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Effect of Slag Composition on Fatigue Life of High Speed Wheel Steel

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Abstract.

In order to improve fatigue life of wheel steel, secondary-refining process was done with Al-deoxidation and slag of high basicity, high Al_2O_3 content and low oxidizing property. By morphology observation and composition analysis with FESEM, it is found that during LF-VD process, by slag-steel-inclusion interaction, Al_2O_3 inclusions could transform to MgO-Al_2O_3 spinel, and later on to CaO-MgO-Al_2O_3 inclusions, which are inclined to be eliminated by floatation, lowering T[O] content to 0.0007%, enhancing fatigue life of wheel steel. By In-Situ observation with CONFOCAL laser scanning microscope, it is found that MnS precipitates during solidification process, which would core oxide inclusion to form MnS-oxide complex inclusion, contributing to fatigue life improvement of wheel steel. By INSTRON fatigue testing machine, it is found that by successful inclusion control, tested samples achieve ultra-high cycle of 10^8 above, realizing experimental purpose of improving fatigue life of wheel steel, boosting domestic production process of CRH high speed wheel steel.

1. Introduction

High speed wheel steel suffers from recycling and alternative stress in its service life, leading to fatigue destruction. Especially with the dramatic rise of speed of rail train, fatigue destruction plays a vital role more and more in wheel destruction. In order to meet the demand of the development of high speed rail train, high quality wheel steel is required to have excellent fatigue performance, which mostly depends on T[O] content of wheel steel. That is to say, ultra-low oxygen content is the major feature for high speed wheel steel.

In current steelmaking process, ultra-low oxygen content is obtained by Al-deoxidation. But for Al-killed wheel steel, the problem is that Al-deoxidation products are mainly Al_2O_3 inclusions of high melting point, un-deformable, with edges and corners, ruining fatigue performance of steel. During secondary refining process, Al_2O_3 could be transformed to other kinds of inclusions. That is the opportunity to avoid the disadvantage of Al-deoxidation, meanwhile realizing ultra-low oxygen, enhancing the fatigue performance of wheel steel.

Previous reports on inclusion control show that during secondary refining process of ultra-low oxygen steel, with the decrease of T[O], MgO-Al_2O_3 spinel would appear[1,2], which would be promoted by the increase of MgO, Al_2O_3, CaO/SiO_2, CaO/Al_2O_3 in slag[3-6]. However, SiO_2 in slag would suppress reduction of MgO, CaO in slag by [Al]s in steel, which is not beneficial for transformation of the product of Al-deoxidation. Previous reports on calcium treatment show that calcium treatment would transform inclusions of high melting point to those of lower melting point, protecting nozzles from clogging. However, if calcium treatment is not controlled well, CaO-Al_2O_3 of high melting point and CaS inclusions would appear, also leading to clogging of nozzles[7-10]. In addition, when Si-Ca cored wire is fed into molten steel, it is easy to boil intensively, leading to re-oxidation. Based on the above, a new process is done by experiment in steelmaking plant and academy laboratory, aiming to realizing ultra-low T[O], as well as avoiding the disadvantage of Al-deoxidation and calcium treatment.

Technique of inclusion control by top slag is used for Al-killed wheel steel, transforming Al_2O_3 inclusions to CaO-MgO-Al_2O_3 inclusions of lower melting point, slightly deformable in hot-working process of steel, achieving ultra-low content of total oxygen and making inclusions' composition enter 1500℃ liquid zone of CaO-MgO-Al_2O_3 ternary phase diagram, enhancing fatigue performance of wheel steel.

2. Experimental and Results

2.1. Experimental

Three heats are studied in plant. Production flow is LD → LF → VD → calcium treatment (NO.1, NO.2 heat) → soft bottom-blown by Ar bubbling → continuous casting. Calcium treatment is used in NO.1 and NO.2 heat in order to make sure of smooth casting, while NO.3 heat is exempted from calcium treatment. Steel and slag samples are fetched all through the whole process from beginning of LF to round billets.

Morphology and composition of inclusions are investigated by FESEM. Fatigue life of wheel steel is tested by INSTRON fatigue testing machine. Melting behaviour of MnS inclusion is observed by CONFOCAL laser scanning microscope.

2.2. Results

2.2.1. Typical complex inclusions after secondary refining and during solidification

With top slag of high basicity, high Al_2O_3 content and low oxidizing property, Al_2O_3 inclusions, the products of Al-deoxidation, could transform to MgO-Al_2O_3 spinel, and later on to CaO-MgO-Al_2O_3 inclusions.

Fig.1 shows morphology and element mapping of CaO-MgO-Al_2O_3 inclusion at the end of secondary refining. It is shown by Fig.1 that MgO-Al_2O_3 spinel is cored by CaO-Al_2O_3. This kind of cored structure could reduce the harm of MgO-Al_2O_3 spinel to fatigue performance because of low melting point and good deformability of CaO-Al_2O_3 outside the complex inclusion.

After secondary refining, in the process of continuous casting, MnS would precipitate around oxide inclusion in the molten steel during solidification process. Fig.2 shows melting behaviour of MnS-oxide complex inclusion during heating process, observed by confocal laser scanning microscope from room tempature to 1300℃.

It is shown by Fig.2 that in heating process, long strip MnS inclusions change gradually into string inclusions composed of near-spherical inclusions which grow up later. During insulation at 1300℃, MnS inclusion slowly melts into steel matrix and gets smaller and smaller.

Fig.3 shows several kinds of MnS-oxide complex inclusion.

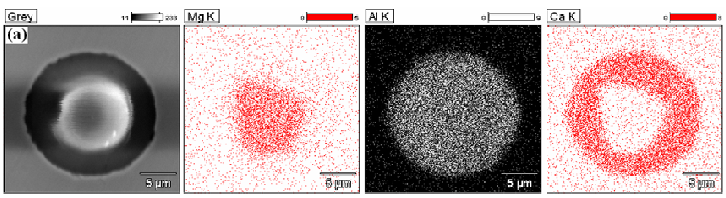


Fig.1 Morphology and element mapping of CaO-MgO-Al_2O_3 inclusion

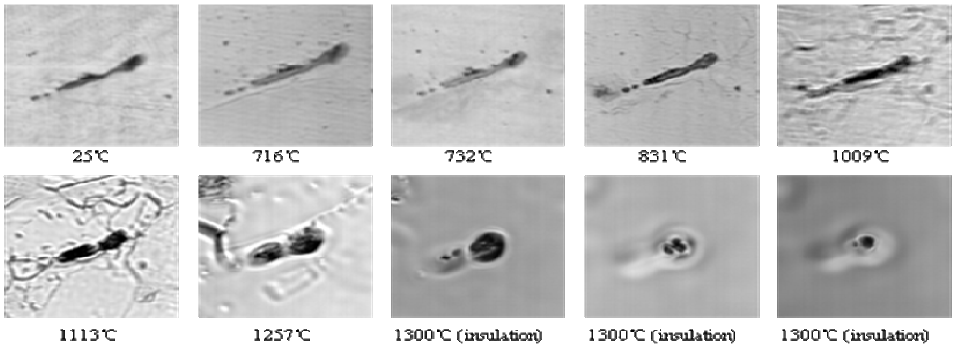
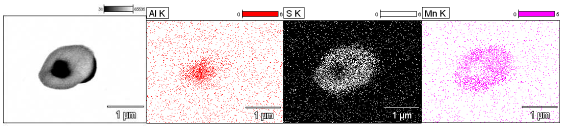
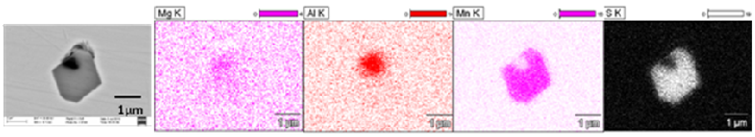


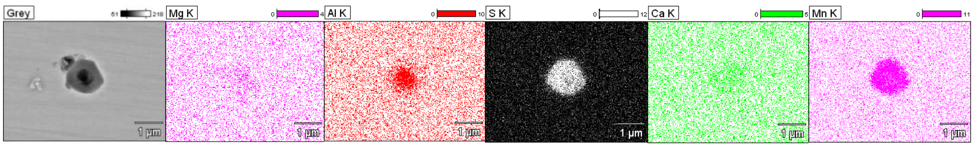
Fig.2 Melting behaviour of MnS-oxide complex inclusion during heating process



a) $MnS-Al_2O_3$ complex inclusion



b) $MgO-Al_2O_3-MnS$ complex inclusion



c) $CaO-MgO-Al_2O_3-MnS$ complex inclusion

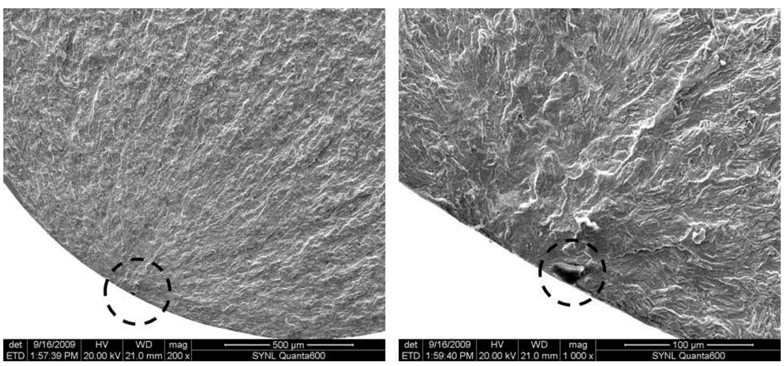
Fig.3 MnS-oxide complex inclusion formed in solidification process

2.2.2. Fatigue testing

In order to directly prove the outcome of inclusion control for the enhancement of fatigue performance, sample of round billets is tested by INSTRON fatigue testing machine in accordance to fatigue testing standard.

It is shown by the test that tested samples have ultra-high cycle of 10^8 above. That is to say, tested wheel steel has comparatively long fatigue life, realizing experimental purpose.

On the other hand, when stress is set beyond fatigue limit, fatigue fracture of wheel steel could be obtained. Fig.4 is the fatigue fracture of wheel steel by 200 and 1000 magnification times . It is shown that the origin of fatigue crack is the inclusion near sample surface.



a) Fatigue fracture in 200 magnification times   b) Fatigue fracture in 1000 magnification times

Fig.4 Fatigue fracture of wheel steel by a) 200 and b) 1000 magnification times

2.2.3. T[O] of wheel steel

By the analysis of chemical composition of round billet samples, T[O] content is 0.0007%. Fig.5 is comparison of T[O] in wheel steel made in China, Japan and this experiment. It is shown that T[O] of Japannese wheel steel is 0.0004%, which symbolize high cleanness and is excellent data for fatigue performance of wheel steel. By comparison, T[O]of tested sample is 0.0007%, higher than Japanese wheel steel and lower than Chinese wheel steel. That is to say, comparatively high cleanness of wheel steel is realized in this experiment.

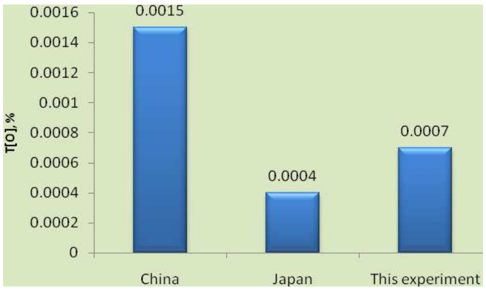


Fig.5 Comparison of T[O] in wheel steel made in China, Japan and this experiment

3. Discussion

3.1. Factors influencing inclusion transformation

During LF process, in order to boost transformation of Al_2O_3 inclusions to MgO-Al_2O_3 spinel and finally to CaO-MgO-Al_2O_3 of low melting point, it is vital to obtain proper content of [Mg], [Ca] which is produced by slag-steel interations shown as (1)(2). In reaction (1)(2), (MgO) and (CaO) in slag is reduced by [Al]s in steel. Products of reaction(1)(2) will react with Al_2O_3 inclusions to transform them to CaO-MgO-Al_2O_3 complex inclusions shown as (3)(4).

$$2[Al]s+3(MgO)=3[Mg]+(Al_2O_3) \quad (1)$$

$$2[Al]s+3(CaO)=3[Ca]+(Al_2O_3) \quad (2)$$

$$3[Mg]+n(Al_2O_3)_{inclusion}=(3MgO\cdot(n-1)\,Al_2O_3)_{inclusion}+2[Al] \quad (3)$$

$$x[Ca]+[yMgO\cdot zAl_2O_3]_{inclusion}=[xCaO\cdot(y-x)MgO\cdot zAl_2O_3]_{inclusion}+x[Mg] \quad (4)$$

In essence, reaction (1)(2) is slag-steel interaction, while reaction (3)(4) is steel-inclusion interaction. Based on this, inclusion transformation is accually a process of slag-steel-inclusion interaction. Factors influencing the whole process originates from slag composition. By thermo-dynamic calculation, it is known that slag of high basicity, high Al_2O_3, and low oxidizing property can boost transformation process of inclusions.

$(CaO+MgO)/Al_2O_3$ could be used to stand for the extent of reaction (3) and (4). Fig.6 shows the influence of slag compostion on $(CaO+MgO)/Al_2O_3$ in inclusion. It is shown that $(CaO+MgO)/Al_2O_3$ in inclusion increases as R, (Al_2O_3) increases, and as $(CaO)/(Al_2O_3)$, (SiO_2) decreases. When $CaO/Al_2O_3=1$, $(CaO+MgO)/Al_2O_3$ gets to the maximum.

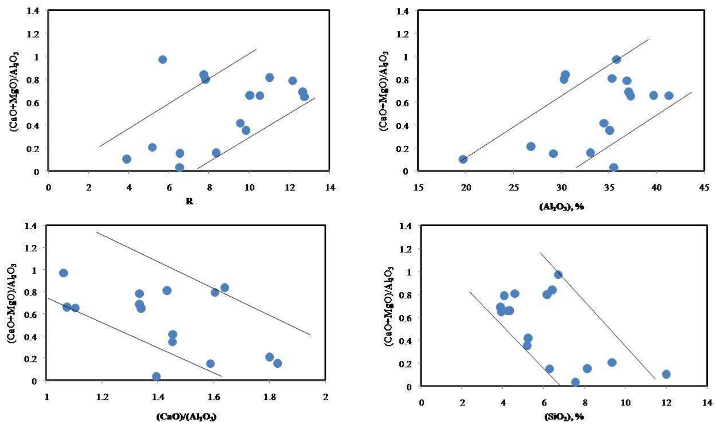


Fig.6 Influence of slag compostion on(CaO+MgO)/Al_2O_3 in inclusion

3.2. Precipitation of MnS

If reverse the heating process shown as Fig.2, precipitation behaviour of MnS in solidification process could be imagined. So it could be proven that precipitation of MnS occurs during solidification of molten steel, coring oxide inclusion, forming MnS-oxide complex inclusion of lower melting point and better deformability.

The precipitation of MnS could further reduce harm of oxide inclusion especially Al_2O_3 and MgO-Al_2O_3 spinel which do not completely transform to CaO-MgO-Al_2O_3 inclusion.Therefore, low and proper content of [S] is required to avoid harm of [S] as well as contribute to precipitation of MnS which is the second assurance of successful inclusion control in case of uncomplete transformation to CaO-MgO-Al_2O_3. The slag used for inclusion control has high capacity of desulfurization, leaving trace level [S] able to precipitate MnS.

On the other hand, oxide inclusions inside MnS-oxide complex inclusion could reduce anisotropy of MnS, which is benificial for fatigue performance of wheel steel.

It could be shown by Fig.3 that in round billets, the size of MnS-oxide complex inclusion is almostly 1~2μm and spherical or spherical alike. This kind of inclusion is benificial for improvement of fatigue life because of small size, profile of non-long strip and good deformability.

3.3. Fracture analysis

In common cases, fracture crack originates from inclusions located near the steel surface or inside of it besides surface defect. If facture crack originates from internal inclusion, there would be fish eye in the fracture[11-14]. In all tested sample fracture, fish eye is not observed. That is to say, tested sample fracture is not caused by internal inclusion, indicating that tested wheel steel has high cleanness by inclusion control.

It could be seen from Fig.4 that fatigue crack originates from the inclusion near sample surface, and expand to inside, leading to fatigue fracture. Therefore, inclusions near steel surface would do harm to fatigue performance.

4. Conclusions

Under the condition of Al deoxidation and slag of high basicity, high Al_2O_3 content and low oxidizing property, effect of slag composition on fatigue life of wheel steel is investigated. Conclusions are drawn as below.

1) Owing to Al-deoxidation and successful inclusion control in LF-VD process, T[O] decreases to 0.0007% in round billets, close to T[O] content in Japanese wheel steel, achieving high cleanness of steel;

2) With slag of high basicity, high Al_2O_3 content and low oxidizing property, Al_2O_3 inclusions transform to $MgO\text{-}Al_2O_3$, then to $CaO\text{-}MgO\text{-}Al_2O_3$ with low melting point, contributing to the enhancement of fatigue performance.
3) Precipitation of MnS takes place during solidification process, which would core oxide inclusion such as Al_2O_3, $MgO\text{-}Al_2O_3$ and $CaO\text{-}MgO\text{-}Al_2O_3$ to form MnS-oxide complex inclusion composed of MnS ouside of it and oxide inclusion inside of it. This kind of structure is helpful to improve fatigue performance of wheel steel because MnS inclusion has low melting point and good deformability, reducing the harm of Al_2O_3 and $MgO\text{-}Al_2O_3$ inclusions.
4) By fatigue testing, tested samples achieve ultra-high cycle of 10^8 above, realizing the experimental purpose of improving fatigue life of wheel steel. On the other hand, by fatigue fracture analysis, it could be seen that fatigue crack originates mainly from the inclusions near steel surface, showing that tested samples have high internal cleanness.

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