Effect of Rare Earth Ce on the Morphology and Distribution of Al_2O_3 Inclusions in High Strength IF Steel Containing Phosphorus during Continuous Casting and Rolling Process

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This paper analyzes the control of Al_2O_3 inclusions in high strength IF steel containing phosphorus. The inclusion statistics and two-dimensional morphology of samples with slab thickness of 1/8, 1/2 and 7/8, and the samples with hot rolling, cold rolling and continuous annealing processes were observed and compared by ASPEX SEM. In addition, the three-dimensional morphology of the inclusions extracted from the electrolysis of slab samples and the original morphology of inclusions from the rolling process samples were observed and compared. The results show that: When rare earth Ce is added to the steel, the combination of Ce with activity O and S in the steel has lower Gibbs free energy, and it is easy to generate CeAlO_3 , $\text{Ce}_2\text{O}_3\text{S}$, Ce_2O_3 , composite rare earth inclusions combined with other inclusions. The concentration and supersaturation of aluminum and oxygen are reduced, and the ability of single particle Al_2O_3 to aggregate into large-scale cluster inclusions is reduced. The average size of Al_2O_3 inclusions decreased from 5–7 μm to 2–5 μm in each thickness direction. The morphology of inclusions changed from long strip, sharp angle and cluster to spherical, spindle and round surface. Meanwhile, the number density of Al_2O_3 inclusions increase, but the area density decreases during continuous casting and rolling process. The size of Al_2O_3 inclusions in the steel without rare earth addition is mostly large-scale strip shape, and it is crushed during rolling, resulting quality defects on the exposed surface and causing the stamping crack problem. When rare earth is added to the steel, the inclusions in the steel change into small-sized circular inclusions with dispersion distribution. The modulus of elasticity is close to that of the steel matrix, which will not affect the continuity of the strip structure, and is beneficial to the relevant properties of the product.

KEY WORDS: high strength IF steel containing P; Al_2O_3 inclusion; rare earth Ce.

1. Introduction

Aluminum deoxidized IF steel has become the main material for automobile outer panel production in the world because of its good deep drawing performance and economy.^{1,2)} According to the application characteristics of automobile outer plate, IF steel is required to have high cleanliness to ensure that the steel plate has good surface quality and deep stamping performance.^{3,4)} In recent years, the majority of research institutes and iron and steel enterprises have been committed to improving the cleanliness of aluminum deoxidized IF steel by optimizing the traditional

smelting process.^{5,6)} For the conventional process of producing aluminum deoxidized IF steel in BOF-RH-CCM, in order to avoid destroying the balance of slag steel and causing the oxygen in high oxidation slag to return to the molten steel, after aluminum deoxidization at the end of RH refining, Al_2O_3 inclusions in steel cannot be removed by calcium treatment and argon stirring like LF refining. It is agreed by scholars that the typical Al_2O_3 inclusions with large size, triangle shape, chain shape and dendrite shape will be exposed on the strip surface in the subsequent rolling and rolling process, forming strip and pinhole surface defects. Meanwhile, the existence of this type of inclusions will also affect the continuity of the material structure, resulting in product stamping cracking and other problems.^{7,8)}

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Rare earth has become an important microalloying element in high value-added iron and steel materials because of its unique outer electronic structure, strong activity, variable valence state and large atomic size.^{9,10)} The steel studied involves die steel, silicon steel, low alloy steel, *etc.*, and reflects the special role of rare earth.^{11–13)} Some scholars have also made a research on increasing the cleanliness of IF steel by adding rare earth in the laboratory, and found that rare earth can improve inclusion morphology and reduce inclusion size.^{14,15)} However, the laboratory conditions and control process are quite different from the industrial production site. There is no relevant report on the industrial application of rare earth Ce to control the cleanliness of high strength IF steel containing phosphorus by aluminum deoxidation, and the yield of more than 50%. In this paper, the influence of rare earth Ce on the morphology and distribution of Al_2O_3 inclusions in the whole casting and rolling process of aluminum deoxidized IF steel is studied by industrial test, which provides technical guidance for the industrial application of new ways to improve the cleanliness control of IF steel products.

In this study, the influence of Ce on the morphology and distribution of Al_2O_3 inclusions in the whole process of casting and rolling of aluminum deoxidized IF steel was studied through industrial test, which provided technical guidance for industrial application of CE in improving the cleanliness control of IF steel products through new ways.

2. Research Method

The experimental materials were produced in the Rare Earth Steel Plates Plant of Baotou Iron and Steel Group Corporation, located in Inner Mongolia Autonomous Region. In the hot continuous rolling production line, the production contrast test of high strength IF steel containing phosphorus in the adjacent heats of the same sequence is carried out, and the production process and rare earth addition time are shown in **Fig. 1**. During RH vacuum treatment, the limit vacuum degree is ≤ 0.106 kPa, and the total vacuum treat-

ment time was 30 min. Due to the strong reactivity of rare earth, in order to avoid the oxygen oxidation brought in by other alloys during the alloying process, and to ensure the effective boron content in the steel, after aluminum deoxidization, the addition sequence of the alloy in the RH vacuum treatment process was ferromanganese, ferrotitanium, ferromanganese and ferroboration. 120 kg rare earth Ce Fe alloy (Ce content is 10%) was added at 3 min after alloying. After RH treatment, the sedation time is more than 15 min to ensure the inclusion to fully float. The recovery rate of rare earth Ce was 51%.

In the continuous casting process, strict protective casting measures against secondary oxidation are adopted to prevent nitrogen and oxygen increase. The test steel grade and composition of tundish are shown in **Table 1**, and the specific process of each rolling process is shown in **Fig. 2**. In the whole process of production, except adding rare earth, other processes are identical. The definition of the whole series of samples without adding rare earth is 1# and the whole series of samples with rare earth is 2#.

The specification of the produced slab is 230×1550 mm. The samples with and without rare earth are cut at the end of the second strand and the second slab of each heat respectively. In order to compare and count the types and sizes of inclusions in the whole casting and rolling process, and ensure the representativeness of the test data and the accuracy of the analysis, the locations such as 1/4 of the slab width, 1/8, 1/2 and 7/8 of the slab thickness are selected, as

Fig. 1. Ce–Fe alloy adding during steelmaking processes. (Online version in color.)

Table 1. Chemical composition of test steel (Wt%).

Heat number	C	Si	Mn	P	S	Al _s	Nb	Ti	B	Ce
2th	0.0020	0.15	0.68	0.078	0.005	0.029	0.027	0.022	0.0012

Fig. 2. Hot rolling and continuous annealing processes.

shown in **Fig. 3**. Select the size of slab sample as 10*10*10 mm. The sampling positions of hot-rolled plate, cold-rolled plate and continuous annealing plate correspond to the slab position, which are 1/4 of the width direction of the plate. The sample sizes are 4.3*10*10 mm, 1.15*10*10 mm and 0.7*10*10 mm. The samples were cut, inlaid, ground and polished, and then the inclusions were detected by scanning electron microscope (ASPEX-SEM, ASPEX eXplorer, ASPEX, Pembroke Park, FL, USA). In this study, the edge of metallographic specimen was avoided and the area of field of view was $\geq 50 \text{ mm}^2$. Because the gray scale of rare earth inclusions is different from that of matrix, and it is easy to bond, so rare earth inclusions are not in the statistical range. In addition, due to the better discrimination between rare earth inclusions and other inclusions under scanning electron microscope (ZEISS LEO EVO 50HV, Carl Zeiss, Oberkochen, Germany). Energy dispersive spectrometer (EDS, EDAX, Mahwah, NJ, USA) was used to observe the morphology and composition of the typical inclusions found in the above samples.

In order to compare and observe the morphology and evolution of rare earth inclusions more comprehensively, a series of inclusion extraction processes, such as electrolysis, acid etching, filtration, drying and so on, were used to obtain

different types of three-dimensional inclusions at 1/4 width and 1/4 thickness of the slab. The typical three-dimensional inclusions in the slab were observed and compared by SEM-EDS. 3% nitric acid alcohol was used to corrode the surface of the samples in each rolling process for 1 minute. The original morphology of the inclusions was extracted and the three-dimensional morphology and composition of the inclusions were observed by SEM-EDS.

Through the comparison of the above test results, the influence of the addition of rare earth Ce on the morphology and distribution of inclusions in IF steel during the whole casting and rolling process was analyzed.

3. Test Results and Discussion

3.1. Thermodynamic Calculation of the Formation of Rare Earth Inclusions

The composition of molten steel after adding rare earth is shown in **Table 2**. Because of the high oxidation property of Ce, it will react with oxygen, sulfur and other elements in the molten steel. The thermodynamic calculation of the rare earth compound formed by adding cerium is carried out. **Table 3** shows the chemical reactions and standard Gibbs free energy related to the addition of rare earth into the molten steel.¹⁶⁾

$$a_A = f_A \text{wt}[\%A] \dots\dots\dots (1)$$

Note: A = Ce, O, S, Al.

$$\lg f_i = \sum_{i=1}^n e_i^i [\%i] \dots\dots\dots (2)$$

According to the reaction formula and the activity coefficient of each element in the molten steel in **Table 4**, the Gibbs free energy of each rare earth inclusion at 1 873 K is calculated according to equation Table 3, Eqs. (1) and (2), as shown in **Fig. 4**.¹⁷⁾ It can be seen from the figure that when the content of the rare earth Ce is less than 0.01%, only CeAlO_3 , Ce_2O_3 , $\text{Ce}_2\text{O}_2\text{S}$, and CeO_2 are formed. When

Fig. 3. Schematic diagram of slab sampling location. (Online version in color.)

Table 2. Chemical composition of test steel after add Ce (Wt%).

Heat number	C	Si	Mn	P	S	Al _s	Nb	Ti	B	Ce
3th	0.0018	0.14	0.70	0.074	0.005	0.032	0.025	0.025	0.0010	0.0022

Table 3. Thermodynamic calculation of the formation of Al_2O_3 and rare earth inclusions.

Reaction equations in molten steel	$\Delta G^\theta, \text{J mol}^{-1}$	$\Delta G = \Delta G^\theta + RT \ln J, \text{J mol}^{-1}$			
		$J = \frac{1}{a_{\text{Ce}}^x a_{\text{O}}^y a_{\text{S}}^z a_{\text{Al}}^w}$			
		x	y	z	w
$2[\text{Al}] + 3[\text{O}] = \text{Al}_2\text{O}_3(\text{s})$	$-1\,208\,271 + 390.91T$	0	3	0	2
$2[\text{Ce}] + 3[\text{O}] = \text{Ce}_2\text{O}_3(\text{s})$	$-1\,431\,090 + 360.06T$	2	3	0	0
$[\text{Ce}] + 2[\text{O}] = \text{CeO}_2(\text{s})$	$-854\,274.7 + 249.11T$	1	2	0	0
$[\text{Ce}] + [\text{S}] = \text{CeS}(\text{s})$	$-422\,783 + 120.58T$	1	0	1	0
$3[\text{Ce}] + 4[\text{S}] = \text{Ce}_3\text{S}_4(\text{s})$	$-1\,493\,010 + 438.9T$	3	0	4	0
$2[\text{Ce}] + 2[\text{O}] + [\text{S}] = \text{Ce}_2\text{O}_2\text{S}(\text{s})$	$-1\,353\,592.4 + 331.6T$	2	2	1	0
$[\text{Ce}] + [\text{Al}] + 3[\text{O}] = \text{CeAlO}_3(\text{s})$	$-1\,366\,460 + 364T$	1	3	0	1

the content of the rare earth Ce is more than 0.01%, inclusions such as CeS, and Ce_3S_4 will be successively generated. Because of the content such as dynamics, local concentration, the stability of alloying and solidification process, there may be different contents of inclusions such as Al–O–Ce type and S–O–Ce type in the steel.

3.2. Effect of Ce on Morphology, Size and Quantity of Al_2O_3 Inclusions in Slab

The number, size and proportion of inclusions in different thickness direction positions of slab samples were analyzed by ASPEX-SEM. The main types of inclusions in slab samples 1# are Al_2O_3 , Al–O–Ti, Al–O–Ti–N, TiN, MnS, etc. The comparison of the statistical results of Al_2O_3 inclusions at different locations of the slab is shown in Fig. 5. It can be seen that the average size of Al_2O_3 inclusions at 1/8, 1/2 and 7/8 thickness direction position are 5.5 μm , 7.6 μm and 7.1 μm , which is significantly larger than that at the same position of slab samples 2#, which is 2.8 μm , 2.5 μm and 2.3 μm . However, the number of Al_2O_3 inclusions in the slab is 29, 12, 16, which is significantly higher than that of 8, 7, 10.

Figure 6 shows the distribution of the number density and area density of Al_2O_3 . It can be seen that the number density of Al_2O_3 in 2# slab 1/8, 1/2 and 7/8 of thickness direction position are 0.54/mm², 0.24/mm² and 0.32/mm² respectively, which are higher than 0.16/mm², 0.14/mm² and 0.20/mm² in the same position of slab 1#. The total area density of inclusions (2.1 $\mu\text{m}^2/\text{mm}^2$, 3.87 $\mu\text{m}^2/\text{mm}^2$ and 1.39 $\mu\text{m}^2/\text{mm}^2$) in same position of the slab 2# is lower than that of the slab 1# (8.2 $\mu\text{m}^2/\text{mm}^2$, 8.38 $\mu\text{m}^2/\text{mm}^2$ and 10.5 $\mu\text{m}^2/\text{mm}^2$). The results show that Al_2O_3 inclusion becomes a small size inclusion after adding rare earth, the quantity increases, the distribution is more dispersive, but the total area ratio decreases.

In order to further analyze the influence of rare earth on the morphology of Al_2O_3 inclusions, the samples were

Fig. 4. Precipitation of rare earth inclusions in steel. (Online version in color.)

Fig. 5. Size and quantity statistics of Al_2O_3 inclusions at 1# and 2# slab. (Online version in color.)

Table 4. Interaction coefficient of elements.^{18–20)}

Element	C	Si	Mn	P	S	Al	Ti	O	N	Ce
S	0.091	0.075	−0.026	0.035	−0.046	0.041	−0.27	−0.27	0.007	−9.1
Al	0.091	0.006	−	0.033	0.041	0.045	0.004	−6.6	−0.01	−0.52
O	−0.421	−0.066	−0.021	0.07	−0.133	−1.17	−1.8	−0.20	−0.12	−64
Ce	−0.077	−	0.13	1.77	−10.32	−2.58	−3.62	−106	−6.6	0.0069

Note: 1% (mass percent) dilute solution was chosen as the standard state for activity calculation of solutes.

Fig. 6. Statistics of number density and area density of Al_2O_3 in different positions of slab (a) number density (b) area density.

Fig. 7. Scanning results of typical Al_2O_3 inclusions in slab 1# (a) clustered (b) Long strip. (Online version in color.)

Fig. 8. Scanning results of typical rare earth inclusions in slab (a) Al-O-Ce type (b) Al-O-Ce-S-Mn type. (Online version in color.)

observed by SEM. It can be seen from Fig. 7 that the typical Al_2O_3 inclusions in the slab 1# are mostly chain like and long strip like, bridging each other, and the overall size can reach 20 μm .

The research show that,²¹⁾ after Ce treatment, irregular Al_2O_3 inclusions are wrapped by rare earth and then gradually modified into spheroidal CeAlO_3 , Ce_2O_3 , and $\text{Ce}_2\text{O}_2\text{S}$ inclusions and distributed into interstitial free slabs.

Figure 8(a) shows the typical type of rare earth inclusions in slab 2# mainly include CeAlO_3 . The morphology of the inclusions is spherical and elliptical, with a size of 3–5 μm . There is no bridging or aggregation. It can be seen from the figure that when rare earth is added to the steel, part of Ce adsorbs Al_2O_3 around and reacts to CeAlO_3 inclusions. Figure 8(b) shows the surface scanning results of Al-O-Ce-S-Mn type rare earth inclusions. It can be seen that when rare earth is added to the steel, the rare earth Ce will react with Al_2O_3 , and MnS inclusions will also be adsorbed, and finally form Al-O-Ce-S-Mn composite inclusions. It shows that Ce has a denaturation effect on Al_2O_3 and MnS inclusions.

In order to observe the effect of rare earth on inclusions

more comprehensively, the inclusions in electrolytic slab samples were observed by SEM-EDS. Figure 9 shows the overall three-dimensional morphology of inclusions in the slab sample. The inclusions include: Al_2O_3 and MnS in large-scale strip shape, Ti-C and Ti-N in square shape, and other composite inclusions. The maximum size is about 20 μm . The typical Al_2O_3 inclusions are mostly long strip, sharp angle, coral, cluster and large size.

Figure 10 shows the overall three-dimensional morphology of inclusions in slab samples 2#, including small-size particles of CeAlO_3 , $\text{Ce}_2\text{O}_2\text{S}$, Ce_2O_3 , composite rare earth inclusions combined with other inclusions, Al_2O_3 , MnS, etc. The inclusions are spherical and spindle in shape. The surface is round without sharp angle, and the proportion of long inclusions is less. Most inclusions are about 4–10 μm in size.

3.3. Effect of Ce on Transformation Mechanism and Distribution of Al_2O_3 Inclusions

The research show that,¹⁸⁾ after the nucleation of Al_2O_3 inclusions in molten steel, the Fe-O-Al melt is a multiphase

Fig. 9. Inclusion morphology after electrolysis of slab 1#. (Online version in color.)

Fig. 10. Inclusion morphology after electrolysis of slab 2#. (Online version in color.)

Fig. 11. Simulation diagram of inclusions evolution in steel (a–c) without Ce addition (d–f) with Ce addition. (Online version in color.)

complex solution system composed of dissolved atoms, alumina clusters, α - Al_2O_3 nuclei, nano-sized α - Al_2O_3 during the growth process and macro-sized α - Al_2O_3 inclusions.

Al_2O_3 inclusions grow in Ostwald mode. Under certain conditions, the higher the content of dissolved oxygen in the steel, the higher the coarsening rate of Al_2O_3 particles,

thus promoting the growth of inclusion size.

Figures 11(a)–11(c) is a simulation diagram of the nucleation and growth of Al_2O_3 inclusions. With the increase of supersaturated oxygen content, Al_2O_3 inclusions are formed and grow into large-scale coral and chain inclusions. After deoxidization of aluminum in the later stage of RH refining of IF steel, Al_2O_3 inclusions larger than $100\text{ }\mu\text{m}$ floated into the steel slag.²²⁾ The atomic oxygen and Al dissolve in the remaining steel are transmitted back to the molten steel by the O in the ladle slag, the poor casting protection in the continuous casting process leads to secondary oxidation, and the flow in the casting process which destroys the dynamic balance, resulting in the continuous combination of the atomic oxygen dissolve in steel, Al and Al_2O_3 smaller than the floating size in the molten steel to grow into large-size inclusions.²³⁾

Figures 11(d)–11(f) is a simulation diagram of inclusions evolution in steel after adding rare earth Ce. After adding rare earth Ce in the later stage of refining, due to the fact that the Gibbs free energy of activity O and S in Ce and steel is much lower than that of Al and O (Table 3), it is easy to form rare earth oxysulfide.^{17,24,25)} Al_2O_3 particles are transformed into rare earth oxides by oxygen extraction and combined with other composite inclusions. Some rare earths even combine with oxygen in Al_2O_3 directly to form Al–O–Ce and other compounds.

As a result, the concentration and supersaturation of aluminum and oxygen are reduced, and the thermodynamic driving force of *in-situ* formation process is greatly reduced or even disappeared. Then some aluminum and oxygen elements can not be further nucleated, and the *in-situ* growth process of inclusions stops. Therefore, the addition of rare earth reduces the ability of forming large-scale cluster inclusions between single Al_2O_3 particles under the condition of high supersaturation. As shown in Figs. 4 and 5, the Al_2O_3 inclusions in samples 2# are mainly dispersed in the form of $1\text{--}5\text{ }\mu\text{m}$ and exist in the steel, and their number density is larger than that of sample 1#, but they have smaller area density.

According to Zhang Wenhui's experiment, in the still solution, the time required for the droplets to contact each other and merge completely is about one thousandth of a second, which is easy to polymerize and coarsen.²⁶⁾ However, the polymerization of small solid particles can not be carried out directly. First of all, it depends on the liquid film or gas bridge on the surface, and the time of interaction and polymerization is much longer than that of the liquid drop.²⁷⁾ The compound with rare earth preferentially combined with O, S and Al_2O_3 has a higher melting point, and first becomes solid and small particles in the process of solidification and nucleation.²⁸⁾ Therefore, the ability of binding growth between rare earth compounds is much lower than that of dissolved oxygen, dissolved aluminum and Al_2O_3 in steel without rare earth addition.

Meantime, according to the research on the aggregation force between inclusions, it is found that, van der Waals force is the main index to measure whether a single Al_2O_3 inclusion particles can gather together.²⁹⁾ The reduction of the original size of inclusions will directly lead to the obvious reduction of their cohesion, and the inclusions are not easy to aggregate and grow, so as to keep the form of small

size inclusions dispersed in the steel.

In addition, because the inclusions are completely immersed in the liquid phase of metal, based on this, the classical theory of current research shows that the small inclusions mainly grow up by their own collision polymerization. The three collision mechanisms of inclusions are brown collision, Stokes collision and turbulence collision.^{30,31)} The above collision theories also show that the reduction of the concentration of reaction elements, nucleation number and inclusion size directly reduces the collision constant (also known as collision volume), the number of collisions between inclusions and the ability of inclusion growth. Based on the above analysis, the rare earth addition is not easy to bridge, aggregate and grow up, and the size is small, so it has better Brownian motion, leading to distribution dispersion. It can also be seen from Figs. 6 and 7, that Al_2O_3 without rare earth is easy to be polymerized into a long chain like large-size inclusion, while the inclusion after rare earth addition is not easy to polymerize, has a small size and is dispersed separately.

Literature³²⁾ shows that the shape and surface morphology of particles are directly related to the particle shape coefficient. The rough surface will increase the particle shape correction coefficient, and the larger the shape coefficient is, the greater the resistance is, the more difficult it is to float. According to the comparison of the test results in Figs. 8 and 9, the morphology of Al_2O_3 inclusions is chain like and coral like, and the rare earth inclusions are mostly spherical and spindle like, while the rare earth inclusions have smaller shape coefficient, which shows that the rare earth inclusions are easy to float up and disperse.

Therefore, for the aluminum deoxidized IF steel produced by BOF–RH–CCM conventional process, in order to avoid damaging the balance of steel slag and causing the oxygen in the high oxidation slag to return to the molten steel, the aluminum deoxidized at the end of RH refining can not be removed by the way of calcium treatment and argon agitation like LF refining. In this study, the addition of rare earth Ce at the end of RH refining can be combined with O and S in the steel first, and the residual can be removed. The large-scale Al_2O_3 inclusions in the retained steel are changed into rounded particles with smaller size and exist in the steel in the form of highly dispersed distribution, which provides an effective means to improve the cleanliness of products.

3.4. Comparison of the Size and Distribution of Al_2O_3 Inclusions in the Whole Casting to Rolling Process with Rare Earth Ce

In order to compare the effect of rare earth on inclusions in products, the test results of Al_2O_3 inclusions in samples of rolling processes by ASPEX SEM are shown in **Fig. 12**. The average size of Al_2O_3 in samples 1# of hot rolling plate, cold rolling plate and continuous rolling plate is $7.33\text{ }\mu\text{m}$, $4.98\text{ }\mu\text{m}$ and $7.34\text{ }\mu\text{m}$, respectively. The average size of Al_2O_3 in each process of samples 2# is $3.38\text{ }\mu\text{m}$, $2.07\text{ }\mu\text{m}$ and $3.13\text{ }\mu\text{m}$, respectively. It can be seen that the overall size of Al_2O_3 in the whole rolling process is reduced, but the quantity is significantly increased.

It can be seen from **Fig. 13** that the number density and area density of Al_2O_3 in sample 1# are $1.47/\text{mm}^2$ and $18.45\text{ }\mu\text{m}^2/\text{mm}^2$ respectively, and the number density and area

density of Al_2O_3 in sample 2# are $5.06/\text{mm}^2$ and $76.11 \mu\text{m}^2/\text{mm}^2$ respectively, indicating that Al_2O_3 becomes a small-size inclusion after adding rare earth, the quantity increases but the overall area proportion decreases, the distribution is more dispersive and the homogenization degree increases. Its evolution trend is the same as that of slab, which is beneficial to the surface quality and stamping performance of finished steel plate.

Figure 14 is a comparative analysis of the two-dimen-

Fig. 12. Statistics of Al_2O_3 inclusions in each rolling process. (Online version in color.)

sional morphology of each rolling process. It can be seen from the figure that the typical Al_2O_3 inclusions in the hot rolling, cold rolling and continuous annealing plate of sample 1# have cluster shape with sharp angle, and the size can reach about $10 \mu\text{m}$. After rolling deformation and annealing process, the large-size Al_2O_3 inclusions have the characteristics of inheritance, and the shape is rolled longer, but there is no fragmentation dispersion. The morphology of Al_2O_3 inclusions in the sample 2# is round without sharp angle, the size is obviously reduced, and it is distributed independently.

Figure 15 is a comparative analysis of the three-dimensional morphology of each rolling process. Al_2O_3 inclusions 1# in each rolling process of the sample are in sharp angle shape, with the size of about $10 \mu\text{m}$, and become chain like distribution after rolling. This type of large Al_2O_3 inclusions is easy to be exposed on the surface of the strip steel, resulting in surface defects, and also easy to scratch the matrix, resulting in crack sources, leading to stamping cracking. The inclusions 2# are Ce aluminates and Ce oxysulfides, most of them are about $2\text{--}5 \mu\text{m}$ in size and dispersed, which can further reduce the stress concentration around inclusions. During the stamping process, the inclusion with round shape

Fig. 13. Statistics of number density and area density of Al_2O_3 in each rolling process (a) number density (b) area density.

Fig. 14. Comparison of two-dimensional morphology of typical inclusions in each rolling process 1#: (a) hot rolling (b) cold rolling (c) continuous annealing, 2#: (d) hot rolling (e) cold rolling (f) continuous annealing. (Online version in color.)

Fig. 15. Comparison of three-dimensional morphology of typical inclusions in each rolling process 1#: (a) hot rolling (b) cold rolling (c) continuous annealing, 2#: (d) hot rolling (e) cold rolling (f) continuous annealing. (Online version in color.)

Fig. 16. Schematic diagram of formation process of linear defects (a) 1# Al_2O_3 inclusions (b) 2# rare earth inclusions. (Online version in color.)

and smaller size has elastic modulus and crack resistance, which can reduce the influence of inclusion on steel structure continuity.³³⁾

Figure 16 is a schematic diagram of the formation process of linear defects in the rolling process of steel strip. The large-scale Al_2O_3 inclusions in the shallow surface layer are hard and brittle. During the rolling process, they are crushed and elongated, deformed and cracked, and exposed. They are distributed on the surface of steel strip in a granular manner, forming the “Sliver defects” on the surface of inclusions. Most of these defects are distributed in a linear manner parallel to the rolling direction.^{34,35)} However, the addition of rare earth plays an obvious role in the modification of Al_2O_3 inclusions. The elastic modulus of the small-sized circular inclusions is close to that of the steel matrix, and the distribution is dispersive. During the hot working process, the damage caused by the shape of the inclusions is reduced,

the stress on the inclusions is even, the anisotropy of the material is reduced, the structure continuity of the steel is improved, and the weldability, fatigue performance and plastic toughness of the steel strip are further improved.³⁶⁾

Based on the above experimental results, it can be concluded that the addition of rare earth Ce in steel can produce fine circular or elliptical rare earth oxides, rare earth aluminates and rare earth oxysulfides, change the morphology of inclusions, reduce the size and dispersion distribution of inclusions. To avoid Al_2O_3 bridging into long chain inclusions, so as to reduce the surface defects and stamping cracks caused by the large inclusions. It provides a new idea for IF steel cleanliness control.

4. Conclusion

The experiment of adding rare earth to high strength IF

steel containing phosphorus was carried out to study the control technology of rare earth to automobile steel cleaning. The main findings can be summarized as follows:

(1) When rare earth Ce is added to the steel, the combination of Ce with activity O and S in the steel has lower Gibbs free energy, and it is easy to generate CeAlO_3 , $\text{Ce}_2\text{O}_3\text{S}$, Ce_2O_3 , composite rare earth inclusions combined with other inclusions. The concentration and supersaturation of aluminum and oxygen are reduced, and the ability of single particle Al_2O_3 to aggregate into large-scale cluster inclusions is reduced.

(2) When rare earth Ce is added to the steel, the average size of Al_2O_3 inclusions decreases from 5–7 μm to 2–5 μm in each thickness direction of the slab, and the morphology of inclusions changes from long strip, sharp angle and cluster shape to spherical and spindle shape with round surface. At the same time, the quantity and density of Al_2O_3 inclusions increase, but the area density decreases.

(3) The size of Al_2O_3 inclusions in the steel without rare earth Ce addition is mostly large-scale strip shape, and it is crushed during rolling, resulting in quality defects on the exposed surface. When rare earth Ce is added to the steel, the inclusions in the steel change into small-sized circular inclusions with dispersion distribution. The modulus of elasticity is close to that of the steel matrix, which will not affect the continuity of the strip structure, and is beneficial to the relevant properties of the product.

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