

COMPOSITE ANTISEISMIC FIREPROOF BUILDING STEEL AND PREPARATION METHOD THEREOF

The present invention relates to a composite antiseismic fireproof building steel and a
5 preparation method thereof.

High-rise, large-span, high safety, conservation and environmental protection is the
development trend of modern large-scale buildings. The steel structure is light in weight,
fast in construction, large in space, comfortable and beautiful, good in earthquake
10 resistance, and recyclable so that it is more and more applied to high-rise buildings and
large public buildings. However, the fire resistance of ordinary building steel is very poor.
As the temperature rises, its yield strength decreases rapidly, especially when the
temperature is above 350°C, and it does not have the load-bearing capacity. Thus, the
steel structure must be sprayed with a thick refractory coating for protection. Spraying
15 the refractory coating doubles the cost of the steel structure buildings and prolongs the
construction period. The splashing of the spraying operation also causes environmental
pollution. Therefore, reducing the use or no use of refractory coatings becomes a driving
force to develop fireproof steel.

20 Mo is an effective alloying element for improving high-temperature strength. Therefore,
since the 1980s, Japan has taken the lead in developing and launching Mo-based
commercial fireproof steel plates. The high-temperature yield strength of fireproof steel
at 600°C shall not be less than 2/3 of the standard yield strength at room temperature.
The component system is mainly based on Mo-Nb series and Mo-Nb-Cr series. The
25 strong high temperature solid solution strengthening effect of Mo is mainly used to

ensure high temperature strength below 600°C. Usually, 0.5wt.% Mo is added and about 0.01-0.06wt.% Nb is used for microalloying.

In South Korea and China, Mo or Mo+Nb are also added to most fireproof steel. In order to reduce alloy cost, the content of Mo has been reduced, but it is still about 0.3wt.%. For example, in the application patents “Fire-resistant Steel and Preparation Method Thereof” (application number: 200810179362.6), “High-Performance Building Structure Refractory Steel Plates and Manufacturing Method Thereof” (application number: 200910011963.0), “Low-Cost High-Strength High-Toughness Shock-Proof Refractory Steel and Preparation Technique Thereof” (application number: 201110080774.6), etc., the content of Mo is 0.2-0.4wt.%, wherein in the patent “Fire-resistant Steel and Preparation Method Thereof”, 0.05-0.12wt.% V is added. As for this patent, the final cooling temperature is controlled to 550-650°C and heat preservation is ensured for 1 to 2 hours so as to control the components of the fireproof steel, and at the same time, it can also promote the precipitation of V during the slow cooling or heat preservation process so as to enhance the performance of the fireproof steel at room temperature. The alloy cost for fireproof steel involved in these patents is high, and it only focuses on the performances at room temperature or high temperature, without consideration into the high heat input welding resistance performance, and it does not have the composite performance characteristics of high strength, high toughness, earthquake resistance, fire resistance or easy welding, etc.

The technical problem to be solved by the present invention is to provide an economical antiseismic fireproof building that can reduce the cost of alloy use and has high strength,

high toughness, excellent weldability and intelligent fire resistance in view of the disadvantages of the above prior art and a preparation method thereof.

The technical solution of the present invention to solve the above technical problem is as follows: a composite antiseismic fireproof building steel, wherein it comprises the following chemical components by weight percentage: C: 0.08-0.16%, Si: 0.15-0.55%, Mn: 0.50 -1.80%, Mo: 0.10-0.50%, Nb: 0.02-0.15%, V: 0.00-0.12% and Ti: 0.01-0.020%, and the rest are Fe and unavoidable impurities.

C: The antiseismic fireproof steel in the present invention is designed with low carbon content, with a carbon content ranging from 0.08-0.16%, which effectively solves the technical problem that the high carbon content has adverse impact on the impact toughness of the steel, especially the impact energy on the upper platform and results in obvious damage to the welding performance;

Si: The content of Si in the steel of the present invention ranges from 0.15-0.55%, and Si is utilized to increase the strength, and it effectively prevents excessive Si from deteriorating the toughness and welding performance of the steel;

Mn: The content of Mn in the steel of the present invention ranges from 0.50-1.80%, which not only expands the solid solubility product of microalloy carbonitrides in the austenite but also avoids excessive microalloy carbonitrides from deformation and induced precipitation during rolling, and in addition it also prevents the increase in segregation tendency in the casting blank to result in disadvantages to welding performance;

Mo: The content of Mo in the present invention is precisely controlled within the range of 0.10-0.50%. In addition to significantly improving the hardenability of steel and inhibiting the segregation of impurity elements such as P and S at the grain boundary to reduce temper brittleness, it mainly plays a role of high temperature solid solution strengthening and precipitation strengthening in the fireproof steel. When the content of Mo is less than 0.10%, the above effects are not obvious, and the fire resistance is poor. When it exceeds 0.50wt.%, the cost is high;

Nb: The content of Nb in the present invention should be controlled to 0.02-0.15%. During rolling, the Nb solid-dissolved in the austenite and the niobium carbonitride particles precipitated due to deformation induction significantly increase the austenite non-recrystallization temperature and a pancake-like austenite is obtained, which helps to refine the ferrite and bainite structure. Nb solid-dissolved in austenite can also improve the hardenability. Nb dissolved in ferrite and bainite also plays a significant role in improving the high temperature strength;

V: The content of V in the present invention does not exceed 0.12%. Because V has a low total solid solution temperature, almost all of it is dissolved during soaking. V solid-dissolved during rolling can effectively improve the hardenability and recrystallization temperature, and it has an intelligent precipitation effect in case of fire similar to that of Nb, and is added as a forming element of MC phase;

Titanium: A small amount of Ti is added to the steel of the present invention, which is aimed to form nanoscale TiN particles and TiOx particles, which can refine the austenite grains during the heating of the casting blank, prevent the grains in heat-affected zone

from coarsening during welding as well as improve the high heat input welding resistance performance. The content of Ti is controlled within the range of 0.01-0.020%. In case of lower than 0.01%, only a small amount of TiN and TiOx particles are formed, so that the effect on grain refinement is small and the welding heat input is low. In case of higher than 0.020%, micron-sized liquid-precipitated TiN will be formed, so that it cannot play the role of grain refinement, the welding heat input is low, and it is harmful to the toughness of the steel plate;

The content of Nb of the present invention should be controlled to 0.02-0.15%, and the precipitation of Nb is suppressed by the fast cooling rate after hot rolling, so that the yield strength will not be too high, which is good for low yield strength at room temperature. However, the unprecipitated Nb will precipitate separately out from ferrite and bainite during self-tempering, or precipitate together with V and Mo to form a nanoscale second phase so as to compensate for the reduction of strength caused by softening of the matrix of the steel at high temperature and improve the fire resistance;

The content of Mo of the present invention is controlled to 0.10-0.50%. In conjunction with the rolling process of the present invention, the solid solubility product of microalloy carbonitrides in austenite can be enlarged, and excessive microalloy carbonitrides can be prevented from deformation-induced precipitation during rolling. In addition, in the present invention, Mo can be combined with microalloying elements V, Nb and Ti to precipitate during heating, which can increase the precipitation amount and increase the thermal stability of the precipitates, thereby stably improving and ensuring the fire resistance of the steel at high temperature.

The solution further limited by the present invention is as follows:

The aforementioned chemical components by weight percentage are as follows: C: 0.08%, Si: 0.37%, Mn: 1.35%, Mo: 0.30%, Nb: 0.025%, V: 0.010% and Ti: 0.018%, and
5 the rest are Fe and unavoidable impurities.

The aforementioned chemical components by weight percentage are as follows: C: 0.16%, Si: 0.15%, Mn: 1.75%, Mo: 0.10%, Nb: 0.08%, V: 0.04% and Ti: 0.010%, and the
rest are Fe and unavoidable impurities.

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The aforementioned chemical components by weight percentage are as follows: C: 0.12%, Si: 0.55%, Mn: 0.50%, Mo: 0.45%, Nb: 0.13%, V: 0.001% and Ti: 0.015%, and
the rest are Fe and unavoidable impurities.

15 The present invention further provides a method for manufacturing a composite
antiseismic fireproof building steel, specifically comprising the following steps:

S1: smelting molten steel: smelting molten steel according to the target chemical
components of the steel plate, adding silicomanganese to the ladle for alloying at the
20 time of tapping, precisely controlling the order of adding alloy during LF refining process,
adding Ti, Mo, Nb and V in sequence, and adjusting the components of the molten steel
to the target components;

S2: continuous casting: casting the molten steel into a continuous cast blank, wherein the thickness of the continuous cast blank is $\geq 100\text{mm}$, and the compression ratio is not less than 3 times;

5 S3: reheating a casting blank: heating the continuous cast blank to $1,100\text{-}1,250^\circ\text{C}$, and the time in furnace is $8\text{-}12\text{min/cm}$;

S4: hot rolling: A two-stage rolling process is adopted, and it is specifically as follows:

(1) rough rolling: performing 3-5 passes of rough rolling, wherein the final rough rolling
10 temperature is $1,020\text{-}1,150^\circ\text{C}$ so that the austenite can be refined by repeated recrystallization in the steel;

(2) finish rolling: performing 5-10 passes of finish rolling, wherein the initial finish rolling temperature is $880\text{-}980^\circ\text{C}$, the final finish rolling temperature is $830\text{-}920^\circ\text{C}$, and a pancake-like austenite structure is obtained after rolling; and then performing laminar
15 cooling at a cooling rate of $5\text{-}15^\circ\text{C/s}$ so that the precipitation of Nb is inhibited, wherein the final cooling self-tempering temperature is $500\text{-}700^\circ\text{C}$, and the unprecipitated Nb precipitates separately out of ferrite and bainite during self-tempering or precipitates in combination with V and Mo to form a nanoscale second phase and obtain a fine-grained ferrite and granular bainite structure, and then cooling in the air to room temperature.

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The beneficial effects of the present invention are as follows:

(1) The present invention is designed with an appropriate amount of Nb, low amount of Mo, low amount of V, micro amount of Ti multi-element composite microalloying and low carbon components. Favorable inclusions are obtained through oxide metallurgical
25 process during the smelting, which improves the high heat input welding resistance

performance. High room temperature strength and low yield ratio are guaranteed by controlling the temperature in the heating stage, adopting the two-stage controlled rolling process, controlling the laminar cooling rate and controlling the final cooling temperature process to produce an antiseismic fireproof steel with fine-grained ferrite/granular bainite structure or granular bainite structure. The fine-grained structure and a lot of microalloy second phase intelligently precipitate during the ignition to ensure high temperature strength, with antiseismic property and intelligent fire resistance. The alloy cost is reduced by low carbon content and carbon equivalent design, addition of a small amount of Nb and V and reduction of more Mo. Fine-grained structure is obtained by controlling rolling and cooling, with high strength, high toughness and excellent weldability.

(2) In the present invention, the order of adding alloys during LF refining is precisely controlled, Ti, Mo, Nb and V are sequentially added and the components of the molten steel are adjusted to the target components. The purpose is to control the type, size and quantity of inclusions in the steel to obtain 1,800-2,200/mm² inclusions containing Ti oxides with a size of 0.2-5 μ m and more than 4*10⁶/mm² inclusions containing Ti nitrides with a size of 10-300nm. During high heat input welding, these inclusions are conducive to pin austenite grains, refine the intragranular structure as well as improve the low temperature toughness of the welding heat-affected zone;

(2) The microstructure of the steel sheet prepared by the present invention is characterized by ferrite + granular bainite; wherein proeutectoid ferrite is distributed at the austenite grain boundary in the welding heat-affected zone, and the average grain size is less than 50 μ m, accounting for an area fraction of less than 40%, and the interior

of the original austenite grain is a fine acicular ferrite, accounting for an area fraction of more than 60%;

(3) As for the steel plate prepared by the present invention, microalloy elements such as Nb, V and so on are solid-dissolved in the matrix at room temperature, and it has the performance characteristics of high strength, high toughness and low yield ratio. Intelligent precipitation of Mo, Nb and V nano-composite precipitates can compensate for the loss of matrix strength and ensure high-temperature fire resistance;

(4) To sum up, in the present invention, a large number of fine and dispersed composite inclusions containing Ti oxides and nitrides are generated by controlling the production process conditions. When the steel plate is welded with large heat input, a large amount of intragranular acicular ferrite is formed at the structure close to the fusion line where the temperature is 1,400°C, and at the same time the original austenite grains are pinned and the intragranular structure is refined in the structure far from the fusion line where the temperature is lower than 1,400°C. The combined effect of the two greatly improves the toughness of the welding heat-affected zone, so that the steel has good welding performance and can resist high heat input welding;

(5) Combining the above effects, the tensile yield strength of the steel plate at room temperature R_{eL} is equal to or more than 345MPa, tensile strength R_m is equal to or more than 490MPa, yield ratio YR is equal to or less than 0.80, elongation after fracture A is equal to or more than 22%, Charpy impact energy at -40°C KV2 is equal to or more than 150J; 600°C high temperature refractory coefficient $[(\text{normal temperature yield strength} - \text{high temperature yield strength}) / \text{normal temperature yield strength}]$ I is equal

to or more than 0.33; and after 50-200kJ/cm high heat input welding, the average value of impact energy at -40°C in the welded joint heat-affected zone is greater than 50J.

Embodiment 1

- 5 The present embodiment provides a composite antiseismic fireproof building steel, wherein it comprises the following chemical components by weight percentage: C: 0.08%, Si: 0.37%, Mn: 1.35%, Mo: 0.30%, Nb: 0.025%, V: 0.010% and Ti: 0.018%, and the rest are Fe and unavoidable impurities.
- 10 The present embodiment further provides a method for manufacturing a composite antiseismic fireproof building steel, wherein it is prepared by three different sets of process parameters, specifically:
- 15 S1: smelting molten steel: smelting molten steel according to the target chemical components of the steel plate, adding silicomanganese to the ladle for alloying at the time of tapping, precisely controlling the order of adding alloy during LF refining process, adding Ti, Mo, Nb and V in sequence, and adjusting the components of the molten steel to the target components;
- 20 S2: continuous casting: casting the smelted molten steel into three identical continuous cast blanks A1, A2 and A3. The thickness of the continuous cast blanks is 220mm, and the compression ratio is guaranteed to be 4 times;
- 25 S3: reheating casting blanks: heating the three continuous cast blanks A1, A2 and A3 to 1,220°C, 1,150°C and 1,250°C respectively, and the time in furnace is 8min/cm for each

of them; controlling the austenitization temperature to be higher than the total solid solution temperature of the microalloying elements Nb and V but lower than the temperature at which TiN re-dissolves and austenite grows abnormally. It makes full use of the solidified TiN to prevent austenite grain from growing so as to obtain a fine and uniform original austenite structure;

S4: hot rolling: A two-stage rolling process is adopted for A1, A2 and A3, and it is specifically as follows:

(1) rough rolling: performing three passes of rough rolling on A1, A2 and A3 respectively so that the austenite is refined through repeated recrystallization inside the steel, wherein the final rough rolling temperature of A1, A2 and A3 is 1,055°C, 1,038°C and 1,100°C respectively;

(2) finish rolling: performing 5 passes of finish rolling on A1, A2 and A3 respectively, wherein the initial finish rolling temperature of A1, A2 and A3 is 950°C, 920°C and 980°C respectively, the final finish rolling temperature is 913°C, 840°C and 920°C accordingly, and a pancake-like austenite structure is obtained after rolling; and then performing laminar cooling on A1, A2 and A3 at a cooling rate of 15°C/s, 10°C/s and 5°C/s respectively so that the precipitation of Nb is inhibited, wherein the self-tempering temperature of A1, A2 and A3 is 500°C, 510°C and 670°C respectively, and the unprecipitated Nb precipitates separately out of ferrite and bainite during self-tempering or precipitates in combination with V and Mo to form a nanoscale second phase and obtain a fine-grained ferrite and granular bainite structure, and then cooling in the air to room temperature.

Embodiment 2

The present embodiment provides a composite antiseismic fireproof building steel, wherein it comprises the following chemical components by weight percentage: C: 0.16%, Si: 0.15%, Mn: 1.75%, Mo: 0.10%, Nb: 0.08%, V: 0.04% and Ti: 0.010%, and the rest are Fe and unavoidable impurities.

The present embodiment further provides a method for manufacturing a composite antiseismic fireproof building steel, wherein it is prepared by three different sets of process parameters, specifically:

S1: smelting molten steel: smelting molten steel according to the target chemical components of the steel plate, adding silicomanganese to the ladle for alloying at the time of tapping, precisely controlling the order of adding alloy during LF refining process, adding Ti, Mo, Nb and V in sequence, and adjusting the components of the molten steel to the target components;

S2: continuous casting: casting the smelted molten steel into three identical continuous cast blanks B1, B2 and B3. The thickness of the continuous cast blanks is 150mm, and the compression ratio is guaranteed to be 5 times;

S3: reheating casting blanks: heating the three continuous cast blanks B1, B2 and B3 to 1,180°C, 1,200°C and 1,280°C respectively, and the time in furnace is 10min/cm for each of them; controlling the austenitization temperature to be higher than the total solid solution temperature of the microalloying elements Nb and V but lower than the temperature at which TiN re-dissolves and austenite grows abnormally. It makes full use

of the solidified TiN to prevent austenite grain from growing so as to obtain a fine and uniform original austenite structure;

S4: hot rolling: A two-stage rolling process is adopted for B1, B2 and B3, and it is specifically as follows:

(1) rough rolling: performing four passes of rough rolling on B1, B2 and B3 respectively so that the austenite is refined through repeated recrystallization inside the steel, wherein the final rough rolling temperature of B1, B2 and B3 is 1,045°C, 1,060°C and 1,150°C respectively;

(2) finish rolling: performing 8 passes of finish rolling on B1, B2 and B3 respectively, wherein the initial finish rolling temperature of B1, B2 and B3 is 890°C, 880°C and 940°C respectively, the final finish rolling temperature is 830°C, 856°C and 885°C accordingly, and a pancake-like austenite structure is obtained after rolling; and then performing laminar cooling on B1, B2 and B3 at a cooling rate of 14°C/s, 5°C/s and 8°C/s respectively so that the precipitation of Nb is inhibited, wherein the self-tempering temperature of B1, B2 and B3 is 580°C, 660°C and 540°C respectively, and the unprecipitated Nb precipitates separately out of ferrite and bainite during self-tempering or precipitates in combination with V and Mo to form a nanoscale second phase and obtain a fine-grained ferrite and granular bainite structure, and then cooling in the air to room temperature.

Embodiment 3

The present embodiment provides a composite antiseismic fireproof building steel, wherein it comprises the following chemical components by weight percentage: C: 0.12%, Si: 0.55%, Mn: 0.50%, Mo: 0.45%, Nb: 0.13%, V: 0.001% and Ti: 0.015%, and the rest are Fe and unavoidable impurities.

The present embodiment further provides a method for manufacturing a composite antiseismic fireproof building steel, wherein it is prepared by three different sets of process parameters, specifically:

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S1: smelting molten steel: smelting molten steel according to the target chemical components of the steel plate, adding silicomanganese to the ladle for alloying at the time of tapping, precisely controlling the order of adding alloy during LF refining process, adding Ti, Mo, Nb and V in sequence, and adjusting the components of the molten steel
10 to the target components;

S2: continuous casting: casting the smelted molten steel into three identical continuous cast blanks C1, C2 and C3. The thickness of the continuous cast blanks is 260mm, and the compression ratio is guaranteed to be 6 times;

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S3: reheating casting blanks: heating the three continuous cast blanks C1, C2 and C3 to 1,200°C, 1,210°C and 1,100°C respectively, and the time in furnace is 12min/cm for each of them; controlling the austenitization temperature to be higher than the total solid solution temperature of the microalloying elements Nb and V but lower than the
20 temperature at which TiN re-dissolves and austenite grows abnormally. It makes full use of the solidified TiN to prevent austenite grain from growing so as to obtain a fine and uniform original austenite structure;

S4: hot rolling: A two-stage rolling process is adopted for C1, C2 and C3, and it is
25 specifically as follows:

(1) rough rolling: performing five passes of rough rolling on C1, C2 and C3 respectively so that the austenite is refined through repeated recrystallization inside the steel, wherein the final rough rolling temperature of C1, C2 and C3 is 1,062°C, 1,050°C and 1,020°C respectively;

5 (2) finish rolling: performing 10 passes of finish rolling on C1, C2 and C3 respectively, wherein the initial finish rolling temperature of C1, C2 and C3 is 910°C, 940°C and 910°C respectively, the final finish rolling temperature is 841°C, 906°C and 868°C accordingly, and a pancake-like austenite structure is obtained after rolling; and then performing
10 laminar cooling on C1, C2 and C3 at a cooling rate of 7°C/s, 10°C/s and 13°C/s respectively so that the precipitation of Nb is inhibited, wherein the self-tempering temperature of C1, C2 and C3 is 700°C, 570°C and 590°C respectively, and the unprecipitated Nb precipitates separately out of ferrite and bainite during self-tempering or precipitates in combination with V and Mo to form a nanoscale second phase and obtain a fine-grained ferrite and granular bainite structure, and then cooling in the air to
15 room temperature.

A total of 9 pieces of composite antiseismic fireproof building steel are manufactured in the above-mentioned Embodiments 1 to 3. The transverse tensile property and longitudinal impact energy at -40°C of the 9 pieces of composite antiseismic fireproof
20 building steel are shown in Table 1 below;

Table 1 Mechanical Properties of Composite Antiseismic Fireproof Building Steel

Steel plate number	Billet number	Stretching at room temperature				Stretching at high temperature (600°C)	Impact energy at -40°C Akv(J)		
		Rp0.2(MPa)	Rm(MPa)	A(%)	Yield ratio	Rp0.2(MPa)	1	2	3
1	A1	474	608	28	0.78	343	298	312	301
2	A2	465	583	26	0.80	328	309	297	315
3	A3	370	516	26	0.72	260	312	303	299
4	B1	487	619	27.5	0.78	339	338	306	296
5	B2	405	544	27	0.74	276	304	310	318
6	B3	491	629	29	0.78	355	299	312	289
7	C1	539	700	26	0.77	360	302	315	327
8	C2	547	719	28	0.76	358	296	326	304
9	C3	562	711	25	0.79	343	331	321	299

In addition to the above-described embodiments, the present invention may include other embodiments. Any technical solution formed by equivalent replacement or equivalent transformation falls within the protection scope of the present invention.

In the application, unless specified otherwise, the terms "comprising", "comprise", and grammatical variants thereof, intended to represent "open" or "inclusive" language such that they include recited elements but also permit inclusion of additional, non-explicitly recited elements.

As used herein, the term "about", in the context of concentrations of components of the formulations, typically means +/- 5% of the stated value, more typically +/- 4% of the stated value, more typically +/- 3% of the stated value, more typically, +/- 2% of the stated value, even more typically +/- 1% of the stated value, and even more typically
5 +/- 0.5% of the stated value.

Throughout this disclosure, certain embodiments may be disclosed in a range format. The description in range format is merely for convenience and brevity and should not be construed as an inflexible limitation on the scope of the disclosed ranges.

10 Accordingly, the description of a range should be considered to have specifically disclosed all the possible sub-ranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed sub-ranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6 etc., as well as individual numbers within that range,
15 for example, 1, 2, 3, 4, 5, and 6. This applies regardless of the breadth of the range.

[0001] It will be apparent that various other modifications and adaptations of the application will be apparent to the person skilled in the art after reading the foregoing disclosure without departing from the spirit and scope of the application and it is
20 intended that all such modifications and adaptations come within the scope of the appended claims.

Claims

1. A composite antiseismic fireproof building steel, the composite antiseismic fireproof building steel, wherein it comprises the following chemical components by weight percentage: C: 0.12%, Si: 0.55%, Mn: 0.50%, Mo: 0.45%, Nb: 0.13%, V: 0.001% and Ti: 0.015%, and the rest are Fe and unavoidable impurities.
2. A method for manufacturing the composite antiseismic fireproof building steel according to claim 1, wherein it specifically comprises the following steps:
 - S1: smelting molten steel: smelting molten steel according to the target chemical components of the steel plate, adding silicomanganese to the ladle for alloying at the time of tapping, precisely controlling the order of adding alloy during LF refining process, adding Ti, Mo, Nb and V in sequence, and adjusting the components of the molten steel to the target components;
 - S2: continuous casting: casting the molten steel into a continuous cast blank, wherein the thickness of the continuous cast blank is $\geq 100\text{mm}$, and the compression ratio is not less than 3 times;
 - S3: reheating a casting blank: heating the continuous cast blank to $1,100\text{-}1,250^{\circ}\text{C}$, and the time in furnace is $8\text{-}12\text{min/cm}$;
 - S4: hot rolling: A two-stage rolling process is adopted, and it is specifically as follows:
 - (1) rough rolling: performing 3-5 passes of rough rolling, wherein the final rough rolling temperature is $1,020\text{-}1,150^{\circ}\text{C}$ so that the austenite can be refined by repeated recrystallization in the steel;
 - (2) finish rolling: performing 5-10 passes of finish rolling, wherein the initial finish rolling temperature is $880\text{-}980^{\circ}\text{C}$, the final finish rolling temperature is $830\text{-}920^{\circ}\text{C}$,

and a pancake-like austenite structure is obtained after rolling; and then performing laminar cooling at a cooling rate of 5-15°C/s so that the precipitation of Nb is inhibited, wherein the final cooling self-tempering temperature is 500-700°C, and the unprecipitated Nb precipitates separately out of ferrite and bainite during self-tempering or precipitates in combination with V and Mo to form a nanoscale second phase and obtain a fine-grained ferrite and granular bainite structure, and then cooling in the air to room temperature.