Research on Composition Design of Titanium Microalloyed High-Strength Weathering Steel

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Abstract: Based on the EAF-LF-CSP process and the composition of SPA-H (container board) of JIS G3125, this article analyzes and compares the chemical composition and performance of weathering steel related standards and the proposed high-strength weathering steel. By studying the range of Ti addition, designing the chemical composition of high-strength weathering steel, and developing high-strength steel with a yield strength of 450~700MPa. The analysis and calculation results show that the optimal Ti content range of weathering steels of various strength grades with yield strength of 450MPa~700MPa is 0.05~0.08%, 0.08~0.12%, and 0.12~0.14% respectively, which meets the strength requirements of weathering steels and can be applied in production practice.

1. Introduction
With the development trend of low dead weight and large scale in the field of large steel structures such as buildings and Bridges, new requirements are put forward for weathering steels, which should have higher strength as well as corrosion resistance. The use of high strength weathering steel can reduce the overall quality of the structure, reduce the construction cost and improve the reliability of the structure. Microalloyed elements in steel play the roles of solid solution, partial polymerization and precipitation, especially the interaction of microalloyed elements with carbon and nitrogen, resulting in a series of effects such as grain refinement, precipitation strengthening, recrystallization control and inclusion property. The effects of these factors on steel strengthening and toughening are widely used in steel products. The application of titanium is mainly micro-titaniuum treatment (≤0.02%). Compared with Nb, V and Ti, the prices of niobium and vanadium iron are more than 10 times more expensive than Those of Ti iron in the market, and there is a trend of rising prices. Secondly, China's reserves of titanium oxide are 630 million tons, accounting for nearly 45.6% of the world's total reserves, which is very rich in resources.

2. Overview of composition design of high strength weathering steel

2.1 Basic principles of composition design
A complete set of stable production technology of weathering steel has been formed by adopting
electric furnace +CSP process and making full use of residual alloy elements in scrap steel. The high-strength weathering steel to be developed is equivalent to ordinary container plates in terms of weather resistance. Therefore, in order to reduce costs and make full use of the alloy elements in the scrap steel to ensure high weather resistance, the Cu-P-Cr-Ni series weathering steel production technology is adopted, which basically guarantees the high weathering performance of the high-strength weathering steel to be developed. At the same time, the developed high-strength weathering steel is easier to industrialize and improve the competitiveness of new products learn from the operating experience of producing container plates.

Grain refinement and microalloying are two ways to improve the strength of steel products. In terms of production technology, we give full play to the characteristics of thin slab continuous casting and rolling process products with fine grains and high strength. At present, the yield strength of ordinary container plates has reached more than 400MPa, but the yield strength must be 450MPa~700 MPa. There is still a big gap in the technical route of grain refinement alone, so microalloying technology must be adopted.

2.2 Comparison of chemical composition and properties of weathering steels and weathering steels under development

Japanese standard JIS G3125 is the most widely used standard for container plates at present. The chemical composition and performance requirements of container steel of medium brand SPA-H of Japanese standard JIS G3125-1987 are shown in Table 1 and Table 2 respectively. The composition control of Container plates of Zhujiang iron and steel is shown in Table 3, and the statistics of mechanical properties of container plates of different thickness of Zhujiang iron and steel are shown in Table 4. The performance requirements of high strength weathering steels to be developed are shown in Table 5.

| Table 1 Chemical composition of SPA-H container steel in JIS G3125-1987 (%) |
|------------------|---------|---------|--------|--------|--------|--------|--------|--------|
| C    | Si   | Mn   | P    | S     | Cu    | Ni    | Cr    |
| ≤0.12 | 0.25–0.75 | 0.20–0.5 | 0.07–0.15 | ≤0.040 | 0.25–0.60 | ≤0.65 | 0.30–1.25 |

| Table 2 JIS G3125 standard SPA-H container steel performance |
|------------------|---------|---------|--------|--------|--------|--------|
| Yield strength(MPa) | tensile strength(MPa) | Elongation(%) | 180° cold bending test |
| ≥345 | ≥480 | ≥22 | ≤6mm, d=a | >6mm, d=1.5a |

| Table 3 Mechanical properties of ordinary container plates with different thicknesses produced by EAF-CSP process (wt%) |
|------------------|---------|---------|--------|--------|--------|--------|--------|--------|
| SPA-H | C    | Si   | Mn   | P    | Al(t) | Ca    | Cu    | Ni    | Cr    |
| Ingredient design | ≤0.06 | 0.35~ | 0.40~ | 0.07~ | <0.010 | 0.025~ | 0.0025~ | 0.25~ | 0.18~ | 0.40~ |
| 0.42 | 0.50 | 0.09 |

| Table 4 Mechanical properties of ordinary container plates with different thicknesses produced by EAF-CSP process |
|------------------|---------|---------|--------|--------|--------|--------|
| Thinness (mm) | Yield Strength (MPa) | tensile strength (MPa) | Elongation(%) | HRB | HV | Cold bending |
| 1.6 | 450 | 530 | 26.1 | 81 | 153 | qualified |
| 2 | 437 | 520 | 27.1 | 82 | 155 | qualified |
| 3 | 434 | 515 | 27.5 | 82 | 155 | qualified |
| 4 | 425 | 508 | 27.7 | 82 | 156 | qualified |
| 6 | 401 | 506 | 37.3 | 90 | 147 | qualified |
Table 5 Mechanical performance requirements of high-strength weathering steel of various strength level

| type     | Yield Strength | tensile strength | Elongation (%) | Cold bending 180° |
|----------|----------------|------------------|----------------|-------------------|
| ZJ500W   | ≥500MPa        | ≥580MPa          | ≥18 (h<6mm)    | d=1.0a qualified  |
| ZJ600W   | ≥600MPa        | ≥660MPa          | ≥14 (h<6mm)    | d=2.0a qualified  |
| ZJ700W   | ≥700MPa        | ≥750MPa          | ≥10 (h<4mm)    | d=2.5a qualified  |

Above tables show that the chemical composition control and mechanical properties of ordinary container board meet the requirements of container board. The strength is higher, and the properties of different thicknesses have relatively large deviations. The yield strength is 401~450 MPa, while the tensile strength is 506~530 MPa, and the elongation is 26.1~37.3%. The strength of the high-strength weathering steel to be developed is quite different from that of ordinary container plates which have 50 to 250 MPa yield strength ranges difference from the former.

3. Composition design of high strength weathering steel Ti

3.1 Design basis for Ti composition of high-strength weathering steel

The yield strength of low carbon ferrite - pearlite steel can be expressed by an extended Hall-Petch [4] relationship:

$$\sigma = \sigma_0 + \Delta\sigma_s + \Delta\sigma_p + \Delta\sigma_d + kd^{-1/2}$$  \hspace{1cm} (1)

Where, \(\sigma_0\) is the lattice friction of pure iron, taking 48MPa; \(\Delta\sigma_s\) is the solid solution strengthening increment, \(\Delta\sigma_p\) is the precipitation strengthening increment, \(\Delta\sigma_d\) is the dislocation strengthening increment, \(kd\)-1/2 is the fine crystal strengthening increment. For low carbon steel, \(K\) is 17.4MPa·mm1/2, \(d\) is the ferrite grain size (mm). Because the test steel is coiled at high temperature and the dislocation density is low, the term \(d\) is ignored in the following calculations.

The grains of steel are refined after micro-Ti treatment. According to statistics, the ferrite grain size of ordinary container plates is 10 microns. Assuming that the steel is refined to 7 microns after micro-Ti treatment, the Hall-Petch formula shows that the yield strength increases by 17.4·(0.007-½-0.01-½) =20.5MPa. As the Ti content increases, precipitation strengthening occur at the same time, resulting in an increase in the strength of the steel sheet.

According to Orowan mechanism, the precipitation strengthening increment of the second phase particles can be expressed by the following formula [5]:

$$\Delta\sigma_p = 8.995 \times 10^3 f^{1/2} \frac{l}{d} \ln(2.417d)$$  \hspace{1cm} (2)

Where, \(f\) is the second phase volume fraction, and \(d\) is the diameter (nm) of the second phase particles.

Assuming that the total Ti content in the steel is Ti, the Ti that can produce precipitation strengthening is effective Ti, called effective Ti, the N in the steel is 70ppm, and S is 50ppm, according to the formula (1).

Effective Ti=Ti-3.4×N-3×S=Ti-3.4×0.007-3×0.005=Ti-0.0388. Assuming that all effective Ti exists in the form of TiC, then according to the weight percentage of effective Ti, the weight percentage of TiC can be obtained.

$$\text{TiC\%} = [(Ti - 0.03889) \cdot \frac{A_{\text{TiC}}}{A_{\text{T}}}] \% = [(Ti - 0.03889) \cdot \frac{59.9}{47.9}] \%$$  \hspace{1cm} (3)

Where, \(A\) is the atomic weight or molecular weight. According to the density of TiC and Fe (4.944 g/cm3 and 7.87 g/cm3 respectively), the weight percentage can be converted into volume fraction.
\[ f = \left[ (Ti - 0.03889) \frac{59.9}{47.9} \right] \% \times \frac{\rho_{Fe}}{\rho_{TiC}} \]  

(4)

Assuming that the diameters of precipitated TiC particles are 5nm, 10nm and 15nm, substituting formula (5) and particle diameter \( d \) into formula (3), the relationship between the precipitation strengthening increment produced by particles of different sizes and the Ti content can be obtained, as shown in Figure 1.

The yield strength of ordinary container plate is 401~450MPa. Therefore, if high-strength weathering steel exceeding 450~700MPa is to be produced, at least 50~250MPa should be added. After deducting 20.5MPa produced by fine grain strengthening, the precipitation strengthening increment should be 30 ~230MPa. Generally, the diameter of TiC precipitated by deformation induced or precipitated from ferrite is 5-10nm[5], as can be seen from Figure 1, the Ti content in steel should be 0.04~0.14%.

![Figure 1 The relationship between the precipitation strengthening increment produced by particles of different sizes and the Ti content](image)

3.2 Preliminary design of composition of high strength weathering steel

In the EAF-CSP process, Ti microalloying technology is used to produce high-strength weathering steel. The composition design is to avoid the peritectic zone with carbon content \([C:0.08~0.16\%]\), and the second is to strictly control \([O], [S], [N]\) content, the third is to select the appropriate Ti content.

The fundamental measure to avoid the peritectic zone of carbon content is to control \(C \leq 0.06\%\), which can ensure the production of anterograde without leakage, reduce the probability of longitudinal cracks, and at the same time ensure the surface quality of the cast slab and the mechanical properties of the product. For the thin slab continuous casting and rolling process, it can ensure low oxygen content, easy to control and ensure the purity of molten steel so that the target \(S \leq 0.005\%, N \leq 0.007\%\). The key is how to choose the appropriate Ti content.

Based on the above analysis results, combined with the specific conditions of ordinary container plates produced by Zhuijiang Steel's thin slab continuous casting and rolling production line and users' needs for different strength weathering steels, it is determined that the Ti content of Ti microalloyed high strength weathering steel ranges from 0.04% to 0.14%. Considering the effects of precipitation strengthening and fine-grain strengthening, the Ti content of Ti microalloyed high-strength weathering steel is selected according to different strengths in the ranges of 0.05~0.08%, 0.08~0.12%, 0.12~0.14%, etc, in order to investigate different Ti The influence of content on the strength of high-strength weathering steel. The specific component design is shown in Table 6.

| Grade  | C   | Si  | Mn  | P   | S   | Cu  | Ni  | Cr  | Ti  | Al(s) | Al(t) |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|-------|
| ZJ500W | 0.06| 0.35| 0.40| 0.07| 0.25| 0.18| 0.40| 0.03| 0.02| 0.020| 0.025 |

Table 6 Composition design of trial steel (wt%)
4. Conclusion

Based on the characteristics of the structure and performance of the thin slab continuous casting and rolling process, the Cu-P-Cr-Ni series of weathering steel production technology and Ti microalloying technology are adopted. Based on the composition of SPA-H (container board) of JIS G3125, The optimal Ti content range of high-strength weathering steel with yield strength greater than 450MPa~700 MPa is designed as 0.05~0.08%, 0.08~0.12%, and 0.12~0.14% respectively, which meet the strength requirements of high-strength weathering steel and can be used in production practice.

Acknowledgements

This work was supported by the Science and Technology Program of Guangzhou City (Grant Nos. 201902010018, 201807010091 and 2017010160670) and the Science and Technology Program of Guangdong Province (Grant No. 2015B090923006).

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