Flux-Steel Reaction of CaO-SiO$_2$ and CaO-Al$_2$O$_3$-based Mold Fluxes with High-Al Steel

J. Yang, J. Zhang, O. Ostrovski, C. Zhang, D. Cai

Advanced properties of high-Al steel such as high mechanical strength and formability make it attractive for the applications in the automobile industry. However, when conventional CaO-SiO$_2$-based mold fluxes are used for the continuous casting of such steel, [Al] in the steel reacts with SiO$_2$ in the fluxes. It changes the chemical composition and in-mold performances of mold fluxes, leading to unstable heat transfer and insufficient lubrication for the steel strands. CaO-Al$_2$O$_3$-based mold fluxes with low SiO$_2$ content are under development, expecting to suppress the interfacial reaction between mold fluxes and high-Al steel. In this article, the effects of different CaO-SiO$_2$ and CaO-Al$_2$O$_3$-based mold fluxes on the reaction kinetics were evaluated through both pilot and laboratory tests. It was found that there were significant changes in SiO$_2$ and Al$_2$O$_3$ concentrations in CaO-SiO$_2$-based mold fluxes, indicating a severe reaction between fluxes and high-Al steel. CaO-Al$_2$O$_3$-based mold fluxes showed a better composition stability than CaO-SiO$_2$-based mold fluxes when reacting with high-Al steel. In the lab tests, CaO-Al$_2$O$_3$-based mold fluxes with different CaO/Al$_2$O$_3$ ratios were also evaluated. It showed that the increase of CaO/Al$_2$O$_3$ ratio accelerated the flux-steel reaction according to the change of [Al] concentration in the steel. CaO-Al$_2$O$_3$-based mold fluxes showed promising results when reacting with high-Al steel, but the fluxing agents, e.g. B$_2$O$_3$ and Li$_2$O, may also react with [Al] in steel and cause an additional increment of Al$_2$O$_3$ in mold fluxes, which needs further research in the future.

KEYWORDS: HIGH-AL STEEL – MOLD FLUXES – INTERFACIAL REACTION – KINETICS – THERMODYNAMICS

INTRODUCTION

Advanced high-strength steels (AHSS) have high mechanical strength, good ductility and low weight, showing a great potential in the modern automotive industry. As a new generation of AHSS, twinning-induced plasticity (TWIP) steel attracts great interests in recent years for its extraordinary mechanical properties (1-5). As such, it is austenitic steel with high content of Mn, providing a complex strain-hardening behavior due to its moderate stacking fault energy (20 – 40 mJ/m2) at room temperature (1, 2). Practically, Al is an important component in TWIP steel. It reduces the density of TWIP steel, stabilizes the formation of deformation twinning, and avoids the transformation of austenite into ε-martensite at low strains (6). Conventional mold fluxes for the continuous casting of steel are based on CaO-SiO$_2$ oxide system. However, [Al] in the molten high-Al steel inevitably reacts with SiO$_2$ in the fluxes at high temperature according to the following equation, which causes the accumulation of Al$_2$O$_3$ and the reduction of SiO$_2$ in molten fluxes (7-9):

$$3SiO_2 + 4[Al] \rightarrow 3[Si] + 2Al_2O_3 \qquad [1]$$
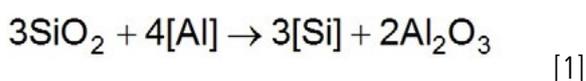
The variation of flux composition may make the in-mold performances of mold fluxes undesirable and unpredictable in the casting of high-Al steel, increasing the likelihood of sticker breakout and surface defects.

CaO-Al$_2$O$_3$-based mold fluxes with low SiO$_2$ content is recently introduced to depress the driving force of reaction [1]. But the increase of Al$_2$O$_3$ and decrease of SiO$_2$ concentrations would raise the liquidus temperature of mold fluxes significantly (10). Fluxing agents, e.g. B$_2$O$_3$ and Li$_2$O, are normally added to reduce the liquidus temperature of mold fluxes. However, B$_2$O$_3$ is also reactive with [Al] in steel (10) and the use of Li$_2$O is limited in industry due to its high cost.

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In this article, the reaction of CaO-SiO$_2$ and CaO-Al$_2$O$_3$-based mold fluxes in the casting of high-Al steels was investigated based on the composition changes of mold fluxes and steel in both pilot and laboratory tests. The aim of this study is to deepen the understanding of the flux behavior in flux-steel reaction, promoting the design of new mold fluxes for the casting of high-Al steel.

EXPERIMENTAL PROCEDURE
Pilot Tests
Both CaO-SiO$_2$ and CaO-Al$_2$O$_3$-based mold fluxes were investigated in the pilot tests. The compositions of mold fluxes and steels used in the pilot tests are given in Tables 1 and 2, respectively. The concentrations of B$_2$O$_3$ and Li$_2$O in mold fluxes were determined using inductively coupled plasma (ICP) analysis; other components were analyzed using X-ray fluoroscopy (XRF). The concentrations of [Al], [Mn] and [Si] in steel were examined using ICP analysis. Two sets of pilot tests were carried out in this study. The first set tested the reaction between CaO-SiO$_2$-based mold fluxes (Fluxes 1 and 2) and high-Al steel. Approximately 150 kg steel was charged in an induction furnace with the protection of non-reactive mold fluxes which were used to avoid oxidation before the introduction of the de-

signed mold fluxes. After the temperature of molten steel was stabilized at 1600 °C, a steel sample was acquired. The composition of this steel is indicated as Steel 1. Then, 4 kg Flux 1 was added on the top of molten steel to replace the non-reactive protection slags. Mold flux samples were taken at 900 and 1800 s after Flux 1 was melted; while the steel sample was acquired at only 1800 s whose composition is defined as Steel 2. Afterward Flux 1 was replaced by Flux 2. It was sampled at 600, 900, 1200, 1500 and 1800s, respectively; while the steel sample was acquired at 1800 s. As [Al] concentration dropped to a low level after the reaction between Flux 1 and Steel 1, an additional experiment was arranged for Flux 2 to react with a new steel with a high Al content whose composition is listed as Steel 3.

The second set of pilot tests investigated the reaction between CaO-Al$_2$O$_3$-based mold fluxes and steel. The steel sample acquired before the introduction of Flux 3 was marked as Steel 4. Flux 3 was then added and sampled at 600, 900, 1200 and 1500 s. Steel composition was acquired at 1500 s, which was marked as Steel 5. Afterward, Fluxes 4 was used to react with Steel 5 and sampled at 600, 900, 1200, 1500 and 1800s, respectively. The final composition of Steel 5 was obtained at 1800 s.

Tab. 1 – Compositions of Mold Fluxes in Pilot Casting. (mass%)

Number	SiO$_2$	Al$_2$O$_3$	CaO	MgO	TiO$_2$	MnO	Na$_2$O	Li$_2$O	F	B$_2$O$_3$
Flux 1	42.0	6.1	28.4	1.8	-	3.3	7.4	1.1	8.5	3.4
Flux 2	43.3	3.2	28.2	0.2	-	4.6	8.6	2.5	18.1	-
Flux 3	15.3	16.9	40.1	2.4	1.8	2.0	5.0	1.9	9.3	1.7
Flux 4	8.1	28.8	28.3	1.5	1.1	0.1	2.8	-	8.5	15.8

Tab. 2 – Compositions of Steel in Pilot Casting. (mass%)

Number	C	Si	Mn	Al
Steel 1	0.65	0.13	17.7	2.00
Steel 2	0.68	0.77	17.5	1.12
Steel 3	0.64	1.04	17.0	1.80
Steel 4	0.58	0.10	18.1	1.79
Steel 5	0.59	0.36	17.9	1.62

Laboratory Tests
The flux-steel reaction between CaO-Al$_2$O$_3$-based mold fluxes and high-Al steel was also carried out in laboratory. CaO-Al$_2$O$_3$-based mold fluxes were prepared by mixing reagent chemicals using an agate mortar.
The mixed powders were then melted in a graphite crucible at

1400 °C for 20 minutes. Afterward, the melt was quenched in water, forming a highly porous glass. It was then crushed to coarse grains with an average diameter of ca. 2 mm. The composition of mold fluxes is listed in Table 3; while the composition range of high-Al steel is given in Table 4. The composition measurements used the same way as in pilot tests.

Continuous casting

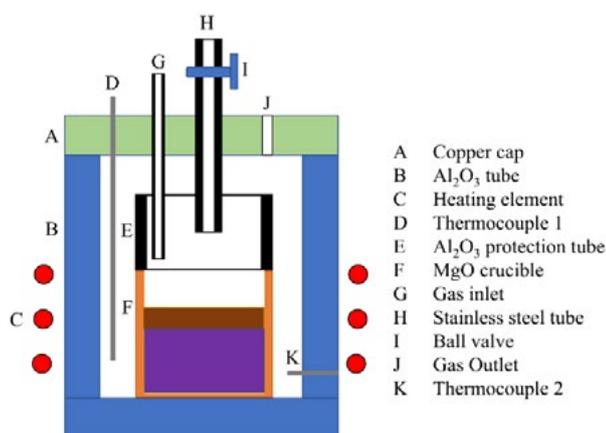Tab. 3 – Compositions of Mold Flues in Lab Tests. (mass%)

Number	SiO$_2$	Al$_2$O$_3$	CaO	MgO	Na$_2$O	Li$_2$O	B$_2$O$_3$
Flux 5	6.9	36.3	36.8	1.8	5.9	2.1	9.5
Flux 6	6.9	17.7	54.1	1.7	5.5	2.1	11.3
Flux 7	6.9	15.1	57.4	1.8	5.0	2.2	11.0

Tab. 4 – Composition Range of High-Al Steel in Lab Tests. (mass%)

Number	C	Si	Mn	Al
Steel 6	0.14-0.20	< 0.15	21-25	1.5-2.5

The flux-steel reaction was carried out in a MoSi$_2$ resistance furnace as illustrated in Figure 1. A MgO crucible (40 x 35 x 81 mm) was used to accommodate steel sample and mold fluxes (8). An Al$_2$O$_3$ protection tube (40 x 35 x 360 mm) was placed above the MgO crucible. The temperature of the sample was measured and calibrated by two thermocouples in the bottom of the furnace. 300 g high-Al steel sample was heated at 1500 °C in the MgO crucible. Highly purified Ar-5H2 gas was flown into the protection tube with a flow rate of 1 L/min in the heating process. After the temperature was stabilized at 1500 °C for 5 min, a quartz tube (8 x 6 x 1200 mm) was lowered to the crucible through a stainless steel tube (14 x 12 x 700 mm) to acquire steel sample and then quenched into water immediately. Afterward, 30 g coarse grained mold fluxes were added to the MgO crucible through the stainless steel tube. Mold fluxes were assumed to take 1 min to melt completely on molten steel after which zero time was set. Quartz tubes were used to sample liquid steel periodically and then quenched into water. The concentrations of [Al] and [Mn] in acquired steel samples were analyzed using ICP analysis.

|	
A	Copper cap
B	Al$_2$O$_3$ tube
C	Heating element
D	Thermocouple 1
E	Al$_2$O$_3$ protection tube
F	MgO crucible
G	Gas inlet
H	Stainless steel tube
I	Ball valve
J	Gas Outlet
K	Thermocouple 2

RESULTS AND DISCUSSION
Flux-Steel Reaction in Pilot Casting
Figure 2 show the changes of SiO$_2$, Al$_2$O$_3$, MgO, MnO, Na$_2$O, and B$_2$O$_3$ contents during the reaction between Flux 1 and Steel 1. The concentrations of [Mn], [Al] and [Si] before and after the reaction were shown in Table 5. The significant changes of SiO$_2$ and Al$_2$O$_3$ in mold fluxes were observed. SiO$_2$ content decreased from 42.0 to 2.9 mass% in 1800 s, which was only 7% of the original concentration; while Al$_2$O$_3$ content increased from 6.1 to 47.7 mass% during the same time span. It indicates that the rapid reaction between SiO$_2$ in Flux 1 and [Al] in Steel 1 took place, leading to the accumulation of Al$_2$O$_3$ in the mold flux and [Si] in the steel. MgO content increased from 1.8 to 5.8 mass% during the experiment, which mainly came from the refractory. Na$_2$O content decreased slightly from 7.4 to 5.9 mass%. It might attribute to the evaporation of Na2O-containing phases at high temperature or the reaction with [Al] in steel. MnO content decreased from 3.3 to 0.8 mass% in the experiment while [Mn] concentration slightly decreased by 0.2 mass%. The decrease of MnO in mold fluxes may be caused by the formation of [Mg, Mn]Al$_2$O$_4$ spinel which was reported by Kim et al.(11). This phase is thermodynamically feasible to form when the Al$_2$O$_3$ content is high, but SiO$_2$ is low. Therefore, the flux/steel interface might be a preferred location for the

precipitation of [Mg, Mn]Al2O4 spinel. The decrease of B_2O_3 content from 3.4 to 0.3 mass% was observed in mold fluxes, which may result from evaporation, or reaction with [Al]. B_2O_3 is thermodynamically possible to be reduced by [Al] according to the following equation:
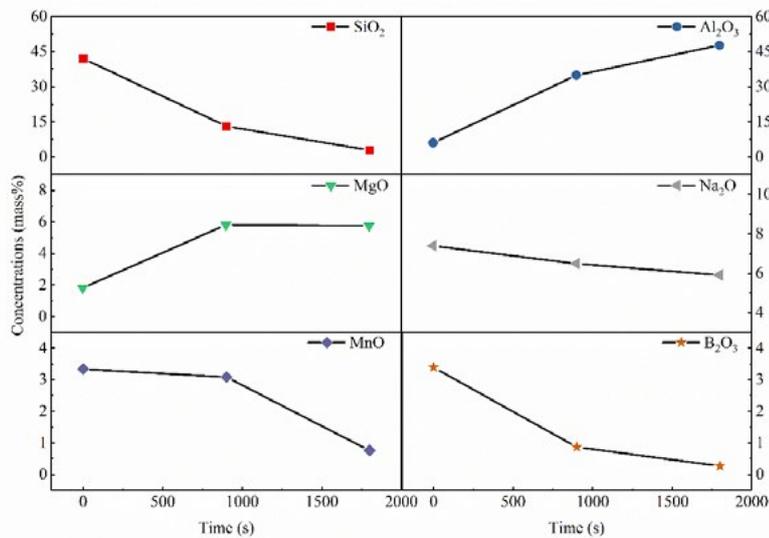
$$B_2O_3 + 2[Al] \rightarrow 2[B] + Al_2O_3$$
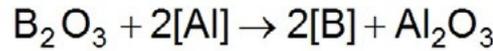
[2]

Fig. 2 – Concentrations of SiO_2, Al_2O_3, B_2O_3, MgO, Na_2O, MnO, and B_2O_3 in mold fluxes during the reaction between Steel 1 and Flux 1.

Reaction	Time	C	Si	Mn	Al
Steel 1/Flux1	Before reaction	0.65	0.13	17.7	2.00
	After reaction	0.68	0.77	17.5	1.12
Steel 2/Flux2	Before reaction	0.68	0.77	17.0	1.12
	After reaction	0.67	1.09	18.1	0.21
Steel 3/Flux2	Before reaction	0.64	1.04	17.0	1.80
	After reaction	0.67	1.07	17.2	1.26
Steel 4/Flux3	Before reaction	0.58	0.10	18.1	1.79
	After reaction	0.59	0.36	17.9	1.62
Steel 5/Flux4	Before reaction	0.59	0.36	17.9	1.62
	After reaction	0.58	0.45	17.6	0.94

The composition change of Flux 2 during the reaction with Steel 2 is given in Figure 3. The composition change of Steel 2 is listed in Table 5. During the reaction between Flux 2 and Steel 2, SiO_2 content decreased from 43.3 to 17.2 mass% in 1800 s, while Al_2O_3 content increased from 3.2 to 27.5 mass% due to the severe reaction. The reduction of SiO_2 was less intense than that in the reaction between Flux 1 and Steel 1 although the initial SiO_2 content was close. It may result from the lower [Al] concentration in Steel 2 as [Al] concentration was proved to strongly affect the reaction rate in Reaction [1] based on the previous investigation on reaction between $CaO-SiO_2$-based mold fluxes and high-Al steel (8). The changes of Na_2O and MgO were similar to those in the reaction between Flux 1 and Steel 1. The concentration of MnO sharply increased in the first 600 s and gradually decreased thereafter. It was noticed that the concentration of MnO in mold fluxes and [Mn] in steel both increased after the reaction between Flux 2 and Steel. There are two possible reasons. The increase of MnO may come from the oxidation of [Mn] by SiO_2, which is possible when [Al] concentration is low in steel (8). But once MnO content reached a

threshold, it might be reduced by [Al] again. The second explanation is related to the [Mg, Mn]Al$_2$O$_4$ spinel. The extra MnO may come from the remnant [Mg, Mn]Al$_2$O$_4$ spinel formed in the previous experiment. The remnant disintegrated into Flux 2 since Al$_2$O$_3$ content decreased and SiO$_2$ content increased in the initial stage of flux pool after the introduction of Flux 2, which moved the flux composition away from the saturation line of [Mg, Mn]Al$_2$O$_4$ spinel. As a result, MnO content increased in the initial stage. After 600 s, the accumulation of Al$_2$O$_3$ and reduction of SiO$_2$ pushed the composition close to the saturation line of [Mg, Mn]Al$_2$O$_4$ spinel that could initiate the formation of [Mg, Mn]Al$_2$O$_4$ spinel again, causing the minimization of MnO content in the later stage. But the decrease of MnO was not severe since the SiO$_2$ content in Flux 2 was not as low as that in the reaction between Flux 1 and Steel 1.
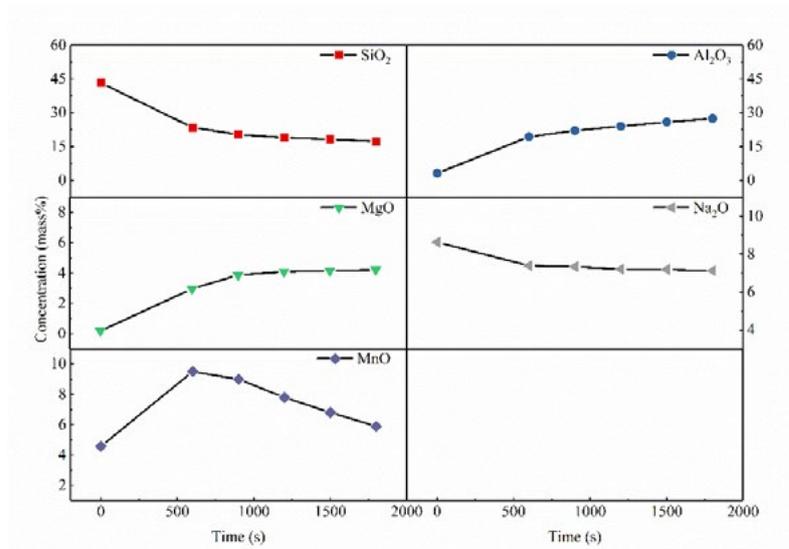

Fig. 3 – Concentrations of SiO$_2$, Al$_2$O$_3$, MgO, Na$_2$O, and MnO in mold fluxes during the reaction between Steel 2 and Flux 2.

The composition change of Flux 2 in the reaction with Steel 3 is indicated in Figure 4; while the composition change of Steel 3 is listed in Table 5. SiO$_2$ content decreased from 43.3 to 1.2 mass% during the experiment; while Al$_2$O$_3$ concentration increased from 3.2 to 52.1 mass% in the meantime. The increment of Al$_2$O$_3$ and the decrement of SiO$_2$ were both more obvious than those in the reaction between Flux 2 and Steel 2. It revealed that a high concentration of [Al] in steel could accelerate Reaction 1. A higher [Al] concentration would facilitate the accumulation of Al$_2$O$_3$ and the reduction of SiO$_2$ in mold fluxes.
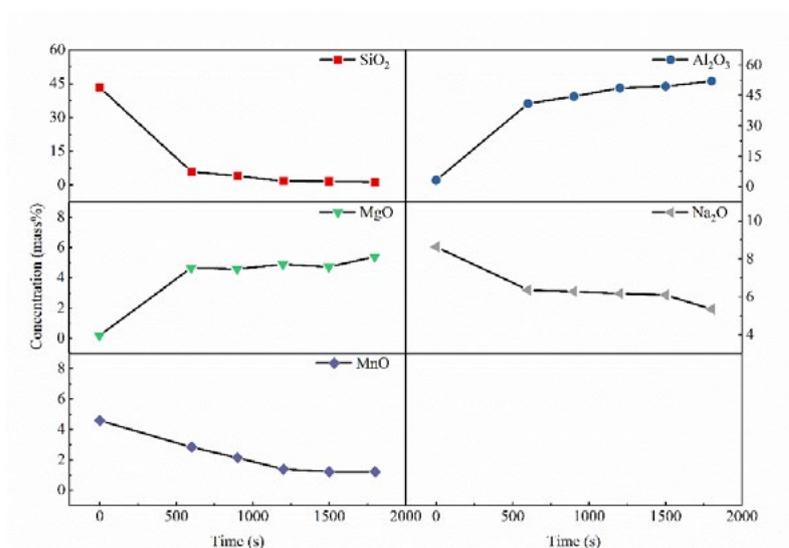

Fig. 4 – Concentrations of SiO$_2$, Al$_2$O$_3$, MgO, Na$_2$O, and MnO in mold fluxes during the reaction between Steel 3 and Flux 2.

In the 2nd set of experiments, two CaO-Al$_2$O$_3$-based mold fluxes were used to react with high-Al steel. Flux 3 was used to react with Steel 4. The composition change of Flux 3 in the reaction with Steel 4 is indicated in Figure 5, and the composition change of Steel 4 is listed in Table 5. The initial concentration of SiO2 in the flux was 15.3 mass%, which was much lower than those in Fluxes 1 and 2. This concentration decreased to 2 mass% after 1500 s; while Al$_2$O$_3$ content increased from 16.9 to 40.0 mass%. In the meantime, [Si] concentration increased from 0.10 to 0.36 mass%, and [Al] concentration dropped from 1.79 to 1.62 mass%. It seems that 15.3 mass% SiO$_2$ in the initial composition of Flux 3 did not obviously retard Reaction 1. Considering the increment of Al$_2$O$_3$ in the mold fluxes, the reductions of Na2O and B$_2$O$_3$ were more likely from the reaction instead of evaporation.
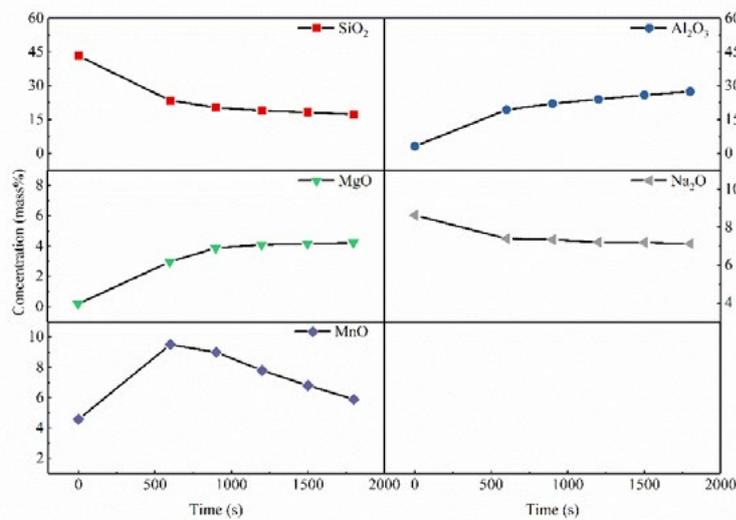

Fig. 5 – Concentrations of SiO$_2$, Al$_2$O$_3$, B$_2$O$_3$, MgO, Na$_2$O, MnO, and B$_2$O$_3$ in mold fluxes during the reaction between Steel 4 and Flux 3.

The composition change of Flux 4 in the reaction with Steel 5 is given Figure 6, and the composition change of Steel 5 is listed in Table 5. Flux 4 is based on CaO-Al$_2$O$_3$ flux system where the initial concentration of SiO$_2$ was as low as 8.1 mass% and CaO/Al$_2$O$_3$ ratio was 1. SiO$_2$ content only decreased from 8.1 to 5.6 mass% throughout the experiment, which means only 30% of SiO$_2$ was reduced. It was much smaller than the decline of SiO$_2$ content in the previous experiments. Al$_2$O$_3$ content increased from 28.8 to 42.4 mass% in 1800 s, which was also relatively insignificant compared with those in the previous experiments. The major source of the Al$_2$O$_3$ accumulation presented in Figure 6 was likely to stem from the reduction of B$_2$O$_3$ whose concentration dropped from 15.8 to 5.4 mass% during the experiment. Aside from the contribution to the increase of Al$_2$O$_3$, the abrupt increase of MnO could attribute to the reaction between [Mn] and B$_2$O$_3$.

According to the results, a low concentration of SiO$_2$ (< 8 mass%) could kinetically benefit the restraint on the accumulation of Al$_2$O$_3$. The low addition of SiO$_2$ requires a large amount of fluxing agent, e.g. B$_2$O$_3$, to decrease the liquidus temperature and adjust other properties. However, the reduction of B$_2$O$_3$ introduced an additional increment of Al$_2$O$_3$ in mold fluxes. Therefore, the balance between the reaction rate and melting property could be a critical factor in the design of CaO-Al$_2$O$_3$-based mold fluxes.
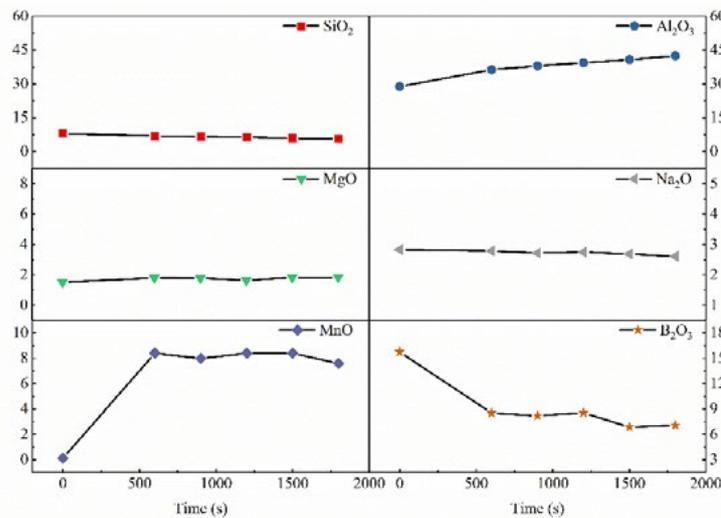
Continuous casting

Fig. 6 – Concentrations of SiO$_2$, Al$_2$O$_3$, B$_2$O$_3$, MgO, Na$_2$O, MnO, and B$_2$O$_3$ in mold fluxes during the reaction between Steel 5 and Flux 4.

Flux-Steel Reaction in Laboratory Tests

Three types of CaO-Al$_2$O$_3$-based mold fluxes (Fluxes 5, 6, and 7) were studied based on the reaction between these mold fluxes and a high-Al steel (Steel 6). Different CaO/Al$_2$O$_3$ ratios were applied to the studied mold fluxes. The changes of [Al] content in steel are compared in Figure 7(a). In Flux 5, [Al] content decreased from 1.65 to 0.53 mass% in 1200 s and 0.37 mass%

in 3600 s. In Flux 6, [Al] content decreased from 1.49 to 0.06 mas% in 3600 s. In Flux 7, [Al] concentration decreased from 1.74 to 0.63 mass% in the first 11 minutes, but no further sample acquisition was made due to a lab incident. It seems that reaction was most intense in first 1200 s. As [Al] concentration should be very low due to the strong affinity of Al and O, the flux of [Al] in steel/flux interface could be written as follows (8):

$$-\ln\frac{[Al\%]_t}{[Al\%]_0} = \frac{k_{Al}A\rho_{steel}}{W_{steel}}t$$

[3]

where [Al%]^t and [Al%]^0 are [Al] concentration at time t and zero, kAl is the mass transfer coefficient of [Al] (m/s), A is the cross-section area (m^2), ρsteel is the density of steel (g/m^3) calculated according to reference (12), Wsteel is the total weight of steel (g), t is reaction time (s). The relationship between -ln([Al]t/[Al]0) and t is plotted in Figure 12(b). As k$_{Al}$ is proportional to the slope of the curve, it is indicated that the decrease of CaO/Al$_2$O$_3$ ratio decelerated the oxidation rate

of [Al]. Besides, the oxidation of [Al] became rather slower as experiment proceeded in the reaction with the k^{Al} decreasing up to 6.8x10^{-6} m/s when CaO/Al$_2$O$_3$ ratio = 1; while it kept relatively constant after 1 min with the kAl = 4.0x10^{-5} m/s during the experiment when CaO/Al$_2$O$_3$ ratio = 3. The oxidation rate of [Al] was also relatively constant in the first 660 s with the kAl = 5.7 x 10^{-5} m/s when CaO/Al$_2$O$_3$ ratio = 4.
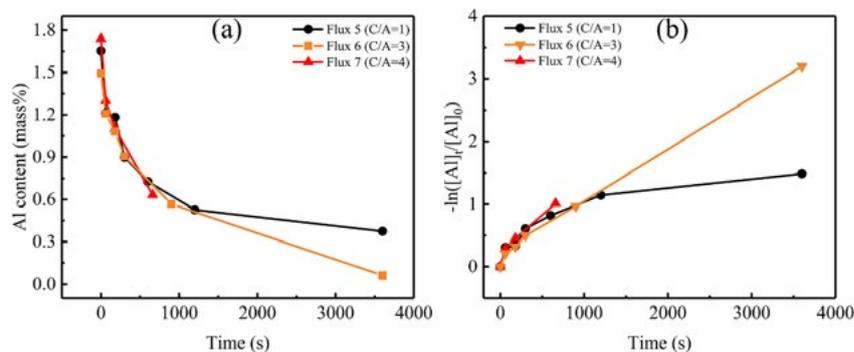

Fig. 7 – Concentration change of Al in steel during the reaction between Steel 6 and Flux 5/Flux 6/Flux 7.

The [Al] losses in the liquid steel was higher in the lab experiments compared with those in pilot tests due to the ratio of mold fluxes to steel was much higher in lab experiments. The change of [Al] concentration in lab and pilot tests may not be comparable in value but their tendency should be similar.

CONCLUSIONS

1. CaO-SiO_2-based mold fluxes showed a severe reaction when casting high-Al steel, which resulted in a significant increase of Al_2O_3 content and a decrease of SiO_2 content during experiments. It makes the in-mold performance undesirable and unpredictable;

2. CaO-Al_2O_3-based mold fluxes showed better a stability in composition when casting high-Al steel. The changes of Al_2O_3 and SiO_2 contents were not as severe as those in CaO-$SiO2$-based mold fluxes. However, the variation of B_2O_3 may also affect the melting property of mold fluxes;

3. The increase of CaO/Al_2O_3 ratio could accelerate the reaction between high-Al steel and CaO-Al_2O_3-based mold fluxes based on the variation of [Al] content in liquid steel.

ACKNOWLEDGEMENT CONCLUSIONS

REFERENCES

[1]   Steinmetz DR, Jäpel T, Wietbrock B, Eisenlohr P, Gutierrez-Urrutia I, Saeed-Akbari A, et al. Revealing the strain-hardening behavior of twinning-induced plasticity steels: Theory, simulations, experiments. Acta Materialia. 2013; 61(2):494-510.

[2]   Gutierrez-Urrutia I, Raabe D. Dislocation and twin substructure evolution during strain hardening of an Fe-22wt.% Mn-0.6wt.% C TWIP steel observed by electron channeling contrast imaging. Acta Materialia. 2011; 59(16):6449-62.

[3]   Grässel O, Krüger L, Frommeyer G, Meyer LW. High strength Fe-Mn-(Al, Si) TRIP/TWIP steels development-properties-application. International Journal of Plasticity. 2000; 16(10):1391-409.

[4]   Sato K, Ichinose M, Hirotsu Y, Inoue Y. Effects of Deformation Induced Phase Transformation and Twinning on the Mechanical Properties of Austenitic Fe–Mn–Al Alloys. ISIJ International. 1989; 29(10):868-77.

[5]   Pierce DT, Jiménez JA, Bentley J, Raabe D, Wittig JE. The influence of stacking fault energy on the microstructural and strain-hardening evolution of Fe–Mn–Al–Si steels during tensile deformation. Acta Materialia. 2015; 100:178-90.

[6]   Dumay A, Chateau JP, Allain S, Migot S, Bouaziz O. Influence of addition elements on the stacking-fault energy and mechanical properties of an austenitic Fe–Mn–C steel. Materials Science and Engineering: A. 2008; 483-484:184-7.

[7]   Cho J-W, Blazek K, Frazee M, Yin H, Park JH, Moon S-W. Assessment of CaO-Al_2O_3 Based Mold Flux System for High Aluminum TRIP Casting. ISIJ International. 2013; 53(1):62-70.

[8]   Kim M-S, Lee S-W, Cho J-W, Park M-S, Lee H-G, Kang Y-B. A Reaction Between High Mn-High Al Steel and CaO-SiO_2-Type Molten Mold Flux: Part I. Composition Evolution in Molten Mold Flux. Metallurgical and Materials Transactions B. 2013; 44(2):299-308.

[9]   Kang Y-B, Kim M-S, Lee S-W, Cho J-W, Park M-S, Lee H-G. A Reaction Between High Mn-High Al Steel and CaO-SiO_2-Type Molten Mold Flux: Part II. Reaction Mechanism, Interface Morphology, and Al2O3 Accumulation in Molten Mold Flux. Metallurgical and Materials Transactions B. 2013; 44(2):309-16.

[10]   Blazek K, Yin H, Skoczylas G, McClymonds M, Frazee M. AIST Transactions-Development and Evaluation of Lime-Alumina Based Mold Powders. Iron and Steel Technology. 2011; 8(8):231.

[11]   Kim DJ, Park JH. Interfacial Reaction Between CaO-SiO_2-MgO-Al_2O_3 Flux and Fe-xMn-yAl (x = 10 and 20 mass pct, y = 1, 3, and 6 mass pct) Steel at 1873 K (1600 °C). Metallurgical and Materials Transactions B. 2012; 43(4):875-86.

[12]   Thu Hoai L, Lee J. Density of Liquid Fe-Mn-C Alloys. Metallurgical and Materials Transactions B. 2011; 42(5):925-7.