni	Cu	Ti	V	Fe
	61.1	20.0	0.99	1.1	0.10	1.75	0.50	0.07	3.1	4.2	7.0

The magnesium ingots used have 99%Mg. The used calcium-silicon was produced on site using the existing 400 KVA-submerged arc furnace in the company at Edfo. Ferrosilicon fines are available at the company resulting from crushing the ferrosilicon alloy to the suitable sizes for industry.

One of the four 25 MVA-submerged electric arc furnaces available at EFACO, currently used to produce ferrosilicon, was used to produce molten ferrosilicon. Ferrosilicon smelting is a continuous process conducted in the submerged arc furnaces using Søderberg self-baking electrodes. Respectively raw materials are fed into the furnace from the top as a mixed batch consisting of quartz, an iron carrier (mill scale), and carbon reducers (Poly-char and semi-coke). At regular intervals, molten metal is tapped into a hot ladle through tap hole positioned near the furnace hearth. The required heat for the endothermic reactions involved in the reduction of silica and iron oxides is generated directly within the furnace charge through resistive heating from the current flow and arc heating.

For accommodating the facilities to produce FeSiMg alloy, the receiving ladle was modified. In the production process of ferrosilicon alloy, ladles lined with refractory ramming material are used to receive 3-4 tons molten ferrosilicon. For producing FeSiMg alloys, brick lined ladles with higher volume, suitable for receiving the added materials in addition to the molten FeSi were prepared for producing about 5 tons of ferro-silicon -magnesium alloy.

For preparing to produce ferro-silicon-magnesium alloy, different percentages of the added magnesium-ingots were simply coated by protective layer of FeSi-fines (less than 3 mm in size) using sodium silicate as a binder. Based on the chemical compositions of molten FeSi, magnesium, rare earth elements, CaSi, FeSi fines and steel scrap, material balance calculations were performed to determine the different amounts of additives for producing FeSiMg alloys with the desired chemical composition. The amounts of the coated and non-coated magnesium-ingots in addition to rare earth elements were placed on the bottom of the hot ladle and covered with the calculated amounts of calcium-silicon (0-5 mm in size), FeSi fines and steel scrap to produce FeSiMg with different Mg-contents. During tapping, the heat content of the molten ferrosilicon was used to melt the magnesium ingots and other ladle constituents to produce ferrosilicon-magnesium alloy in one step. The different amounts of molten FeSi and additions of the conducted heats are given in **Table 5**.

Table 5: The different amounts of molten FeSi and additions of the conducted heats for producing ferro-silicon-magnesium alloys

Heat No	Input, Ton					
	FeSi 73%	Steel scrap	CaSi alloy	Mg-ingots	REE	FeSi fines
1	3.100	0.800	0.600	0.560	0.100	0.400
2	2.700	0.650	0.650	0.700	0.080	0.460
3	3.000	0.400	0.550	0.675	0.080	0.500
4	3.500	0.900	0.650	0.870	0.120	0.400
5	3.150	0.900	0.800	0.850	0.100	0.560
6	2.800	0.675	0.675	0.625	0.080	0.155
7	2.100	0.675	0.675	0.720	0.080	0.350
8	3.300	0.750	0.700	0.790	0.100	0.600
9	2.250	0.650	0.550	0.805	0.080	0.560
10	2.500	0.700	0.700	0.865	0.100	0.400
11	2.890	0.700	0.750	0.855	0.100	0.420
12	1.475	0.750	0.500	0.640	0.080	0.240
13	2.600	0.750	0.500	0.600	0.080	0.175
14	1.865	0.900	0.425	0.600	0.080	0.175
15	3.320	0.750	0.500	0.850	0.100	0.280

After complete tapping and melting all constituents of ladle, the ladle containing the molten metal was transferred to the rotating casting machine for performing the casting process. Pouring the produced molten alloy from the ladle into the cast iron molds in the rotating casting machine was performed to attain metal slabs of 60-80 mm thickness. The produced FeSiMg alloy with this thickness revealed homogeneity. **Figure 1** illustrates the casting process. Once cooled, the solidified ferro-silicon-magnesium was weighed, and representative alloy samples were collected for analysis.

Figure 1: The casting process of FeSiMg alloy, (a) during pouring, (b) after complete pouring.

The different data of the performed heats are given in **Table 6**. The percentage of Mg-ingots coated surface was calculated by dividing the number of coated Mg-ingots by the total added Mg-ingots. The tapping time is the duration of complete tapping of molten metal into the ladle. The power consumption is the total electric energy consumed in the heat.

Table 6: Data of the different conducted heats for producing FeSiMg alloys.

Heat No	Total No of Mg-Ingots	No of Coated Mg-Ingots	No of Un-coated Mg-Ingots	% of Coated Surface	Tapping Time, min	Power Consumption, MWh
1	75	60	15	80.0	20	34
2	93	60	33	64.5	25	33
3	90	55	35	61.1	30	38
4	116	80	36	69.0	30	44
5	113	83	30	73.5	40	40
6	83	53	30	63.9	20	33
7	96	58	38	60.4	25	37
8	105	80	25	76.2	25	43
9	107	75	32	70.1	25	32
10	115	80	35	69.6	30	35
11	115	80	35	69.6	20	36
12	85	50	35	58.8	45	39
13	80	50	30	62.5	45	41
14	80	50	30	62.5	45	36
15	113	80	33	70.8	30	41

The solidified FeSiMg is crushed into the desired sizes, and then screened and classified based on particle size. Photos of the produced FeSiMg alloy before and after crushing are shown in **Figure 2**.

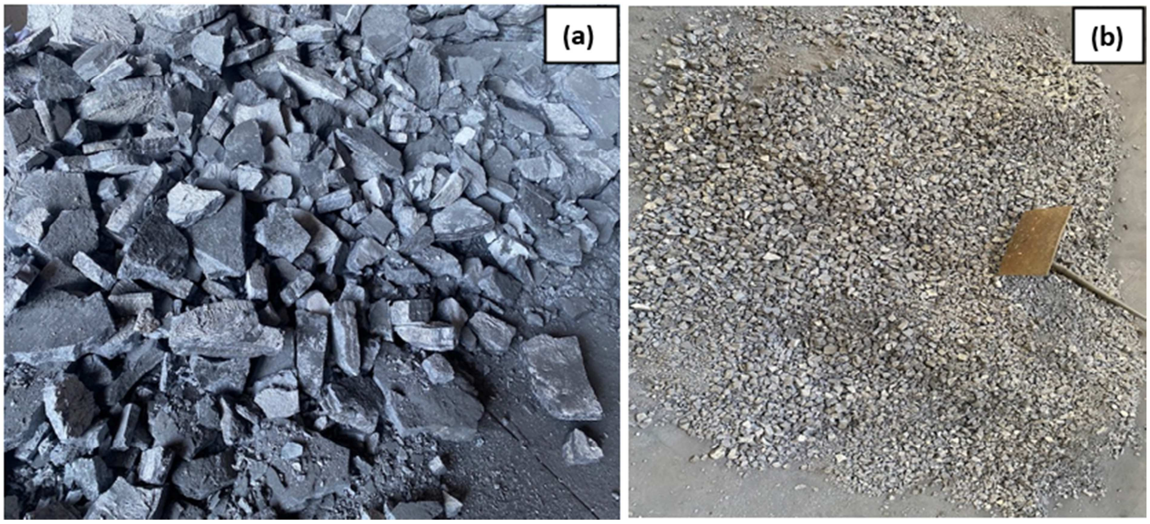

Figure 2: Photos of the produced FeSiMg alloy, (a) before crushing, (b) after crushing

The representative alloy samples collected for analysis were subjected to XRF chemical analysis. The chemical analysis of the different samples supported the homogeneity of the produced alloy. Additionally, a sample of the alloy was analyzed using XRD.

3. Results and Discussions

The results of the fifteen heats performed to produce MgFeSi are presented in **Table 7**.

Table 7: Weight of the produced FeSiMg alloys and their chemical composition.

Heat No	FeSiMg Wt., Ton	FeSiMg Chemical composition, wt.%					
		Si	Mg	Ca	Al	Ce+La	Fe
1	5.360	44.39	7.74	2.20	0.65	1.24	Balance
2	5.040	48.00	10.20	2.26	0.70	1.27	Balance
3	4.900	50.00	8.00	1.84	0.92	1.20	Balance
4	6.120	45.20	9.60	1.60	0.52	1.30	Balance
5	6.130	44.00	10.04	1.65	0.68	1.30	Balance
6	4.740	46.29	7.02	2.14	0.75	1.04	Balance
7	4.200	44.57	8.72	1.85	0.69	1.09	Balance
8	6.050	45.51	9.60	1.51	0.62	1.30	Balance
9	4.620	48.18	11.20	1.62	0.71	1.30	Balance
10	5.230	42.23	11.73	1.56	0.51	1.30	Balance
11	5.730	44.70	10.00	1.95	0.73	1.30	Balance
12	3.430	40.34	8.00	1.99	0.47	1.22	Balance
13	4.620	48.86	7.50	1.45	0.60	1.00	Balance
14	3.900	43.11	7.50	1.39	0.48	1.08	Balance
15	5.800	45.92	10.04	1.35	0.57	1.28	Balance

Magnesium-recovery was determined using the following formula:
Magnesium Recovery = (Amount of Mg in the produced alloy) X 100 / (Amount Mg-addition)

The tapping rate was calculated from the data of FeSiMg weight and tapping time, while the power consumption per ton FeSiMg was calculated from the total power consumption for every heat and the weight of the produced FeSiMg alloy. The calculated tapping rate, power consumption per ton FeSiMg and Mg-recovery are given in **Table 8**.

Table 8: Tapping rate, power consumption per ton FeSiMg and Mg-recovery.

Heat No	Tapping Rate Kg/min	Power Consumption, MWh /Ton	Mg-recovery %
1	268	6.343	74.83
2	202	6.548	74.18
3	163	7.755	58.66
4	204	7.190	68.21
5	153	6.525	73.14
6	237	6.962	53.78
7	168	8.810	51.38
8	242	7.107	74.26
9	185	6.926	64.93
10	174	6.692	71.64
11	287	6.283	67.69
12	76	11.370	43.31
13	103	8.874	58.33
14	87	9.231	49.24
15	193	7.069	69.20

From the results obtained, **Figures 3-6** are plotted illustrating the effect of both tapping rate and surface coated percentage of Mg-ingots on magnesium-recovery and power consumption per ton FeSiMg.

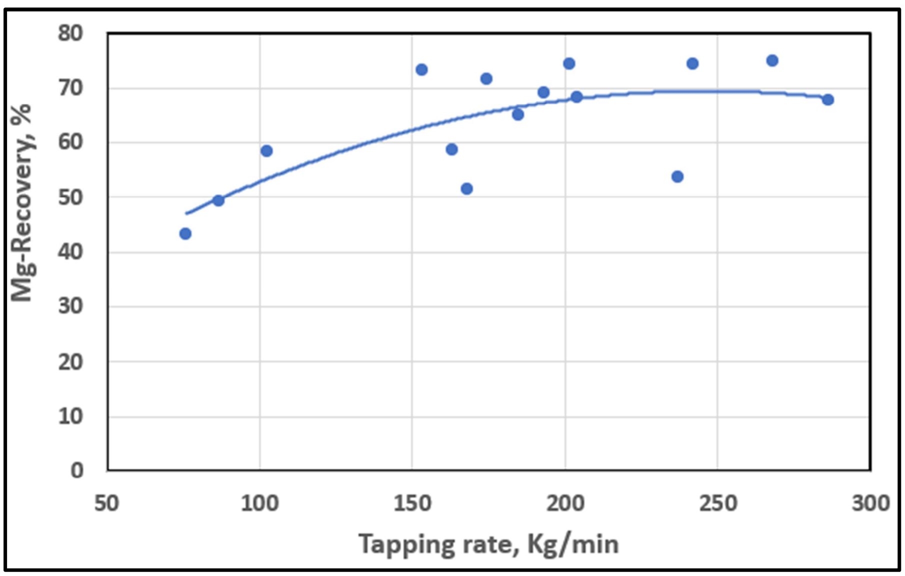

Figure 3: Effect of tapping rate on magnesium-recovery

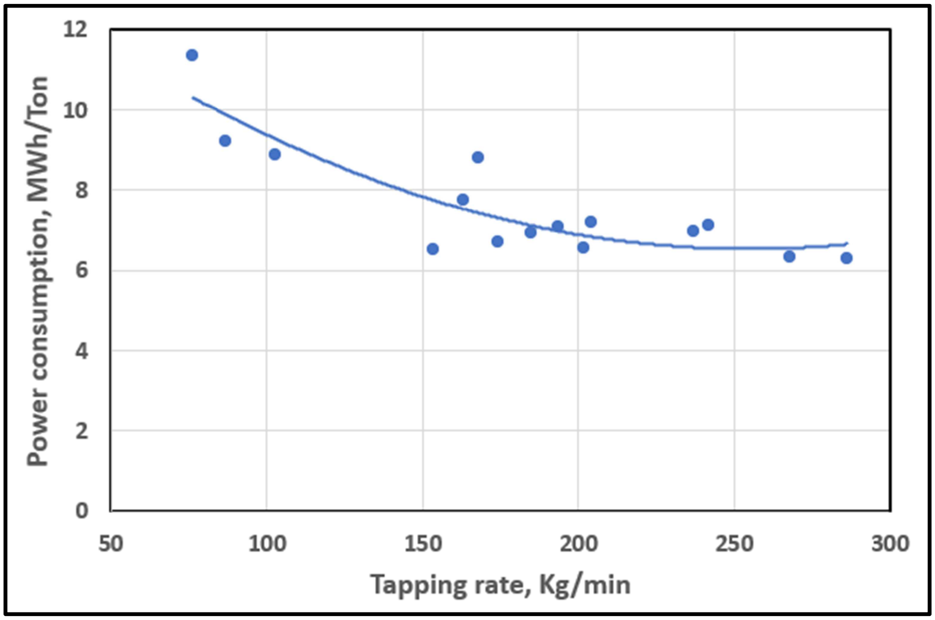

Figure 4: Effect of tapping rate on power consumption per ton FeSiMg

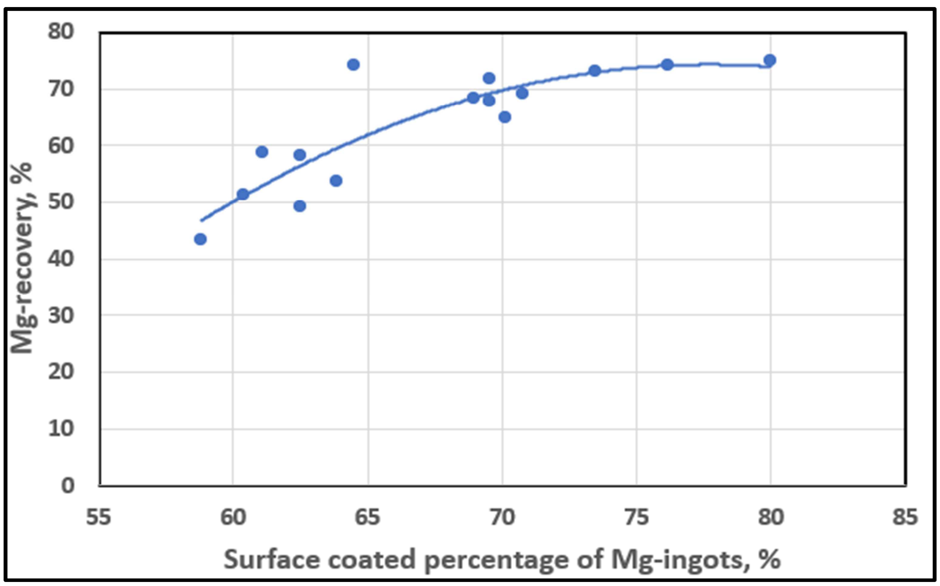

Figure 5: Effect of surface coated percentage of Mg-ingots on magnesium-recovery

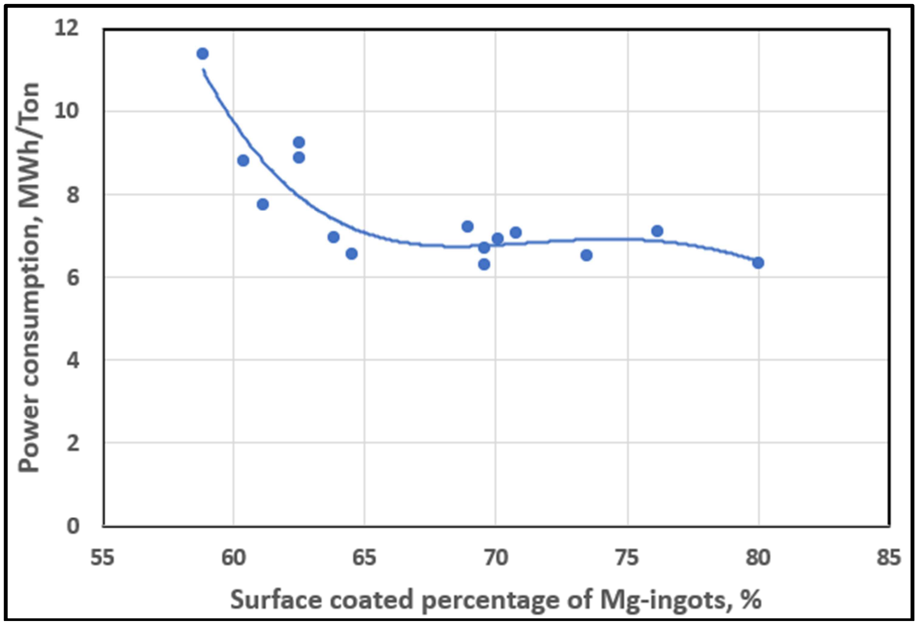

Figure 6: Effect of surface coated percentage of Mg-ingots on power consumption per ton FeSiMg

Figures 3–6 clearly show that magnesium-recovery increases and power consumption decreases by increasing both tapping rate and surface coated percentage of Mg-ingots. Lower tapping rates of 76-87 kg/min led to poor Mg-recovery values of only 43-49% increased to 74-75% at tapping rate of 202-268 kg/min. Protective layer coating of Mg-ingots is effective in enhancing the magnesium-recovery, where lower Mg-recovery of 50% was obtained at coating of only 60% of Mg-ingots surface, increased to 75% by coating 75% of Mg-ingots surface.

Similar trend is observed for power consumption. Lower tapping rates of 76-87 kg/min led to higher power consumption values of 9.2-11.3 MWh/ton FeSiMg decreased to 6.3-6.5 MWh/ton FeSiMg at tapping rate of 202-268 kg/min. Coating only 59% of Mg-ingots surface is accompanied with higher power consumption of 11.3 MWhlton FeSiMg decreased to 6.3 MWh/ton FeSiMg by coating 80% of Mg-ingots surface.

By partially coating the surface of Mg ingots, the uncoated portion initiates the reaction, while the coated layer significantly reduces magnesium losses. When Mg ingots are coated with FeSi fines, the melting of FeSi fines is an endothermic process that absorbs heat, lowering the temperature of the molten bath. This, in turn, slows down the Mg reaction, minimizes magnesium losses due to evaporation, and consequently enhances magnesium recovery. Lower tapping rate causes the magnesium to be exposed to oxidation by the atmosphere, thus increasing the magnesium evaporation and reducing its recovery. On the contrary, increasing the tapping rate accelerates the coverage of magnesium with molten metal and reduces the period of its exposure to the atmosphere. This reduces oxidation and evaporation, ultimately improving magnesium recovery. Higher magnesium recovery, by higher tapping rate or by coating the surface of Mg ingots with protective layer is associated with increased alloy production and, consequently, lower power consumption per ton of produced alloy.

XRF analysis of the produced alloys identified Si, Fe, and Mg as the primary constituents, with Ca, Ce, and La present in smaller amounts. XRD analysis was conducted to determine the magnesium, calcium, and rare earth compounds. Examination of a sample from heats 2 and 12, as shown in **Figure 7**, revealed various Si, Fe, Mg, and Ca compound phases, including magnesium silicide (Mg_2Si), iron silicide (FeSi), iron di-silicide ($FeSi_2$), calcium magnesium silicide ($Ca_7Mg_{7.25}Si_{14}$) and silicon. Additionally, minor phases of lanthanum silicide ($LaSi_2$) and cerium silicide ($CeSi_2$) were detected.

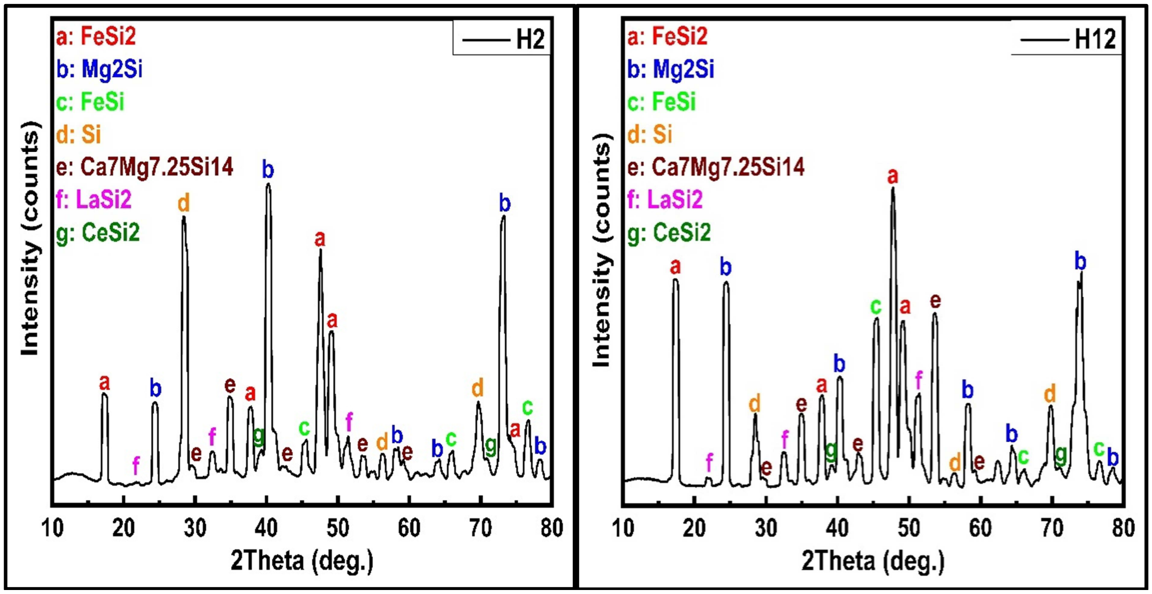

Figure 7: XRD pattern of the produced alloy, H2: heat 2, H12: heat 12

Energy saving

A follow-up on the submerged arc furnace production process of ferrosilicon alloy at the Egyptian Ferroalloys Company (EFACO) in Edfo, conducted one month prior to this study, revealed that an average of 10,665 kWh of electric energy is consumed to produce one ton of FeSi alloy with an average silicon content of 73%. Further energy of average 1000 kWh is consumed in re-melting of ferrosilicon and steel scrap in induction furnace for producing one ton of FeSiMg alloy. Consequently, the total energy consumption for producing one ton of FeSiMg alloy using the conventional two-step (SAF-IF) amounts to 11665 kWh. In contrast, the one-step process under optimal conditions requires only 6,343 kWh per ton. Therefore, adopting the one-step process instead of the conventional two-step (SAF-IF) route results in an energy savings of 5,322 kWh per ton FeSiMg alloy.

4. Conclusions

A one-step, energy-efficient process has been used instead the conventional two-step (SAF-IF) energy-intensive method for producing ferro-silicon-magnesium alloy containing calcium and rare earth elements. A submerged electric arc furnace was used to generate molten ferrosilicon, and its heat was utilized during tapping to melt coated magnesium ingots, rare earth elements, calcium-silicon, and steel scrap, enabling the production of ferro-silicon-magnesium alloy in a single step. Additionally, an innovative technique was implemented to improve magnesium recovery by applying a protective layer of ferrosilicon fines to the surface of the magnesium ingots.

By applying this technology and the results obtained, the following conclusions have been drawn:

- Magnesium-recovery increased and power consumption decreased by increasing both tapping rate and surface coated percentage of Mg-ingots.
- By applying higher tapping rate of 202-268 kg/min and coating of 76-80% of Mg-ingots surface, higher Mg-recovery of 74.2-74.8% and lower power consumption of 6.3-6.5 MWh/ton FeSiMg were obtained.
- The produced FeSiMg alloys have 40-50% Si, 7-11.7% Mg, 1.3-2.3% Ca, 0.47-0j.92%Al, 1-1.3%Ce + La, and balance Fe.
- Major compound phases of magnesium silicide (Mg_2Si), iron silicide (FeSi), iron di-silicide ($FeSi_2$), calcium magnesium silicide ($Ca_7Mg_{7.25}Si_{14}$), silicon and minor phases of lanthanum silicide ($LaSi_2$) and cerium silicide ($CeSi_2$) were detected in the produced FeSiMg alloy.
- Adopting the one-step process instead of the conventional two-step (SAF-IF) route results in an energy savings of 5,322 kWh per ton FeSiMg alloy.

5. Conflicts of interest

There are no conflicts to declare by the authors.

6. Formatting of funding sources

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