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Casting of Fe-(2–12)Mn-(4–14)Al-(0.09–0.7)C low-density steel via artificial slag practice

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ABSTRACT

In this research theoretical and practical studies have been highlighted about alloy design, casting and steel-slag interaction. The use of a protective slag layer was identified as an advantageous method in the production of low-density steels. For the first time in this study, a unique synthetic steelmaking (CaO/Al_2O_3:1.57) slag was implemented in an induction furnace with no vacuum chamber to produce high aluminum in steel. This study showed that manganese and aluminum directly influence the solidification structure and carbide formation. Coarser k-carbides have been detected at grain boundaries in austenite as-cast matrix when the Aluminum increases in the low-density steel.

1. Introduction

The Fe-Mn-Al-C alloys have been developed for different purposes, including aircraft industries, automotive, cryogenic usage, AHSS applications and high entropy alloys [1]. Low-density steels are next-generation materials in the automotive industry. Next-generation high aluminum steels are considered for potential usage in special-lightweight applications. Thus, the density of the steel can be decreased by 1.3 % per 1% Al addition [1,2]. Moreover, reducing CO_2 emissions, increasing mechanical properties and decreasing car weight are crucial points for alloy design and metallurgical studies. This study aims to get low-density steel ingots with high homogeneity and optimum alloy yield in an induction furnace. Slag usage in induction melting, the furnace has been implemented in the process route. Steelmaking slags play an essential role to optimize steel cleanliness, porosity, detrimental gas effect, inclusion capacity, the yield of alloying and refractory material. Homogeneity of the material and the relationship between slag and liquid metal are critical elements for smooth casting. Steelmaking slags mainly consist of oxides such as CaO, MgO, Al_2O_3, SiO_2, FeO, MnO, P_2O_5. An ideal metallurgical slag should be in a physically creamy-liquid form with a low reducible oxide (FeO, MnO) content, high desulfurization and inclusion capacity [3,4]. The slag composition is the most critical factor that determines the melting temperature, viscosity, sulfur and inclusion capacity of the slag. If the appropriate slag composition cannot be provided, it is impossible to produce steel with low sulfur and inclusion content. In addition, the chemical and physical changes of the slag after the melting process directly affect the chemical composition of the alloying elements in the liquid steel and the alloy yield. Hence, it is emphasized that melting characteristic is another metallurgical phenomenon for carbide (MnC_3-FeMnX) morphology in solidified structure. Literature studies showed that high manganese content in the structure control austenite phase, but the larger austenitic grains could be observe up to 3 wt% Al in the matrix. Increasing aluminum ratio in the steel influences carbide morphology and growth and phase equilibrium. On the other hand, higher melting temperature is also other factor for reducing the carbides in this mechanism [5–7].

2. Materials & method

An induction-melting furnace (Inductotherm 275 kW VIP-I, Turkey) with a capacity of 350 kg was used as the heating equipment. The structure of the induction furnace is shown in Fig. 1. Alumina refractory material ($Al_2O_3 \geq 85$ wt%, $MgO > 14$ wt% Vesuvius, Germany) was selected for the furnace lining material for each heat. Iron-based scrap was chosen to use from Eregli Iron and Steel (ERDEMIR) plant. Three

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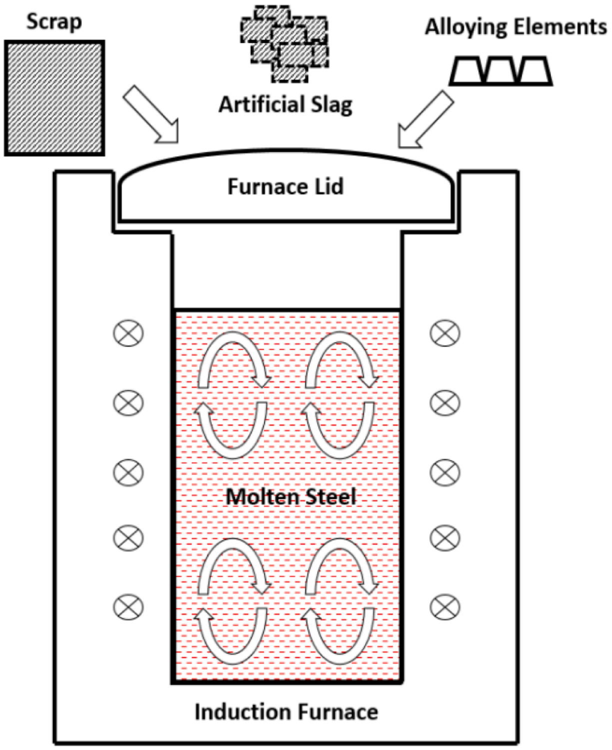

Fig. 1. Schematic diagram of experimental device.

different heats were cast in an induction furnace. For the first time in this study, artificial slag application was used. The slag composition has been specified with the ratio of 55% CaO, 35% Al_2O_3, 4% MgO and 5% SiO_2. Alumina in the artificial slag was supplied from alumina-based refractory material. After grinding and crushing, it was used and mixed with the lime. After that, some Ladle furnace (LF) slag from Erdemir Plant was added the artificial slag mixture. The ideal slag usage amount in the melting process was calculated. The phases formed in the slag were indicated in Fig. 2. To control the amount of aluminum in liquid steel, optimum slag composition has been considered. The alloy design has been studied with metallurgical simulation program tools. Before the melting process, solidification patterns of low-density steel ingot and liquidus temperature of Heat 1 were calculated via FactSage 7.3 computational thermodynamic program in Fig. 3. For Heat 1, the solidus point of the alloy was determined as 1431.38 °C. 1517.17 °C has been demonstrated as the liquidus point, and it has been detected that the solidification transformations occur with this temperature theoretically. The melting temperature of Heat 2 was detected as 1500.74 °C, while it was detected as 1372.17 °C for Heat 3. It has been analyzed that the general structure in solidification transformations is the BCC phase. In addition, it was detected that the MeS (Fe,Mn,Cr-S) structure was formed between the temperatures of 1438.06 °C and 1431.38 °C. Before melting, 350 kg alumina-based- liquid metal transfer crucible- was preheated. The melting of the specified alloy was carried out in an open induction furnace. An open induction furnace used according to melting process, low carbon steel scrap, low carbon Ferromanganese, Ferro niobium and aluminum ingots were used. The chemical composition of the liquid steel was determined by taking a preliminary sample, and then the alloying elements were charged. The melting process was completed in 2 h in an induction furnace with a frequency of 3000 Hz and a power of 275 kW. Casting temperatures were measured between the ranges of 1600 °C and 1475 °C, taking into account the superheat conditions. The molten liquid metal was charged to transferring ladle. The ladle was contacted with the runner system (vertical and horizontal pre-cast high alumina type) from its below side and then transferred from the ladle to mold. The dimension of mold was designed at

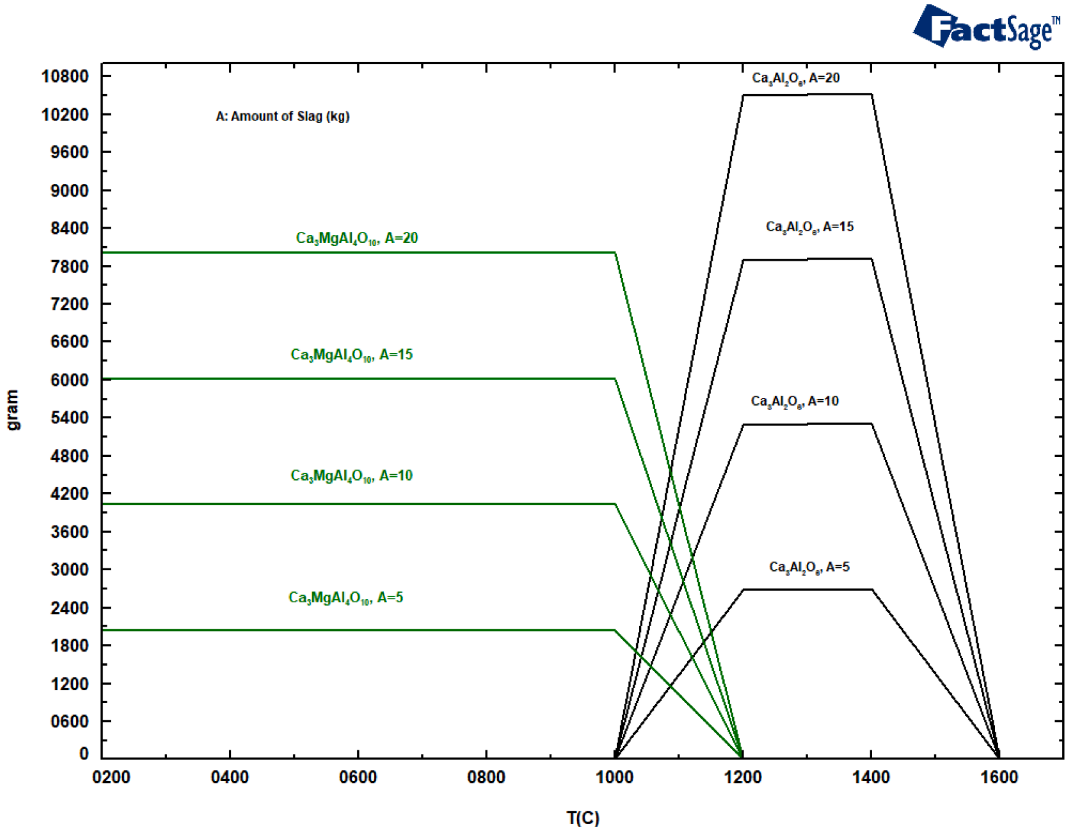

Fig. 2. Investigation of steel-slag reactions at different slag amounts.

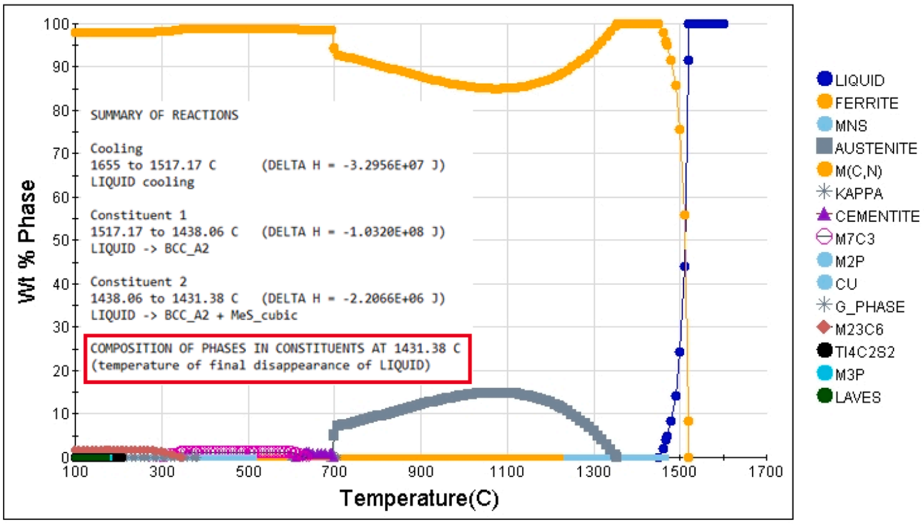

Fig. 3. Phase transformation with solidification (Heat 1)-FactSage and JmatPro calculations.

200x350x500 mm. The material of mold was selected as GGG20 because of its high resistant to heat and corrosion.

3. Result and discussion

Chemical analysis of heats analyzed with ICP (Inductively Coupled Plasma) spectroscopy. The final heat compositions are given in Table 1. Solidification structure and grain size were investigated by an optical microscope. All -as-cast- samples were embedded into bakelite. Samples were etched 3 s with Aqua Regia (30 ml HCl + 10 ml HNO_3) solution. Grain size of the sample was measured as 1500 μm approximately at X25 magnification. Kappa-carbide precipitates were found in the structure at X500 magnification. Equiaxed grain structure has been detected in transverse inspections. After melting, slag composition was analyzed with XRF (X-Ray Fluorescence) method. The analysis showed that the composition of slag was included 30% CaO, 50% Al_2O_3, 6% MgO, 9% SiO_2 and some other oxide impurities. In this research, it was important to understand the mechanism between slag and liquid metal, since adjusting the alloy yield and steel cleanliness are significant characteristics in the melting process. The final slag composition end of casting was observed with XRD (X-Ray Diffraction) technique. It was found that krotite and grossite crystal structures were formed in the slag. Before this study, some plant trials were carried on aluminum yield without slag consumption. It was detected that the best conditions for aluminum in liquid metal were gained with basic type-alumina based slag usage. Due to the amount of alumina content in slag, some substitution reactions may occur with kinetic effects of high inductive stirring and contact surface between steel and liquid metal. Kappa carbide (K-carbide) is one of the typical metastable phase (Fe, Mn)AlC_x in low-density steel grades. In solidification or hot rolling conditions, this phase is generally spread around the austenite matrix and grain boundaries [6,7]. These precipitated phases play a positive role if controlled or homogenized around the matrix. The K-carbide structures and Al-Mn-Fe-C based precipitates were expanded in grain boundaries. K-carbides in the inner solidification structure was presented with the EDS-Mapping method and elemental density separation. Regions with high element content appeared brightly. It is considered that the density of the detected elements in these regions was higher than in other regions. The macrostructure and the element contents in the peak scan of the kappa-carbide precipitate is shown. The mapping of aluminum, manganese and iron are also indicated in Fig. 4 with SEM-EDS analysis.

4. Conclusions

This study showed that artificial slag utilization in induction furnaces positively affects alloy yield and sustainable casting. Therefore, induction-melting process is reasonable and alternative method-with specialized slag utilization-compared to vacuum induction melting. Aluminum in liquid steel is hard to control due to oxygen activity and interaction reactions between steel & slag. Thus, it has been investigated that 5 kg of synthetic slag for 350 kg steel (14.28 kg per ton steel) should be used for stable production of ingots in the melting process. In addition, the research also displayed that optimal as-cast structure before hot rolling process of low-density steel. Ingot casting parameters of low-density steel was discussed with the scope of specific alloy composition (to obtain and control K-carbide), artificial-slag practice, phase transformation of solidification and equiaxed grain size. In the microstructural evaluation, it is observed that fine carbides tend to turn into a coarser structure with the effect of increased alloying elements. In Heat 3, carbide phases appear more prominently in the austenite structure. These phases are presumed to be kappa carbide.

CRediT authorship contribution statement

Memduh Kagan Keler: Project administration, Writing – original draft, Writing – review & editing. **Sibel Daglilar:** Conceptualization, Writing – original draft. **Nilgun Kuskonmaz:** Conceptualization, Writing – review & editing. **Zafer Cetin:** Formal analysis. **Onur Kart:** Formal analysis, Project administration. **Oguz Gunduz:** Resources, Writing – review & editing. **Oguzhan Gunduz:** Visualization, Writing – original draft.

Table 1

Chemical composition (weight %) of produced ingots.

	C	Al	Si	Cr	Mn	Mo	Ti	V	Nb	Fe
Heat 1	0,095	4,83	0,24	0,02	2,46	0,025	0,007	0,005	0,019	Bal.
Heat 2	0,090	9,61	0,19	0,02	2,20	0,040	0,006	0,005	0,020	Bal.
Heat 3	0,75	14,27	0,33	0,08	11,97	0,028	0,005	0,053	0,019	Bal.

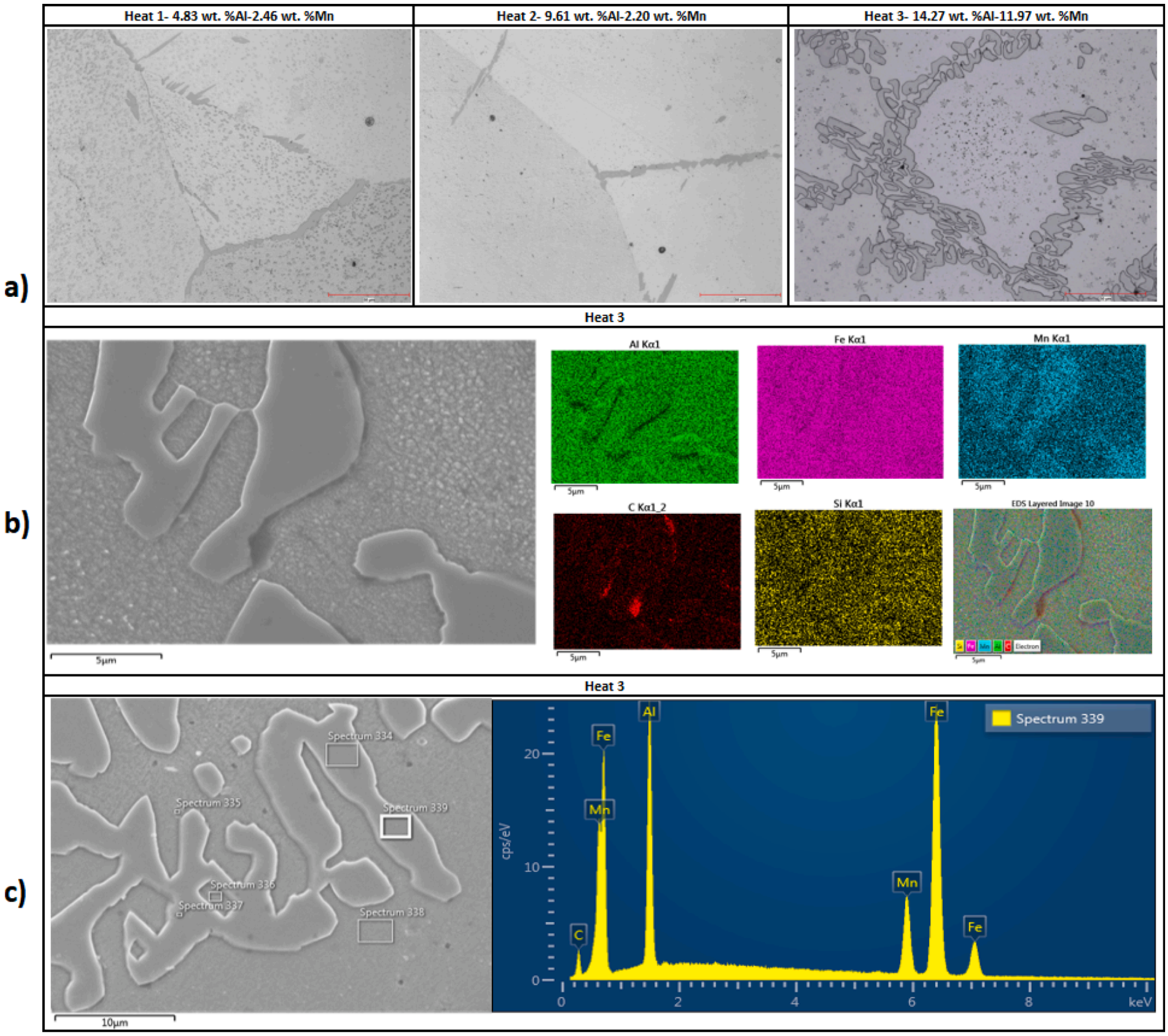

Fig. 4. Optical images and SEM-EDS analysis of as-cast material (a) Casting structure of all heats at 500X (b) K-Carbide precipitation in structure and elemental spectrum with EDS-Mapping method in Heat 3c) EDS point analysis of carbide in Heat 3.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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