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Effects of K_2CO_3 Addition on Inclusions in High-Carbon Steel for Saw Wire

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Abstract: In order to avoid the formation of crack initiation sites, inclusions in high-carbon steel for saw wire are strictly required to have excellent deformability. However, it is hard to achieve this goal with only conventional inclusion softening art, such as Si-Mn deoxidation and low basicity top slag refining. Therefore, a new method should be put forward to enhance the deformability of inclusions. Low melting temperature inclusions are widely considered to have good deformability, hence, adding K (potassium) into inclusions may become a potential new method to better enhance the deformability of inclusions due to the pronounced effect of K_2O on lowering the melting temperature of inclusions. In the present study, the influences of Fe/ K_2CO_3 (weight ratio), K_2CO_3 addition amount and reaction time on inclusions were investigated by using a graphite tube resistance furnace. Through this study, a solution to adding K into inclusions effectively by K_2CO_3 addition was developed and the melting temperature of inclusions was significantly reduced. In addition, the reaction mechanism between K_2CO_3 /slag/steel/inclusion was deduced and the relation between deformability and crystallinity of inclusions was also briefly discussed.

Keywords: K_2CO_3 addition, inclusions containing K_2O , deformability, crystallinity, saw wire

Solar energy generation emits no CO_2 during power generation. This is in accord with the global effort to reduce the environmental burden. Therefore, the market for solar energy generation has been rapidly growing in

the last decades. Saw wire is generally used to cut silicon wafers in solar panels and its production is the key to the development of solar photovoltaic industry. In order to improve the yield and quality of silicon wafers, it is very essential to produce saw wire with high tensile-strength and superfine diameter [1]. This accordingly required rigid control of inclusions in high-carbon steel for saw wire. Non-deformable inclusions are very likely to act as crack initiation sites to cause wire breakage, which severely limited the production of high-carbon steel for saw wire. With only conventional inclusion control technique, such as Si-Mn deoxidation combined with low basicity top slag refining [2–4], inclusions may not be sufficiently stretched and still deteriorate the drawability of saw wire. Therefore, it is quite necessary to develop a new method of inclusion control to improve the deformability of inclusions in high-carbon steel for saw wire.

The relationship between composition and deformability of inclusions has been widely reported [5–7] and it is generally believed that inclusions with low melting temperature perform excellent deformability during hot rolling process [8–11]. In addition, according to the research conducted by Lu et al., K_2O can obviously reduce the melting temperature of mold flux with low fluoride [12]. This is consistent with the result calculated by FactSage that K_2O can remarkably lower the melting temperature of inclusions. To sum up, K_2O has the potential to improve the deformability of inclusions by lowering the melting temperature of inclusions. However, it is not easy to add K into inclusions due to the strong reducibility of metal K as well as low boiling temperature and decomposition temperature of compound containing K. So far, the method of adding K into inclusions has scarcely been reported, not to mention the relevant reaction mechanisms and deformability of inclusions containing K_2O .

In order to develop an effective approach to adding K into inclusions to obtain inclusions with low melting temperature and excellent deformability, the effects of Fe/ K_2CO_3 , K_2CO_3 addition amount and reaction time on inclusions were comprehensively studied in this research. The results show that Fe powder can suppress the volatilization of K_2CO_3 and thus facilitate K within K_2CO_3 to

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enter into steel and then into inclusions. Through the research, an effective method of K₂CO₃ addition by mixing K₂CO₃ with Fe powder was put forward and the melting temperature of inclusions was remarkably lowered. In addition, a presumable reaction mechanism between K₂CO₃/slag/steel/inclusion was deduced and the relation between deformability and crystallinity of inclusions was also briefly discussed.

Experimental

Sample preparation

A continuous casting billet of high-carbon steel for saw wire in a certain steel plant was sectioned into steel blocks and used as experimental raw material. The composition of the billet is shown in Table 1. Reagent grade CaO, SiO₂, MgO and Al₂O₃ powder was mixed evenly, oven-dried at 473 K for 10 h, then pressed into lumps and used as initial slag. The composition of the initial slag is shown in Table 2. Reagent grade K₂CO₃ was oven-dried at 473 K for 10 h, mixed with pure iron powder uniformly in predetermined proportions (shown in Tables 3 and 4), then pressed into lumps and wrapped with pure iron foil.

Table 1: Composition of initial steel/mass%.

C	Si	Mn	P	S	Al ₅
0.87	0.17	0.52	0.007	0.005	0.0005

Table 2: Composition of initial slag/mass%.

CaO	SiO ₂	MgO	Al ₂ O ₃
36	36	20	8

Table 3: Chemical compositions of slag after reaction.

Heat	Slag/mass%							Addition/g		Fe/K ₂ CO ₃
	CaO	SiO ₂	MgO	Al ₂ O ₃	Fe ₂ O ₃	MnO	K ₂ O	K ₂ CO ₃	Fe	
a	35.1	35.9	20.5	7.3	0.71	0.55	0	0	0	1
b	34.8	35.7	20.2	7.4	0.67	0.68	0.28	0.2	0.2	1
c	34.6	35.5	20.4	7.3	0.78	0.74	0.43	0.4	0.4	1
d	34.6	35.0	20.8	7.2	0.88	0.87	0.37	0.4	0.8	2
e	34.5	35.0	20.5	7.3	0.85	0.89	0.62	0.8	0.8	1
f	34.0	35.4	19.0	7.1	0.60	0.42	3.18	0.8	0	0

Table 4: Chemical compositions of steel after reaction.

Heat	Steel (mass%)					Addition (g)		Fe/K ₂ CO ₃
	C	Si	Mn	Al ₅	K	Fe	K ₂ CO ₃	
a	0.85	0.16	0.49	0.0006	–	0	0	1
b	0.81	0.15	0.48	0.0007	–	0.2	0.2	1
c	0.78	0.13	0.46	0.0006	–	0.4	0.4	1
d	0.78	0.14	0.51	0.0006	–	0.4	0.8	2
e	0.74	0.16	0.46	0.0007	0.0017	0.8	0.8	1
f	0.83	0.15	0.47	0.0009	–	0.8	0	0

Experimental apparatus

All the smelting experiments were carried out using a graphite tube resistance furnace. The schematic diagram is shown in Figure 1. In order to prevent the oxidization of steel, argon gas (99.9 % purity) blew from the bottom to the top of the graphite tube in the furnace throughout the experiments. The graphite tube serves as heating unit. The Al₂O₃ tube is used to avoid carbon pick-up in steel caused by the graphite tube. Prior to the experiments, an empty magnesia crucible was heated to

Figure 1: Schematic diagram of graphite tube resistance furnace.

1550 °C for temperature calibration. The temperature at point A was collected using a Pt-Rh thermocouple and compared with that at point B to eliminate the error caused by the limitation of temperature measurement position, since the temperature at point A is closer to practical temperature of molten steel while difficult to collect in the course of the experiment.

Experimental procedure

A magnesia crucible containing 100 g steel blocks and 20 g prepared slag was initially placed in a graphite tube resistance furnace at 1550 °C (Heats a through f). Once the slag and steel were completely melted, the prepared mixture of K_2CO_3 and Fe was inserted into the molten steel. After preserving heat for 25 min, the crucible was taken out and quenched in cold water after solidification of steel. Afterwards, the cooled ingot was placed in a muffle furnace at 1100 °C for 1 h, and then hot forged into wire rod (7 mm in diameter). Finally, the longitudinal section of the wire rod was mounted using resin, and then ground, mirror polished and gold-sprayed for the detection of inclusions.

In order to further explore the reaction mechanism, an additional experiment on the effect of reaction time between K_2CO_3 and steel was conducted. Firstly, 400 g steel blocks (without slag) were put in a magnesia crucible and melted at 1550 °C (Heat g). Secondly, the prepared mixture of 1.5 g K_2CO_3 and 1.5 g Fe powder was inserted into the molten steel. This moment was regarded as the starting point of the reaction between K_2CO_3 and steel (defined as 0 min). Steel samples were taken from the molten steel using a quartz tube coupled with rubber suction bulb at 0 min, 5 min, 20 min and 50 min respectively and then immediately quenched in water. After taking samples at 50 min, the remaining molten steel was cooled to room temperature in the furnace and a steel sample was cut from the cooled ingot. Finally, all the steel samples were mounted using resin, and then ground, mirror polished and gold-sprayed for the detection of inclusions.

Detection methods

The contents of conventional elements in steel including [Si], [Mn] and [Al] were determined by optical emission spectrometry, while [K] content in steel was determined by inductively coupled plasma mass spectrometry (ICP-MS) and [C] content in steel was determined by a

combustion method. The compositions of slag were analyzed by using an X-ray fluorescence spectrometer (XRF). In addition, a scanning electron microscope (SEM) coupled to an energy dispersive X-ray spectrometry (EDS) microanalysis was employed to detect the morphology and compositions of inclusions. In each steel sample, thirty inclusions were characterized randomly.

Results and discussion

Chemical compositions of slag and steel

The chemical compositions of slag after reaction are shown in Table 3. It can be seen that the slag in Heats b through e (with a mixture of K_2CO_3 and Fe powder added) contained considerably less K_2O compared with the slag in Heat f (with only K_2CO_3 added). The most probable cause is that Fe powder diluted K_2CO_3 and lowered the localized concentration of K_2CO_3 in molten steel at the beginning of K_2CO_3 addition [13], accordingly inhibiting the volatilization of K_2CO_3 and further the entrance of K_2CO_3 into slag. This can also be supported by the experimental phenomena that the splash of molten steel at the beginning of K_2CO_3 addition was weakened with the addition of Fe powder.

The chemical compositions of steel after reaction are shown in Table 4. Heats b through f (with K_2CO_3 added) had lower levels of [C] in steel than Heat a (with no K_2CO_3 added). Moreover, [C] content in steel decreased gradually with the increase of K_2CO_3 addition amount (Heats a, b, c and e) when Fe/ K_2CO_3 was fixed at 1. Therefore, it can be indicated that [C] in steel reacted with K_2CO_3 . As can be seen from Table 4, [K] in steel was detected but only in Heat e due to the low concentration of [K] in steel as well as the limitation of detection method. However, this is enough to prove that K_2CO_3 was reduced into [K] in steel. Based on the analysis above, it is not difficult to deduce the reaction $K_2CO_3 + 2[C] = 2[K] + 3CO(g)$ between K_2CO_3 /steel.

Chemical composition of inclusions

The effect of K_2CO_3 addition amount on the compositions of inclusions is shown in Figure 2. As K_2CO_3 addition amount increased (with Fe/ K_2CO_3 fixed at 1), K_2O content increased obviously against the fall of MnO content while the other compositions in inclusions changed little. This

Figure 2: Effect of K_2CO_3 addition amount on compositions of inclusions.

implies the occurrence of the reaction $2[K] + (MnO)_{inc} = [Mn] + (K_2O)_{inc}$.

It has been reported that Al_2O_3 - SiO_2 - CaO inclusions (with $CaO > 9.5\%$) in tire cord steel mainly originated from collisions and coalescences between entrapped slag particles and endogenous inclusions [14]. Hence, the number of Al_2O_3 - SiO_2 - CaO inclusions can represent the degree of slag entrainment. The effects of Fe/K_2CO_3 on the types and compositions of inclusions are shown in Figure 3. It is evident that there were far more Al_2O_3 - SiO_2 - CaO inclusions in Heat f (with no Fe added) than in Heats c and d (with Fe added). This proved indirectly that Fe powder inhibited the volatilization of K_2CO_3 , accordingly impairing slag entrainment. Due to the inhibition of Fe on the volatilization of K_2CO_3 , the reaction $K_2CO_3 + 2[C] = 2[K] + 3CO(g)$ was facilitated, which further accelerated the reaction $2[K] + (MnO)_{inc} = [Mn] + (K_2O)_{inc}$.

Figure 3: Effect of Fe/K_2CO_3 on the types and compositions of inclusions.

Therefore, Heats c and d (with Fe powder added) had a far higher level of K_2O in inclusions than Heat f (without Fe powder added).

In order to verify the reaction between K_2CO_3 /steel/inclusions, the average composition change of inclusions in Heat g (without slag) with reaction time after K_2CO_3 addition was investigated, as shown in Figure 4. No slag was added to prevent the interference from slag. At the initial stage, average K_2O content increased and MnO content declined, while the other compositions in inclusions changed little with the increase of reaction time. Therefore, the reactions between K_2CO_3 /steel/inclusions were confirmed to be $K_2CO_3 + 2[C] = 2[K] + 3CO(g)$ and $2[K] + (MnO)_{inc} = [Mn] + (K_2O)_{inc}$ when no slag was added. With the consumption of K_2CO_3 , the reactions approached equilibrium, thus the average compositions of inclusions approached stable gradually.

Figure 4: Average composition change of inclusions with reaction time in Heat g (without slag).

Reaction mechanism

It has been widely accepted that Reaction (1) will take place at slag/steel interface during the refining process of tire cord steel [15–17].

Since the composition of high-carbon steel for saw wire is similar to that of tire cord steel, it can be deduced Reaction (1) will also occur in high-carbon steel for saw wire. The reaction will definitely lead to the increase of $[Al]$ content in steel when Al_2O_3 content in slag is relatively high (8% in this study). The increased $[Al]$ is very

likely to reduce MnO in inclusions through Reaction (2) due to the strong reducibility of Al and strong oxidizability of MnO, leading to the increase of Al_2O_3 content in inclusions.

When the reaction time is the same, the degree of Reactions (1) and (2) will keep the same. Thus, the average Al_2O_3 content changed little with the increase of K_2CO_3 addition amount (see Figure 2) with the same reaction time. Because no slag was added in Heat g, Al_2O_3 content in inclusions remained a lower level (below 5%) due to the absence of Reactions (1) and (2), as shown in Figure 4.

The reaction between 100 g steel (0.87C-0.17Si-0.52Mn-0.0005Al-98.44Fe) mass% and various amount of K_2CO_3 at 1550 °C was calculated by Equilib module of FactSage 7.0, as shown in Figure 5. It can be seen the generated CO(g) and K(g) increased while [C] content in steel decreased with the increase of K_2CO_3 addition amount. Though the content of [K] in steel was not obtained due to the limitation of the FactSage databases, it can still be deduced that K_2CO_3 will be reduced by [C] to generate CO(g) and K(g). The generated K(g) will inevitably dissolve into steel, causing the increase of [K] in steel. Therefore, Reaction (3) is very likely to occur after K_2CO_3 addition. This can be supported by the experimental results that [C] content in steel decreased gradually with the increase of K_2CO_3 addition amount when Fe/ K_2CO_3 was fixed at 1 (Heats a, b, c and e) and that [K] was also detected in Heat e (see Table 4). In addition, no $CO_2(g)$ is generated after K_2CO_3 addition, as shown in Figure 5. This also rules out the possibility of the decomposition reaction $K_2CO_3(l) = K_2O(l) + CO_2(g)$.

Figure 5: Composition changes of [C], CO(g) and K(g) with K_2CO_3 addition calculated by FactSage.

The dissolved [K] in steel caused by the Reaction (3) will definitely reduce MnO in inclusions to [Mn] in steel through the Reaction (4) due to the strong reducibility of K and strong oxidizability of MnO. This can be proved by the fact that average K_2O content increased sharply against the notable fall of MnO content in inclusions with the increase of K_2CO_3 addition amount (Fe/ K_2CO_3 fixed at 1, see Figure 2).

Based on the analysis mentioned above, a reasonable reaction mechanism between K_2CO_3 /slag/steel/inclusion can be deduced, as shown in Figure 6. Al_2O_3 in slag was reduced by [Si] in steel through Reaction (1), leading to the increase of [Al] against the fall of [Si] in steel. The increased [Al] further reduced MnO in inclusions through Reaction (2), causing the rise of Al_2O_3 against the drop of MnO in inclusions; K_2CO_3 was reduced by [C] in steel through Reaction (3), leading to the increase of [K] against the decrease of [C] in steel. The increased [K] further reduced MnO in inclusions through Reaction (4), resulting in the rise of K_2O against the decline of MnO in inclusions.

Figure 6: Schematic diagram of the reaction mechanism between K_2CO_3 /slag/steel/inclusion.

As shown in Figure 6, when there is slag, Reactions (2) and (4) will take place simultaneously between inclusions and steel, causing the rise of K_2O and Al_2O_3 as well as the decline of MnO in inclusions at the same time. This can be supported by the fact that Al_2O_3 increased while MnO declined with the increase of K_2O content in different inclusions (shown in Figure 7).

Figure 7: Change of Al_2O_3 and MnO with the increase of K_2O in different inclusions (Heats b through e).

Melting temperature and deformability

All the phase diagrams in this article were calculated using Phase Diagram module of FactSage 7.0. By plotting the SiO_2 - Al_2O_3 -MnO phase diagram with different K_2O content, the relation between K_2O content and the proportion of low melting temperature (defined as melting temperature lower than $1400^\circ C$) area in SiO_2 - Al_2O_3 -MnO- K_2O phase diagram can be obtained, as shown in Figure 8. It can be seen that the proportion of low melting temperature area in SiO_2 - Al_2O_3 -MnO- K_2O phase diagram increased at first and then decreased with the increase of K_2O . Proper content (0–30%) of K_2O will promote the proportion of low

Figure 8: Relation between K_2O content and the proportion of low melting temperature area in SiO_2 - Al_2O_3 -MnO- K_2O phase diagram.

melting temperature area in SiO_2 - Al_2O_3 -MnO- K_2O phase diagram, namely lower the melting temperature of SiO_2 - Al_2O_3 -MnO inclusions.

The composition distributions of inclusions in phase diagrams are shown in Figure 9. The proportion of low melting point inclusions (PI) showed a notable rise from 16.7% to 100% with the increase of K_2O content in inclusions from 0% (Heat a) to 9% (Heat e). This agrees well with the conclusion mentioned above that proper content of K_2O could lower melting temperature of SiO_2 - Al_2O_3 -MnO inclusions.

The effect of K_2O content on the deformability and melting temperature of inclusions is shown in Figure 10. The proportions of low melting temperature inclusions and plastic inclusions (length/width > 3) increased at the same time with the increase of average K_2O content. This means that the proportion of low melting temperature inclusions was positively related to that of plastic inclusions. However, plastic inclusions had a far lower increasing amplitude in proportion than low melting temperature inclusions. This may be caused by the crystallization of inclusions containing K_2O , as explained in the following section ‘Crystallinity and deformability’.

Crystallinity and deformability

The backscattered electron images of typical inclusions in steel are shown in Figure 11, and chemical compositions of typical inclusions corresponding to Figure 11 are shown in Table 5. Inclusions in Heats a and f contained little or no K_2O and were mainly ellipsoidal (non-deformable) and amorphous (containing a single phase). Their chemical compositions were mostly distributed outside the low melting temperature area of phase diagram (shown in Figures 9(a) and (f)). This may be the cause of their poor deformability. Inclusions in Heats b through e can be roughly classified into two subcategories according to their compositions, named K_2O - Al_2O_3 - SiO_2 -MnO inclusions (with $K_2O < 15\%$, $MnO > 10\%$) and K_2O -MgO- Al_2O_3 - SiO_2 inclusions (with $K_2O > 15\%$, $MnO < 10\%$), as shown in Table 5. Both of the two types of inclusions were mostly distributed in the low melting temperature area of phase diagram (shown in Figures 9(b) through (e)) and thus should have had good deformability according to a popular belief that inclusions with low melting temperature have good deformability during hot rolling [8–11]. However, K_2O - Al_2O_3 - SiO_2 -MnO inclusions (Inclusions b, c2, d2 and e2) were very likely to crystallize (form dual

Figure 9: Composition distributions of inclusions in phase diagrams (PI – proportion of low melting point inclusions).

Figure 10: Effect of K_2O content on the deformability and melting temperature of inclusions.

phase) (shown in Figure 11), which deteriorated the deformability of inclusions according to the previous reports [18, 19]. Thus, $K_2O-Al_2O_3-SiO_2-MnO$ inclusions were nearly spherical (non-deformable), despite of their low melting temperature. $K_2O-MgO-Al_2O_3-SiO_2$ inclusions (Inclusions c1, d1 and e1) tended to remain amorphous (containing a single phase), and thus was stripe-like in shape (deformable), as shown in Figure 11.

According to the research of Beskow et al., the measured compositions of tiny particles were likely to be effected by their neighboring phase when analyzing with an energy dispersive X-ray spectrometry (EDS) [20]. That is

to say, the phases in $K_2O-Al_2O_3-SiO_2-MnO$ inclusions were hard to determine by EDS due to their extremely tiny size. Therefore, in order to verify the type of the precipitated phase, Equilib module of FactSage 7.0 was employed to calculate the phase translation of $K_2O-Al_2O_3-SiO_2-MnO$ inclusions during cooling process, as shown in Figure 12. The average composition of $K_2O-Al_2O_3-SiO_2-MnO$ inclusions in Heats b through e ($2.33MgO-9.46Al_2O_3-57.15SiO_2-6.94K_2O-0.86CaO-23.3MnO$) mass% was employed for calculation. It can be seen that $MnSiO_3$ is prior to precipitate from the matrix of inclusions during cooling process. Moreover, it should also be noted that MnO content in $MnSiO_3$ (54.2%) is far higher than average MnO content in inclusions (23.3%). This is consistent with the experimental result that the grey phase contained much more MnO than black phase in $K_2O-Al_2O_3-SiO_2-MnO$ inclusions (see Table 5). Therefore, the grey phase precipitated in the matrix (black phase) of $K_2O-Al_2O_3-SiO_2-MnO$ inclusions was deduced to be $MnSiO_3$ phase.

$K_2O-Al_2O_3-SiO_2-MnO$ inclusions in Heat g were also found to crystallize (form dual phase) after cooling in furnace, as shown in Figure 13. This implies that the crystallization of inclusions may occur during cooling of molten steel. Given that $K_2O-Al_2O_3-SiO_2-MnO$ inclusions are very likely to crystallize, which further deteriorates the deformability of inclusions, a new method should be developed in our future research to prevent the crystallization of $K_2O-Al_2O_3-SiO_2-MnO$ inclusions.

Figure 11: Backscattered electron images of typical inclusions in steel (cross-type dot – black phase, round-type dot – grey phase).

Table 5: Chemical compositions of typical inclusions corresponding to Figure 11/mass%.

Inclusion No.	Color of phase	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	MnO
a	black	4.3	8.7	51.0	0.0	0.0	35.9
b	grey	1.6	3.8	47.7	2.3	0.0	44.6
	black	0.0	9.4	59.6	5.8	0.0	25.2
c1	black	10.1	15.5	52.7	16.5	0.0	5.2
c2	grey	2.5	10.3	49.8	9.1	0.0	28.3
	black	0.0	10.1	53.5	13.9	0.0	22.4
d1	black	8.7	25.4	49.1	16.8	0	0
d2	grey	1.2	2.3	48.9	3.6	0.0	48.1
	black	0.0	6.8	50.9	10.0	0.0	29.2
e1	black	13.0	20.2	43.0	23.8	0.0	0
e2	grey	2.4	3.9	47.0	2.7	0.0	44.0
	black	0.0	8.9	55.5	3.7	0.0	32.0
f	black	22.2	27.4	40.2	0.0	10.2	0.0

Figure 12: Phase translation of K₂O-Al₂O₃-SiO₂-MnO inclusions during cooling process (Heats b through e).

Figure 13: Backscattered electron image of typical $K_2O-Al_2O_3-SiO_2-MnO$ inclusions in Heat g after cooling in furnace.

Conclusions

In the present work, a graphite tube resistance furnace was employed to investigate the effects of K_2CO_3 addition amount, Fe/K_2CO_3 and reaction time on inclusions. Through these studies, an effective method of K_2CO_3 addition by mixing K_2CO_3 with Fe powder was put forward and the melting temperature of inclusions was significantly lowered. The conclusions can be summarized as follows:

1. K_2CO_3 can be reduced into [K] by [C] in steel under the experimental temperature (1550 °C). The dissolved [K] will further enter into inclusions by reducing MnO in inclusions.
2. Fe powder mixed with K_2CO_3 can inhibit the volatilization of K_2CO_3 at the beginning of K_2CO_3 addition, accordingly facilitating the entrance of K within K_2CO_3 into steel, and further into inclusions.
3. As K_2CO_3 addition amount increases (with Fe/K_2CO_3 fixed at 1), K_2O increases obviously while MnO in inclusions decreases sharply.
4. When slag is added, for an individual inclusion, Al_2O_3 will increase gradually while MnO will fall sharply with the increase of K_2O in the inclusion.
5. The melting temperature of inclusions will be dramatically lowered after K_2CO_3 addition. However, the generated $K_2O-Al_2O_3-SiO_2-MnO$ inclusions are very likely to crystallize, which further deteriorates the deformability of inclusions; while the generated $K_2O-MgO-Al_2O_3-SiO_2$ inclusions tend to remain amorphous and thus have perfect deformability.

In order to fully improve the deformability of inclusions, a new method should be developed in our future research to prevent the crystallization of $K_2O-Al_2O_3-SiO_2-MnO$ inclusions.

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