Effect of Mg Addition on the Evolution of Inclusions in Al–Ca Deoxidized Melts

Tongsheng ZHANG,* Yi MIN, Chengjun LIU and Maofa JIANG

School of Materials and Metallurgy, Northeastern University, P. O. Box313, No. 3-11, Wenhua Road, Heping District, Shenyang, 110819 P. R. China.

(Received on October 24, 2014; accepted on March 30, 2015)

To investigate the effect of magnesium addition on the evolution of inclusions in Al–Ca deoxidized melts, both thermodynamic calculations and deoxidized experiments were carried out in the present work. The samples took from the melts were polished and analyzed by field emission scanning electron microscopy (FE-SEM) and energy dispersive X-ray spectroscopy (EDX). The results showed that the utilization of magnesium significantly influenced the size of oxide inclusions in Al–Ca deoxidized melts. Superfluous MgO raised the melting point of the complex inclusions, and then worsen the steel castability. Therefore, the amount of magnesium addition should be under control. Based on thermodynamic calculations and experimental results, the recommend range of [Mg] is 1–5 ppm. All inclusions observed in the sample were nearly spherical except for solid calcium aluminates inclusions. Oxide inclusions were modified quickly after magnesium addition. Meanwhile, magnesium can also modify solid calcium aluminate inclusions in the melts similarly, but there are unreacted cores in the inclusions at the initial stage. The evolution mechanisms of inclusions were comprehensively discussed, and models for the formation of oxide inclusions were set up. As for the production practice, to achieve the full liquid inclusions in molten steel, the addition amount of magnesium and calcium should be considered simultaneously.

KEY WORDS: magnesium; calcium; inclusion; thermodynamic.

1. Introduction

Nonmetallic inclusions in steel are well-known to induce severe product defects. However, it is impossible to achieve the goal that the harmful inclusions are completely removed from liquid steel during refining process. As an alternative approach to minimize the harmful effects, the modification of the residual inclusion composition is widely investigated.

Aluminum is one of the most popular deoxidizers for its strong affinity to oxygen. But alumina deoxidation products cause the clogging of submerged entry nozzle during continuous casting. Therefore, performing calcium treatment is very common in steelworks in order to have complex liquid inclusions, which can avoid or prevent the inclusions from clogging the nozzle. As result, many researches of nonmetallic inclusions in Al–Ca deoxidized steel, such as thermodynamic calculation, size distribution, formation mechanism and kinetics, have been intensively studied in recent years. It has been proven by thermodynamic calculation that very small amount of calcium enables the formation of liquid inclusion. Owing to the contact angle and interfacial tension, it is difficult to agglomerate and remove form molten steel for liquid calcium aluminate inclusions. A mathematical model has been proposed by Fernandes et al. to investigate the movement of liquid inclusions in low-carbon steel, during refining process, and the results indicate that inclusions with diameters larger than 25 μm are able to float. So from this point of view, these residual large inclusions with a large size can have negative effects on improving the quality of the steel.

Moreover, many researchers found that that the dissolved magnesium was supplied from the raw materials, slag and refractory, and the spinel inclusions formed by the reaction between alumina inclusions and dissolved magnesium. Spinel inclusions have been thought to be hard, irregular and nondeformable, and it is commonly very harmful to the final products. Calcium treatment can similarly modify spinel inclusions to complex liquid inclusions. Many scholars have contributed to research the formation thermodynamics and evolution mechanism of these inclusions, such as Itoh et al., Seo et al., Verma et al., Park et al. and Yang et al. However, there are controversies in the modification of spinel in Ca treatment process. Harkness et al. reported that the spinel, which has a stable face centered cubic structure with high melting point, can be not effectively suppressed by calcium treatment. Furthermore, for the reason of kinetics, Yang et al. proposed that it is difficult to modify spinel inclusions with size of > 5 μm, nevertheless, the core of the inclusion after calcium treatment is still pure MgO-Al2O3. Furthermore, Ca treatment is strictly prohibited in some grade of steel production process such as bearing steel. Hence, Mg treatment has also been studied for replacing Ca treatment.

* Corresponding author: E-mail: neu_zts@163.com
DOI: http://dx.doi.org/10.2355/isijinternational.ISIJINT-2014-691

© 2015 ISIJ
Magnesium has strong thermodynamic affinities with oxygen,\textsuperscript{18,31} further, MgO-contained inclusions present a poorer agglomeration characterization.\textsuperscript{4,32,33} By using in-situ CSLM observation, Kimura \textit{et al.} found that alumina-magnesia complex inclusions on the surface of molten steel have a much weaker tendency to aggregate and to form clusters than alumina inclusions.\textsuperscript{34,35} It is probably a good idea that the inclusions after calcium treatment can be refined through magnesium addition. Once the addition time is appropriate, the residual large inclusions are refined, which can improve the final quality of steel. Therefore, it is of importance to study the formation and control of Al–Mg–Ca–O complex inclusions in detail. However, investigations on the deoxidization, especially inclusion modification by magnesium and calcium complex added to the melts are limited.\textsuperscript{36,37} Besides, the mechanism and phase stability of the inclusion in melts are not clarified due to lack of exact thermodynamic calculation. Therefore, it is difficult theoretically to control the occurrence of large-volume hard inclusions.

In this present study, to reveal the effects of magnesium on the evolution of inclusions in Al–Ca deoxidized melts, the melts containing different aluminum and calcium concentration were prepared respectively. After magnesium addition, the samples extracted at different time were analyzed by scanning electron microscopy and energy dispersive spectroscopy. Consequently, the composition, morphology and size of inclusions in the samples were comprehensively investigated. At the same time, the thermodynamics of the formation of all inclusions during co-deoxidation with aluminum, calcium and magnesium was discussed in the present work. The results were performed to discuss the evolution process of inclusions. Current studies aiming at controlling inclusions in molten steel will lay a foundation for further industrial application.

2. Experimental Procedures

The experiments were carried out by using a Si–Mo heating tube furnace, the schematic of which is shown in Fig. 1. Approximately 300 g pure iron was placed into a high purity fused MgO crucible (56 mm diameter and 100 mm height) and transferred to a vacuum induction furnace. The melt was heated to 1 873 K under argon atmosphere at a flow rate of 5.0 L·min\textsuperscript{−1}. Then the master irons were hold for 30 min at 1 873 K to achieve sufficient homogenization. Subsequently, the solved oxygen in the melt was measured using an electrolyte oxygen probe, and it was defined as the initial oxygen content (No.1 [O]). Based on the final oxygen level, a certain amount of initial deoxidant (Al wires and Ca–Fe alloy) was added, and the melt was immediately stirred for ten seconds using a molybdenum stick. After five minutes from the addition of initial deoxidant, the dissolved-oxygen content (No.2 [O]) was subsequently measured, which was defined as the final oxygen content. Sample 1 was taken by a quartz pipe and quenched in an ice bath. Then Ni–Mg alloy, packed in iron foil to prevent it from being oxidized by air, was inserted to the melt except for Melt D. Thereafter, the melt was respectively held for one minutes, five minutes at 1 873 K and then sampled by a quartz tube, followed by rapid quenching (Sample 2 to Sample 3). Experimental process was provided in Fig. 2. In all experiments, [Al], [Mg] and [Ca] in the steel were controlled by adding different masses of alloy. The compositions of raw materials contain pure iron, Al wires, Ca–Fe alloy and Ni–Mg alloy are shown in Table 1.

After all the experiments, the dissolved aluminium, calcium and magnesium in the samples were determined using ICP–OES. The dissolved nitrogen levels were measured by the inert gas fusion-infrared absorption technique with an accuracy of ±1 ppm. The dissolved nitrogen content in each metal kept almost constant, so the data is not given in Table 2. The measured compositions of soluble aluminum, calcium, magnesium and oxygen of steel samples are listed in Table 2. The quenched iron samples were cross-sectioned and polished, for analyzing the morphology and chemical

![Fig. 1. Schematic diagram of experimental furnace.](image1)

![Fig. 2. Melting and sampling sequences of the present experiments.](image2)

<table>
<thead>
<tr>
<th>Type</th>
<th>Fe</th>
<th>Ni</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Al</th>
<th>Mg</th>
<th>S</th>
<th>P</th>
<th>Ca</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure iron</td>
<td>99.944</td>
<td>–</td>
<td>0.002</td>
<td>0.01</td>
<td>0.03</td>
<td>0.001</td>
<td>–</td>
<td>0.007</td>
<td>0.007</td>
<td>–</td>
<td>0.043</td>
</tr>
<tr>
<td>Al wire</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>99.99</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.01</td>
</tr>
<tr>
<td>Ca–Fe alloy</td>
<td>69.8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>30.1</td>
</tr>
<tr>
<td>Ni–Mg alloy</td>
<td>0.93</td>
<td>80.12</td>
<td>0.78</td>
<td>0.19</td>
<td>–</td>
<td>–</td>
<td>17.98</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

© 2015 ISIJ 1542
3. Results and Discussion

3.1. Morphology and Composition Distribution of Mg–Al–Ca–O Complex Inclusions

To assess the evolution process of inclusions, the analyses of inclusions composition are very necessary. Energy dispersive spectroscopy results in each experimental melts after addition of Al/Ca/Mg alloy for 1 or 5 min were converted into mass percentage of CaO, MgO and Al₂O₃ and were projected into the calculated CaO–MgO–Al₂O₃ ternary system phase diagram (with FactSage software), as given in Fig. 3. As can be seen, majority of the CaO–Al₂O₃ type complex inclusions in sample A-1 concentrated in or around the lower melting point zone after addition of aluminium.

Table 2. Chemical analyses of experimental samples (mass%).

<table>
<thead>
<tr>
<th>No.</th>
<th>[Al]</th>
<th>[Ca]</th>
<th>[Mg]</th>
<th>[O]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>0.115</td>
<td>0.0006</td>
<td>–</td>
<td>0.0003</td>
</tr>
<tr>
<td>A-2</td>
<td>0.098</td>
<td>0.0005</td>
<td>0.0005</td>
<td>0.0006</td>
</tr>
<tr>
<td>A-3</td>
<td>0.102</td>
<td>0.0006</td>
<td>0.0004</td>
<td>0.0004</td>
</tr>
<tr>
<td>B-1</td>
<td>0.098</td>
<td>0.0002</td>
<td>–</td>
<td>0.0006</td>
</tr>
<tr>
<td>B-2</td>
<td>0.113</td>
<td>0.0001</td>
<td>0.0018</td>
<td>0.0005</td>
</tr>
<tr>
<td>B-3</td>
<td>0.096</td>
<td>0.0002</td>
<td>0.0015</td>
<td>0.0005</td>
</tr>
<tr>
<td>C-1</td>
<td>0.218</td>
<td>&lt;0.0001</td>
<td>–</td>
<td>0.0004</td>
</tr>
<tr>
<td>C-2</td>
<td>0.216</td>
<td>&lt;0.0001</td>
<td>0.0005</td>
<td>0.0004</td>
</tr>
<tr>
<td>C-3</td>
<td>0.202</td>
<td>&lt;0.0001</td>
<td>0.0008</td>
<td>0.0004</td>
</tr>
<tr>
<td>D-1</td>
<td>0.122</td>
<td>0.0008</td>
<td>–</td>
<td>0.0002</td>
</tr>
<tr>
<td>D-2</td>
<td>0.118</td>
<td>0.0004</td>
<td>–</td>
<td>0.0003</td>
</tr>
<tr>
<td>D-3</td>
<td>0.112</td>
<td>0.0003</td>
<td>–</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Fig. 3. Composition distributions of typical inclusions in the melts Red lines (1 873 K) represent the liquidus line. a) In melt A; b) In melt B; c) In melt C; d) In melt D.
wire and Ca–Fe. The same case also exists in sample A-2 and A-3 after magnesium addition, with a large part of inclusions locating inside the lower melting point region. Furthermore, as shown in Fig. 3(a), effect of magnesium addition on reducing the size of inclusions in Al–Ca deoxidized melts is obvious. Consequently, improved properties of steel can be expected.

Before magnesium addition, the inclusions in sample B-1 are mainly CaO–Al$_2$O$_3$ type complex liquid oxides (showing in Fig. 3(b)). The size of these inclusions are relatively large (>5 μm). After addition of magnesium alloy, CaO–MgO–Al$_2$O$_3$ type complex inclusions can be frequently observed in the samples. The size of inclusions reduces to 2 μm probably due to the modification of the contact angle and interfacial tension between inclusions and molten iron. The work of Kimura et al.\textsuperscript{34,35} can approve it indirectly. The reason for this interesting phenomenon is complicated, and it should be paid more attention in the following research. Due to the high magnesium concentration (0.0015%) in melt B, MgO concentration in inclusions can reach to higher than 25%. Owing to this reason, the composition of the inclusions in melt B deviate the low-temperature liquid region to some extent. However, most of the inclusions observed in sample B-3 display nearly spherical shape as indicated in Fig. 3(b).

It can be seen that the composition of the inclusions in sample C-1 are not all located in liquid region of phase diagram. Due to low calcium concentration in the melt, the inclusions are not spherical but irregular shape. Comparing with sample A-1 and B-1, the inclusions in sample C-1 have a small size, probably because of solid phase. With magnesium alloy adding, the composition of the inclusions in sample C-2 and C-3 move along the direction parallel to the alumina peak. At the same time, inclusion compositions become much more scattered, and much more MgO based inclusions were formed in melt when magnesium addition amount increased. It can be seen clearly that the modifying inclusion is not homogeneous. Whereas, there is an unreacted core in the inclusion of sample C-3 (showing in Fig. 3(c)).

To confirm the effect of magnesium on the size of inclusions in Al–Ca deoxidized melts, verifying experiments have been carried out, as shown in Fig. 3(d). The inclusions in sample D-1, D-2 and D-3 are mainly CaO–Al$_2$O$_3$ type complex liquid oxides, which also have a relatively large diameter (>5 μm). Furthermore, larger inclusions (>10 μm) can be clearly observed in sample D-3. Therefore, under no magnesium addition condition, it can be conjectured easily that size of the inclusions increase obviously in Melt D with extending the holding time. The similar work was carried out by Zhang and co-workers\textsuperscript{24,27} in molten steels.

To reveal the modification process, elemental mapping analyses for typical inclusions are carried out by using SEM/EDX. The results are presented in Figs. 4 and 5. It is clear that all elements are mainly distributed all over the inclusions in sample A-3 and B-3. It is worth noting that this phenomenon could continue after magnesium addition. This phenomenon proves that morphology and composition of inclusions can be effectively controlled by magnesium soon. However, in the image of Fig. 4, inhomogeneous calcium-magnesium aluminate inclusion is observed obviously in sample C-3, so it can be speculated easily that the modification reaction rate in solid phase is much lower than liquid phase. The inclusion had a calcium aluminates core and a spinel shell as shown in Fig. 5.

### 3.2. Thermodynamic Calculation and Evolution Mechanism of Mg–Al–Ca–O Complex Inclusions

To assess determine the evolution mechanism of Mg–Al–Ca–O complex inclusions, the thermodynamic calculations are very necessary. Mg–Al–O and Al–Ca–O equilibrium phase diagrams have been reported by many literatures.\textsuperscript{5,16,17} In the present study, the thermodynamic calculation is based on the theory of minimum Gibbs free energy. Since magnesium, calcium, aluminium and oxygen concentration involved in present study is very low, the melt could be assumed an ideal solution. Thus, dilute solution of one mass pct standard state has been used in present study. Table 3 presents the Gibbs free energy data of chemical reactions involved in the present work.

Since aluminium and calcium have a strong affinity with oxygen in liquid iron. After the deoxidants added in the melt, CaO·6Al$_2$O$_3$ can be firstly formed by dissolved calcium, aluminium and oxygen react directly, which is shown in Eq. (9). This reaction is determined by linear combination from Eqs. (1), (3) and (5) (showing in Table 3).

$$
\text{CaO} \cdot 6\text{Al}_2\text{O}_3(s) = [\text{Ca}] + 12[\text{Al}] + 19[\text{O}]$$

$$
\Delta G^\circ = 5\,359\,607 - 1\,234.427\,T \text{ J mol}^{-1} \quad (9)
$$

When calcium concentration is high enough, CaO·6Al$_2$O$_3$ would react with Ca to form CaO·2Al$_2$O$_3$ as shown in Eq. (10).

$$
7(\text{CaO} \cdot 6\text{Al}_2\text{O}_3)(s) + 12[\text{Ca}]
= 19(\text{CaO} \cdot 2\text{Al}_2\text{O}_3)(s) + 8[\text{Al}]
$$

$$
\Delta G^\circ = 1\,628\,586 - 1\,873.527\,T \text{ J mol}^{-1} \quad (10)
$$

Referring to the CaO–Al$_2$O$_3$ binary phase diagram, it can be read that CaO·Al$_2$O$_3$, 12CaO·7Al$_2$O$_3$ are all in liquid phase at 1873 K. So these two phases are chosen as the liquid phase for the calculation of phase stability between solid phases (eg. MgO·Al$_2$O$_3$, CaO·2Al$_2$O$_3$ and CaO) and liquid calcium aluminate, and the phase diagram is calculated from Eqs. (11)–(13).
Fig. 4. Elemental mapping of typical CaO–Al₂O₃–MgO inclusions (a) liquid phase inclusion in Sample A-3; (b) solid phase inclusion in Sample B-3.

Fig. 5. Elemental mapping of typical MgO–Al₂O₃-riching solid phase inclusion in Sample C-3.
CaO·Al2O3(l) = [Ca] + 6[Al] + 4[O]  
\[ \Delta G^\circ = 1023 \, 637 - 142.12T \, J \cdot mol^{-1} \]  

\[ 12\text{CaO} \cdot 7\text{Al}_2\text{O}_3(l) = 12[\text{Ca}] + 17[\text{Al}] + 33[\text{O}] \]  
\[ \Delta G^\circ = 7113 \, 224 - 189.4T \, J \cdot mol^{-1} \]  

\[ \text{MgO} \cdot \text{Al}_2\text{O}_3(s) = [\text{Mg}] + 2[\text{Al}] + 4[\text{O}] \]  
\[ \Delta G^\circ = 978 \, 182 - 128.93T \, J \cdot mol^{-1} \]  

The corresponding interaction coefficient adopted by the present calculation is listed in Table 4. Based on the thermodynamic data and equations, the stability diagram of CaO, xCaO·yAl2O3 and MgO·Al2O3 at 1873 K as a function of mass percent of calcium and aluminium in liquid iron has been calculated using the Matlab software, as shown in Fig. 6. As presented in Fig. 6(a), liquid oxide phase and three solid phases, viz. CaO, CaO·2Al2O3, and CaO·6Al2O3 are in equilibrium with molten steel with calcium and aluminium concentration ranging from 0.1 to 50 ppm, 1 to 10 000 ppm, respectively. It is noteworthy that the liquid oxide phase region is wide when calcium concentration is higher than 1 ppm. When the aluminium concentration is more than 1 000 ppm, however, liquid inclusion forms with calcium concentration ranging from 0.5 to 10 ppm. However, with the existence of magnesium in the steel at most 1 ppm, the stability region of spinel appears while that of liquid inclusion dramatically decreases as shown in Fig. 6(b). When the Al content in the molten iron is 1 000 ppm, liquid inclusions form at calcium concentration values above 0.5 ppm. It is obvious that magnesium exerts a large influence on stable phase, which means increase in magnesium content in the steel can greatly narrow the liquid inclusion region. In Fig. 6, it indicates that the composition points of sample A-1, A-2, A-3, B-1, D-1, D-2 and D-3 locate in the liquid region, and the composition points of sample B-2, B-3, C-2 and C-3 locate in the spinel region. The results are in conformity with SEM images shown in Fig. 3.

On the basis of above analysis, the modification process of inclusions can be speculated as follows. Individual modification mechanism was induced. As illustrated in Fig. 7(a), the modification mechanism of inclusions in melt A and melt B is similar. Because of a strong affinity of aluminium with oxygen in liquid iron, when Al wire added in the melt, Al2O3 inclusion formed first as shown in Eq. (14).

\[ 2[\text{Al}] + 3[\text{O}] = \text{Al}_2\text{O}_3(s) \]  

Further, when calcium is added to the melt, the following modification reaction can be expected.

\[ x[\text{Ca}] + y\text{Al}_2\text{O}_3 = (2x/3)[\text{Al}] + x\text{CaO} - (y/3)\text{Al}_2\text{O}_3 \]  

In liquid iron, xCaO·yAl2O3 can be formed by dissolved calcium, aluminium and oxygen react directly, which is shown in Eq. (16).

| Table 4. The mass percent interaction parameters of Fe–Mg–Al–Ca–O system at 1 873 K. |
|-----------------|----------------|----------------|----------------|
| \( i \) \( j \) \( k \) \( e_i^j \) \( r_i^j \) \( e_{ij}^{(k)} \) | \( i \) \( j \) \( k \) \( e_i^j \) \( r_i^j \) \( e_{ij}^{(k)} \) |
| Mg | O | 0.047^{(1)} | 0^{(2)} | -61 \, 000^{(1)} |
| Al | O | -0.046^{(1)} | 0^{(2)} | -61 \, 000^{(1)} |
| O | Mg | 460^{(4)} | 350 \, 000^{(7)} | -230^{(3)} |
| Al | Ca | -0.12^{(6)} | 0^{(5)} | 0^{(6)} |
| Mg | Ca | 0^{(4)} | 0^{(5)} | 0^{(6)} |
| Mg | Al | -0.13^{(4)} | 0^{(2)} | 0^{(2)} |
| O | Mg | -1.98^{(4)} | 39.8^{(9)} | -0.028^{(4)} |
| Al | Mg | 0.045^{(3)} | 0^{(5)} | -0.028^{(4)} |
| Ca | O | -0.001^{(1)} | 0^{(6)} |
| O | Ca | 0.001^{(1)} | 0^{(6)} |
| Mg | Ca | 0.0042^{(1)} | 0^{(6)} |

© 2015 ISIJ
from calcium aluminate. If Ca addition is sufficient, liquid calcium aluminate inclusions was formed.

\[ x[Ca] + 2y[Al] + (x + 3y)[O] = xCaO - yAl_2O_3 \] ... (16)

If there is a trace of dissolved magnesium in liquid steel, the CaO–Al_2O_3 system inclusions will be unstable and change into CaO–MgO–Al_2O_3 system inclusions, as predicted by Eq. (17).

\[ z[Mg] + xCaO - yAl_2O_3(I) = (x - z)CaO - zMgO - yAl_2O_3 + z[Ca] \] ... (17)

If Mg addition is excess, MgO content in complex inclusions increases gradually with time and the maximum content affect the morphology of inclusions. Very similar results were also reported by Park et al. for control of
MgO-Al₂O₃ spinel inclusions in Stainless steels and Nishi et al. for in Fe–Ni alloys. In order to control the morphology of inclusions, the dissolved magnesium concentration in the melts should be controlled strictly.

However, in the melt C, due to low calcium addition amount, the inclusions in the melts are solid calcium aluminate. Therefore, the modification mechanism of inclusions in melt C is shown in Fig. 7(b). At the initial stage, there are unreacted solid calcium aluminate cores in the inclusions. This phenomenon has been confirmed by many chemical experiments and thermodynamics calculations at 1 873 K. The main findings can be summarized as follows.

(1) The size of oxide inclusions in Al–Ca deoxidized melts could be controlled well by magnesium, but the amount of magnesium addition should be limited to a certain value. Excessive MgO concentration in complex inclusions rise the melt point of the inclusions, and then worsen the steel castability. Based on thermodynamic calculations and experiments, the recommend value of [Mg] in present work is 1–5 ppm.

(2) All inclusions observed in the sample were nearly spherical except for solid calcium aluminate inclusions. Oxide inclusions were modified quickly after magnesium addition. Meanwhile, magnesium can also modify solid calcium aluminate inclusions in the melts similarly, but there are unreacted cores in the inclusions at the initial stage.

(3) Sufficient calcium addition could be considered to ensure formation of liquid inclusions, and then increase modification efficiency. Therefore, to achieve the full liquid inclusions in molten steel, both the amount of magnesium and calcium addition should be considered simultaneously in practice. When the addition time is appropriate, the residual large inclusions are refined, which can improve the final quality of steel.

4. Conclusions

The effects of magnesium on the evolution of inclusions in Al–Ca deoxidized melts have been determined by the chemical experiments and thermodynamics calculations at 1 873 K. The main findings can be summarized as follows.

Acknowledgments

The authors wish to thank the National Natural Science Foundation of China (No. 51374059, No. 51374060) and the Fundamental Research Funds for the Central Universities of China (N120602005) for their financial support for the current study.

REFERENCES

42) N. Satoh and T. Taniguchi: Tetsu-to-Hagané, 95 (2009), 827.