



(11)

EP 4 509 626 A1

(12)

EUROPEAN PATENT APPLICATION
published in accordance with Art. 153(4) EPC

(43) Date of publication:
19.02.2025 Bulletin 2025/08

(21) Application number: **23803269.2**

(22) Date of filing: **29.03.2023**

(51) International Patent Classification (IPC):
C22C 38/00 ^(2006.01) **C21D 1/00** ^(2006.01)
C21D 9/00 ^(2006.01) **C22C 38/04** ^(2006.01)
C22C 38/60 ^(2006.01)

(52) Cooperative Patent Classification (CPC):
C21D 1/00; C21D 9/00; C22C 38/00; C22C 38/04;
C22C 38/60

(86) International application number:
PCT/JP2023/012744

(87) International publication number:
WO 2023/218786 (16.11.2023 Gazette 2023/46)

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB
GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL
NO PL PT RO RS SE SI SK SM TR

Designated Extension States:
BA

Designated Validation States:
KH MA MD TN

(30) Priority: **09.05.2022 JP 2022077090**

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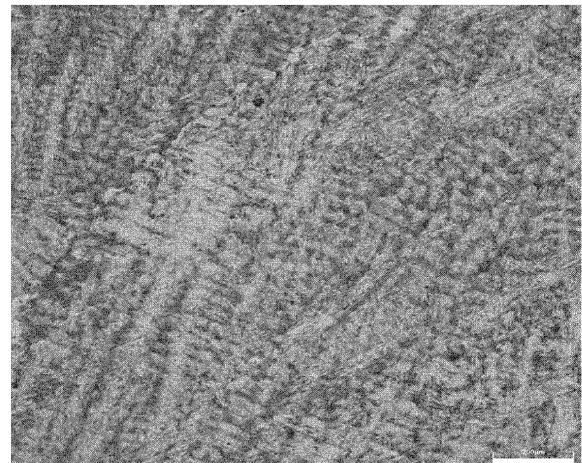
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(54) **CONTINUOUS CASTING SLAB AND METHOD FOR MANUFACTURING SAME**

(57) Provided are a continuously cast slab that can prevent thermal cracking during cooling therefor even if the toughness of the slab is low, and a method for producing the same. Specifically, provided is a continuously cast slab for high-strength steel with features such that the average prior austenite grain size at a position of 10 mm from the surface layer of the continuously cast slab is in the range of 0.5 mm to 2.0 mm; and in the microstructure of the slab, the total area ratio of bainite and ferrite is 90% more, and the area ratio of ferrite is 0%, or 3% or more.

[Fig. 3]



EP 4 509 626 A1

Description

Technical Field

5 **[0001]** The present invention relates to a continuously cast slab that does not cause cracking during cooling, and a method for producing the same. More specifically, the present invention relates to a continuously cast slab for high-strength steel (high tensile steel) that can effectively prevent the occurrence of thermal cracking therein, and a method for producing the same.

10 Background Art

[0002] In recent years, the automotive industry has been developing high-strength steels with higher strength and higher alloying levels in order to further reduce the thickness of car bodies and improve crash safety. Increasing the level of alloying has resulted in a significant reduction in the toughness of a slab.

15 **[0003]** As the toughness of a slab decreases with an increase in the alloying level, cracking in the slab during cooling, known as "thermal cracking", in other words, "season cracking", has occurred more frequently. Such thermal cracking may cause the slab to fracture while being conveyed, preventing the slab from being hot rolled. Even if the slab does not fracture, the cracks in the slab may open during hot rolling, causing the resulting hot-rolled steel sheet to fracture. Meanwhile, small cracks in a slab may appear as surface defects, such as scabs or slivers, on the resulting steel sheet after
20 hot rolling, cold rolling, annealing, or plating. Typically, cracks in the surface of a slab are removed with a grinder. However, in a case where the toughness of the slab has decreased with an increase in the amount of alloy added and the cracks in the slab develop due to the stress applied by the grinder, it may be impossible to completely remove the cracks in the slab. Furthermore, small cracks in the slab may be overlooked and appear as surface defects on the resulting steel sheet after hot rolling, cold rolling, annealing, or plating. For the above reasons, it is necessary to suppress thermal cracking in slabs.

25 **[0004]** Fig. 1 is an enlarged photograph of a fracture surface of a cracked portion in a slab for high-strength steel, which has fractured due to thermal cracking, shot with a scanning electron microscope (SEM). As is obvious from Fig. 1, the fracture surface of the cracked portion in the slab exhibits an intergranular fracture surface along a prior austenite grain boundary. Fig. 2 is a micrograph of a cross-section of the cracked portion in the slab. It is found that the depth of the crack in the slab from the surface is mostly about 20 mm. It is also found that the crack in the slab has propagated around the prior
30 austenite grain boundary, and grain-boundary ferrite is present at the tip end of the cracked portion in the slab. Further, pearlite or pearlite and bainite is/are observed in prior austenite grains.

[0005] An intergranular fracture occurs when prior austenite grains are coarse, and their grain boundaries are embrittled. Precipitates and ferrite are more likely to be formed at grain boundaries than within grains. Precipitates at grain boundaries are a factor that reduces the grain boundary strength and also reduces the toughness of the slab. When
35 prior austenite grains are coarse, the ratio of their grain boundaries is low, and the density of precipitates at the grain boundaries is correspondingly high, so that the grain boundaries are further embrittled. When grain-boundary ferrite is formed, there is a difference in strength between the grain-boundary ferrite and the pearlite and bainite in the grains, causing stress concentration at the grain-boundary ferrite portion with lower strength. This can lead to cracks in the slab even when the stress is lower. In such a case, when the prior austenite grains are coarse, grain-boundary ferrite that is
40 linearly thin and elongated is precipitated, making it difficult to avoid the propagation of the cracks in the slab. This can lead to increased damage due to the cracks in the slab. Meanwhile, when the slab is cooled, stress is caused due to the difference in thermal shrinkage or in transformation expansion between the surface and the inside of the slab. When the stress is high, cracks are caused in the slab while the slab is cooled to room temperature. Since the toughness of a slab for high-alloy, high-strength steel produced in recent years is low, it has been difficult to remove deep cracks that have
45 occurred in the slab in the above manner by using some measures such as a grinder. This has been a problem that greatly reduced the yield of the slab.

[0006] From such a viewpoint, a method for suppressing the occurrence of thermal cracking in a slab for high tensile strength steel has been proposed. For example, Patent Literature 1 proposes a method for suppressing bainite/martensitic transformation by slowly cooling at 700 to 500°C, which corresponds to the temperature range in which the transformation
50 from austenite to ferrite occurs, thereby reducing the stress generated due to the transformation expansion. That is, Patent Literature 1 discloses a method capable of suppressing the occurrence of thermal cracking even in high tensile strength steel with a grade that is likely to cause thermal cracking. Specifically, a method for cooling a slab for high tensile strength steel disclosed in Patent Literature 1 is a method for suppressing the occurrence of thermal cracking by controlling the cooling rate for the slab in accordance with the length of an internal crack that has occurred in high tensile strength steel
55 based on the finding that internal stress in the high tensile strength steel depends on its cooling rate.

[0007] Patent Literature 2 proposes a method for reducing a temperature difference and reducing stress due to transformation by starting slow cooling of a slab immediately after the slab is cast, then slowly cooling the slab at a temperature of 700°C or higher for 10 hours or longer and further from 700 to 500°C. That is, Patent Literature 2 discloses a

method for cooling a slab for a high-strength steel sheet that prevents both cracking while the slab is being cooled and defects in quality such as scabs while the slab is being hot-rolled, even if the slab contains Si. Specifically, the cooling method for a slab for a high-strength steel sheet disclosed in Patent Literature 2 includes setting the average cooling rate for a continuously cast slab, which has limited contents of chemical components, such as C, Si, and Mn, for a high-strength hot-rolled steel sheet to 20°C/hr or less in the temperature range of 500 to 700°C.

Citation List

Patent Literature

[0008]

Patent Literature 1: JP-2020-139209A

Patent Literature 2: JP-2019-167560A

Summary of Invention

Technical Problem

[0009] However, the above conventional technologies have the following problems. The method described in Patent Literature 1 of cooling a slab for high tensile strength steel after casting the slab involves controlling the cooling rate for the slab so as to reduce the internal stress to be generated in the slab by focusing only on the temperature range of 700°C to 500°C after the slab is cast and cooled. However, since the toughness of a slab for high-strength steel with a higher amount of alloy added produced in recent years is low, the condition of prior austenite grain boundaries around which thermal cracking propagates is also quite important. However, the method described in Patent Literature 1 does not involve controlling the grain size of prior austenite or grain-boundary ferrite. Thus, even if a slab with an increased carbon content is produced by the cooling method for a slab for high tensile strength steel described in Patent Literature 1, it is not possible to sufficiently suppress the occurrence of thermal cracking in the slab.

[0010] The method described in Patent Literature 2 for cooling a slab for a high-strength steel sheet is based on the finding that cracking in the slab is caused due to thermal stress, which has been caused by the addition of Si to the steel and by the temperature variation in the slab, and suppresses the occurrence of cracking in the slab by focusing on reducing the thermal stress. However, the method described in Patent Literature 2 for cooling a slab for a high-strength steel sheet does not involve limiting the microstructure of the slab. Therefore, even if a slab is produced by the cooling method described in Patent Literature 2 for a slab for a high-strength steel sheet, it is not possible to sufficiently suppress the occurrence of thermal cracking in the slab.

[0011] Further, as a result of intensive studies, the inventors have found that the toughness of a slab produced by conventional technologies to have high C, Si, and Mn contents is significantly low, making it impossible to completely suppress the occurrence of thermal cracking in such a slab simply by slowly cooling the slab with the intention of reducing thermal stress.

[0012] The present invention has been made in view of the above circumstances, and it is an object of the present invention to provide a continuously cast slab that does not cause thermal cracking during cooling of the slab, even when the toughness of the continuously cast slab toughness is low, and a method for producing the same.

Solution to Problem

[0013] The inventors conducted extensive studies in order to achieve the above object. As a result, by analyzing the fracture morphology of slab cracking, the inventors found that its fracture surface includes at least one type selected from an intergranular fracture surface along a prior austenite grain boundary and an intragranular fracture surface (cleavage fracture surface) across a prior austenite grain boundary. Through various detailed studies, the inventors further found that it is impossible to suppress the occurrence of thermal cracking in a slab solely by reducing the stress achieved by controlling the cooling rate and reducing the temperature variation and that the morphology of the microstructure of the slab has a great influence on the occurrence of thermal cracking. Specifically, the inventors found that it is possible to suppress the occurrence of thermal cracking in a continuously cast slab during cooling, by controlling the average prior austenite grain size and microstructure of the continuously cast slab to increase the toughness of the slab, and thus arrived at the present invention.

[0014] That is, a continuously cast slab according to the present invention which advantageously solves the above problems is a continuously cast slab for high-strength steel, characterized in that an average prior austenite grain size at a position 10 mm from a surface layer of the continuously cast slab is in a range of 0.5 mm to 2.0 mm; a total of an area ratio of

bainite and an area ratio of ferrite in a microstructure of the slab is 90% or more; and the area ratio of ferrite is 0%, or 3% or more.

[0015] It is considered that the continuously cast slab according to the present invention may include, in mass%, (a) C: in a range of 0.10% to 0.40%, Si: in a range of 0.10% to 2.50%, and Mn: in a range of 1.00% to 5.00%, as a preferable solution means.

[0016] A method for producing a continuously cast slab according to the present invention is a method for producing a continuously cast slab for high-strength steel, the continuously cast slab preventing thermal cracking due to cooling, the method including subjecting the continuously cast slab having the ingredient composition described in (a) to the following:

a first cooling step of cooling the continuously cast slab under a cooling condition that a retention time while a cooling temperature of a center of the wide face at a position 10 mm from a surface layer of the continuously cast slab is in a range of 1200°C to 1450°C is 130 seconds or less;

a second cooling step of cooling the continuously cast slab under a cooling condition that an average cooling rate when a surface temperature at the center of the wide face of the continuously cast slab is in a range of 700°C to 850°C is between 25°C/hr and 40°C/hr, or 50°C/hr or more; and

a third cooling step of cooling the continuously cast slab under a cooling condition that an average cooling rate when the surface temperature at the center of the wide face of the continuously cast slab is in a range of 500°C to 700°C is 15°C/hr or more.

Advantageous Effects of Invention

[0017] The present invention can provide a continuously cast slab that prevents thermal cracking during cooling, even when the slab has an ingredient composition of a continuously cast slab for high-strength steel.

Brief Description of Drawings

[0018]

[Fig. 1] Fig. 1 is a photograph of a fracture surface of a cracked portion in a continuously cast slab for high-strength steel, which has fractured due to thermal cracking, taken by a scanning electron microscope (SEM).

[Fig. 2] Fig. 2 is a micrograph of a cross-sectional structure of the above cracked portion.

[Fig.3] Fig. 3 is a magnified micrograph of a continuously cast slab produced as an Invention Example (Test No. D-2) for a continuously cast slab of an embodiment according to the present invention, observed with an optical microscope.

Description of Embodiments

[0019] Hereinafter, embodiments of the present invention will be specifically described. Note that the drawings are only schematic, and thus may differ from the actual ones. In addition, the following embodiments only illustrate examples of an apparatus and a method for embodying the technical idea of the present invention. Thus, the configuration of the present invention is not limited thereto. That is, the technical idea of the present invention can be changed in various ways within the technical scope recited in the claims.

[First embodiment]

[0020] A continuously cast slab according to a first embodiment will be described. The continuously cast slab according to this embodiment is a continuously cast slab for high-strength steel and has the following features: (i) an average prior austenite grain size at a position 10 mm from the surface layer of the continuously cast slab is in the range of 0.5 mm to 2.0 mm, (ii) in a microstructure of the slab, a total of an area ratio of bainite and an area ratio of ferrite is 90% or more, and (iii) the area ratio of ferrite is 0%, or 3% or more. That is, by satisfying at least the above features (i) to (iii), the invention according to this embodiment can provide a high-yield continuously cast slab for high-strength steel that prevents thermal cracking during cooling, even if the slab is a continuously cast slab for high-strength steel of recent years that has extremely low toughness.

[0021] First, an appropriate range of the microstructure of the continuously cast slab and the reasons for limiting such a range will be described. In the following description, the symbol "%" representing a constitutional ratio in the microstructure means "area %" unless otherwise stated. It is assumed that the microstructure of the continuously cast slab has been observed at room temperature.

[0022] As previously described, as a result of observing the fracture morphology of a fracture surface of a cracked

portion in a continuously cast slab for high-strength steel that fractured due to thermal cracking, it is found that many of the cracks develop to a position about 20 mm below the surface layer of the slab, and exhibit the morphology of an "intergranular fracture" such that a crack develops in a prior austenite grain boundary. That is, in a continuously cast slab for high-strength steel, thermal cracking due to the fracture of a grain boundary is caused by the coarse grain size of prior austenite, and a ferrite structure at the grain boundary which is a factor for embrittlement of the grain boundary. Thus, this embodiment focuses on the following two including (i) an average prior austenite grain size at a predetermined position from the surface layer of the continuously cast slab, and (ii) to (iii) the microstructure of the continuously cast slab, as the necessary conditions for a continuously cast slab for high-strength steel that does not cause thermal cracking during cooling.

< (i) Average prior austenite grain size >

[0023] The continuously cast slab for high-strength steel according to this embodiment is a continuously cast slab for high-strength steel in which the occurrence of thermal cracking due to cooling is prevented, and has the feature (i) that an average prior austenite grain size at a position 10 mm from the surface layer of the continuously cast slab is in the range of 0.5 mm to 2.0 mm. The average prior austenite grain size is a factor that determines the fracture unit of the slab. This means that the larger the average prior austenite grain size, the lower the toughness of the continuously cast slab. Herein, the average prior austenite grain size refers to a value obtained by averaging the values of a plurality of prior austenite grain sizes calculated from the prior austenite grain sizes measured for a plurality of visual fields.

[0024] In a conventional continuously cast slab, the average prior austenite grain size is as large as several millimeters. This significantly reduces the toughness of the continuously cast slab. Since a conventional low-alloy steel is made from a high-toughness continuously cast slab, the average prior austenite grain size has never been a concern. On the other hand, for high-alloy, high-strength steel, the average prior austenite grain size can be a major concern. Thus, in the continuously cast slab according to this embodiment, the average prior austenite grain size at a position 10 mm from the surface layer of the continuously cast slab is set to 2.0 mm or less. When the average prior austenite grain size is 2.0 mm or less, the toughness of the continuously cast slab is not reduced, which is preferable.

[0025] Meanwhile, the lower limit of the average prior austenite grain size is not strictly defined. However, to achieve a fine average prior austenite grain size of less than 0.5 mm, it is necessary, for example, to strongly cool the slab in the initial stage of solidification, which may cause a risk of breakout due to uneven solidification. Therefore, the lower limit of the average prior austenite grain size is preferably 0.5 mm. Note that the lower limit of the average prior austenite grain size is preferably 0.8 mm, and more preferably 1.0 mm.

[0026] The average prior austenite grain size is determined by using the size of the grains forming the prior austenite structure at a position 10 mm from the surface layer of the continuously cast slab. The reason for setting the position 10 mm from the surface layer of the continuously cast slab in determining the average prior austenite grain size is that the position 10 mm from the surface layer of the continuously cast slab is considered to be the position necessary to suppress the occurrence of thermal cracking in the slab, since most of the thermal cracking in the slab develops to a position about 20 mm below the surface layer of the slab.

[0027] Meanwhile, a region less than 5 mm from the surface layer of the continuously cast slab is rapidly cooled either directly by a casting mold or by a water spray disposed directly below the casting mold. The rapid cooling results in a smaller grain size and increased toughness in the region of the continuously cast slab. Consequently, this region is less likely to become the starting point for thermal cracking. Therefore, such a region located less than 5 mm from the surface layer of the continuously cast slab can be excluded from structure control. This means that the position where the structure of the continuously cast slab needs to be controlled is a position 10 mm deep in the thickness direction of the slab, and may be, for example, a position 5 to 20 mm deep from the surface layer of the continuously cast slab, based on the position 10 mm from the surface layer of the continuously cast slab.

[0028] In the continuously cast slab according to this embodiment, the temperature for cooling the continuously cast slab is a factor that determines the average prior austenite grain size. The temperature for cooling the continuously cast slab is particularly in the range of 1450°C to 1200°C, and the retention time in such a temperature range has an influence. The longer the retention time of the continuously cast slab in the temperature range, the coarser the average prior austenite grain size. That is, in order for the continuously cast slab according to this embodiment to satisfy the condition (i) that an average prior austenite grain size at a position 10 mm from the surface layer of the continuously cast slab is in the range of 0.5 mm to 2.0 mm, it is essential to control the retention time in the temperature range of 1450°C to 1200°C of the continuously cast slab. Specifically, when the retention time in the temperature range of 1450°C to 1200°C at a position 10 mm deep from the surface layer of the slab in the thickness direction of the continuously cast slab is within 130 seconds, it is possible to achieve the average prior austenite grain size of 2.0 mm or less and to control the average prior austenite grain size to be small, suppressing the occurrence of thermal cracking in the slab, which is preferable.

[0029] Furthermore, from such a viewpoint, the retention time of the continuously cast slab is preferably within 120 seconds, more preferably within 110 seconds, and further preferably within 100 seconds.

[0030] It should be noted that the lower limit of the retention time of the continuously cast slab is not defined to a specific value. However, if the retention time is too short, there is a higher risk of breakout due to uneven solidification during continuous casting. Thus, the retention time should be 40 seconds or more.

[0031] That is, when the retention time of the continuously cast slab in the temperature range of 1450°C to 1200°C is 40 seconds or more, it is possible to reduce the risk of breakout and achieve the average prior austenite grain size of 2.0 mm or less, thereby suppressing the occurrence of thermal cracking in the slab, which is preferable. Note that the retention time of the continuously cast slab is more preferably 60 seconds or more, and further preferably 70 seconds or more.

[0032] The retention time of the continuously cast slab can be controlled by adjusting the cooling conditions in the initial stage of the slab casting. For example, in the continuous casting of steel, molten steel with an adjusted ingredient composition is first poured into a water-cooled copper casting mold to form an initial solidified shell. The solidified shell is then removed from the water-cooled copper casting mold and cooled with a water spray. Since the temperature of the slab surface in the above-described range is significantly influenced by cooling performed within the casting mold or immediately below the casting mold, the temperature may be controlled by, for example, increasing the thermal conductivity of mold powder used for lubricating the inside of the casting mold, or by increasing the flow rate of a water spray disposed directly below the casting mold.

[0033] By controlling such cooling conditions, the average prior austenite grain size at a position 10 mm from the surface layer of the continuously cast slab can be controlled. The cooling temperature of the continuously cast slab cannot be directly measured, but it can be estimated, for example, by calculating a temperature history at a position 10 mm below the surface layer in the thickness direction of the slab, representing a region from 5 mm to 20 mm below the surface layer in the thickness direction of the continuously cast slab by heat-transfer analysis. To maximize the retention time within the temperature range in the interior of the continuously cast slab, the position for heat-transfer analysis can be set at the center of the wide face of the slab.

< (ii) to (iii) Microstructure of continuously cast slab >

[0034] The continuously cast slab according to this embodiment has features such that (ii) a total of an area ratio of bainite and an area ratio of ferrite in a microstructure of the slab is 90% or more, and (iii) the area ratio of ferrite is 0%, or 3% or more. That is, in addition to the feature that the average prior austenite grain size at a position 10 mm from the surface layer of the continuously cast slab is 2.0 mm or less, the ratio of internal structures such as bainite and ferrite is also a factor that determines the unit of fracture, and it is known that controlling such a ratio within appropriate range can increase the toughness of the slab. Thus, the inventors have found that it is possible to increase the toughness of the slab by controlling the cooling rate so as to satisfy the condition that a total of an area ratio of bainite and an area ratio of ferrite in the microstructure of the slab is 90% or more and that the area ratio of ferrite is 0%, or 3% or more. Note that the area ratio of bainite and the area ratio of ferrite can be calculated based on the results of observing the microstructure of the continuously cast slab using an observation means such as an optical microscope. In addition, bainite and ferrite contained in the microstructure of the continuously cast slab can be identified using an observation means such as an optical microscope.

[0035] The area S_{total} of the microstructure of the continuously cast slab, the area S_{bainite} of bainite, the area S_{ferrite} of ferrite, and the area $S_{(\text{bainite}+\text{ferrite})}$, which is the sum of the area S_{bainite} of bainite and the area S_{ferrite} of ferrite, are calculated from the results of identifying the microstructure of the continuously cast slab. Then, the ratio of the area S_{bainite} of bainite to the area S_{total} of the microstructure of the continuously cast slab, the ratio of the area S_{ferrite} of ferrite to the area S_{total} of the microstructure of the continuously cast slab, and the ratio of the area $S_{(\text{bainite}+\text{ferrite})}$, which is the sum of the area S_{bainite} of bainite and the area S_{ferrite} of ferrite, to the area S_{total} of the microstructure of the continuously cast slab are calculated as the area ratio of bainite, the area ratio of ferrite, and the total area ratio (%) of bainite and ferrite, respectively.

[0036] The continuously cast slab according to this embodiment has a feature such that (ii) a total of an area ratio of bainite and an area ratio of ferrite in a microstructure of the slab is 90% or more. That is, when the continuously cast slab according to this embodiment has a feature such that (ii) the area ratio (%), which is the ratio of the area $S_{(\text{bainite}+\text{ferrite})}$, which is the sum of the area S_{bainite} of bainite and the area S_{ferrite} of ferrite to the area S_{total} of the microstructure of the continuously cast slab, is 90% or more, it is possible to increase the toughness of the continuously cast slab, which is preferable. Meanwhile, if the area ratio is less than 90%, the toughness of the continuously cast slab decreases, which is unfavorable.

[0037] Further, the continuously cast slab according to this embodiment has a feature that (iii) the area ratio of ferrite is 0%, or 3% or more. That is, the continuously cast slab according to this embodiment has a microstructure of mainly bainite, wherein the area ratio of ferrite, which is the ratio of the area S_{ferrite} of ferrite to the area S_{total} of the microstructure of the continuously cast slab, is 0% or 3% or more. When the area ratio of ferrite is 0%, cracking due to stress concentration on soft ferrite portions as described above does not occur, which is preferable. When the area ratio of ferrite is 3% or more, it is possible to obtain sufficient ferrite portions, so that cracks due to stress concentration on the ferrite portions are not caused, which is preferable. Meanwhile, when the area ratio of ferrite is more than 0% but less than 3%, the slab is in such a state

that thin ferrite is present in grain boundaries and the stress is concentrated in the small ferrite portions, resulting in the development of cracks, which is unfavorable.

[0038] Herein, grain-boundary ferrite is a factor that determines the strength of grain boundaries. When grain-boundary ferrite is formed, the toughness of the continuously cast slab is reduced. Further, since the strength of ferrite is lower than that of austenite, pearlite, and bainite, the application of stress may cause a problem that the stress is likely to be concentrated on the grain-boundary ferrite. The inventors have conducted various studies based on such perspectives and have found that even when the microstructure of the continuously cast slab according to this embodiment is a structure of mainly bainite, it is possible to significantly increase the toughness of the continuously cast slab by suppressing the formation of grain-boundary ferrite or by securing a sufficient thickness of ferrite.

[0039] Note that ferrite contains a maximum carbon content of 0.02 mass% and has a structure close to pure iron. Ferrite is a ferromagnetic material from room temperature to 780°C and is the softest of all steel structures, with excellent ductility. Pearlite is a structure formed when austenite is slowly cooled. Pearlite includes ferrite layers and cementite layers and is formed with such layers alternately arranged.

[0040] The precipitation of grain-boundary ferrite is largely influenced by the cooling rate in the ferrite transformation range. When the cooling rate is lower than the critical rate, ferrite is precipitated. Thus, the cooling rate in each of the temperature range of 850°C to 700°C and the temperature range of 700°C to 500°C is controlled to be constant or above, so that the precipitation of grain-boundary ferrite and pearlite was suppressed in each temperature range. Specifically, by increasing the cooling rate in the ferrite-pearlite transformation region, the precipitation of ferrite and pearlite can be suppressed and a continuously cast slab having a microstructure of mainly bainite can be obtained, thereby increasing the toughness of the slab.

[0041] Bainite is a type of transformation structure formed from austenite in carbon steel or alloy steel and is a structure that is excellent in ductility and impact resistance than a structure obtained by ordinary quenching and tempering, thus exhibiting high toughness and high durability. Bainite has black needle-like crystals and exhibits mechanical properties intermediate between martensite and fine pearlite. Meanwhile, martensite is a hard, brittle structure formed when an austenite structure is rapidly cooled.

[0042] Note that cooling that is performed after the continuously cast slab is removed from the continuous casting machine can be controlled by changing conditions, such as the temperature of the slab at the exit side of the continuous casting machine, the time taken to stack a plurality of slabs, the number of slabs to be stacked, the presence or absence of a heat-retention cover, and a water-toughening process, for example. The cooling rate can be measured by a thermocouple. For example, the cooling rate can be measured by disposing a thermocouple at the central portion of the upper surface of a wider face (a longer side) of the slab after the slab is removed from the continuous casting machine.

[0043] The toughness of a continuously cast slab with high C, Si, and Mn contents is significantly low. Therefore, it is impossible to ensure sufficient slab toughness to prevent the occurrence of thermal cracking, simply by performing a control to satisfy any one of the following requirements: (i) an average prior austenite grain size at a position 10 mm from the surface layer of the continuously cast slab is in the range of 0.5 mm to 2.0 mm; (ii) a total of an area ratio of bainite and an area ratio of ferrite in a microstructure of the slab is 90% or more; and (iii) the area ratio of ferrite is 0%, or 3% or more. Thus, thermal cracking would occur in such a slab. Therefore, it is essential that the continuously cast slab for high-strength steel according to this embodiment satisfies the requirements of (i) the average prior austenite grain size and (ii) to (iii) the microstructure at the same time.

[0044] As described above, the invention according to the first embodiment can obtain a high-yield continuously cast slab for high-strength steel that prevents thermal cracking of the slab during a cooling process even if such a slab is a continuously cast slab for high-strength steel of recent years that has extremely low toughness.

[Second embodiment]

[0045] A continuously cast slab according to a second embodiment will be described. The continuously cast slab according to this embodiment corresponds to the continuously cast slab according to the above embodiment that contains, in mass%, C: in the range of 0.10% to 0.40%, Si: in the range of 0.10% to 2.50%, and Mn: in the range of 1.00% to 5.00%.

[0046] Note that in the following description, the symbol "%" representing the content of a constituent element of steel means "mass%" unless otherwise indicated.

<C: in the range of 0.10% to 0.40%>

[0047] The reasons for limiting each chemical composition contained in the continuously cast slab according to this embodiment will be described. Note that the content of each chemical ingredient contained in the continuously cast slab is expressed in mass%. The reasons for setting the C content in the continuously cast slab in the range of 0.10% to 0.40% are as follows. C contained in a continuously cast slab for high-strength steel is the element necessary to increase the strength of a high-strength steel sheet to be formed using the continuously cast slab as a raw material. If the C content is less than

0.10%, the strength required for the high-strength steel sheet cannot be obtained. Therefore, the lower limit of the C content is 0.10%. Meanwhile, if the C content exceeds 0.40%, it is impossible to obtain a microstructure of mainly bainite and ferrite such as the one described above at a cooling rate in the above range for the continuously cast slab, which is unfavorable.

[0048] From such a viewpoint, the C content in the continuously cast slab according to this embodiment preferably falls within the range of 0.10% to 0.40%, more preferably within the range of 0.12% to 0.35%, and further preferably within the range of 0.15% to 0.30%.

<Si: in the range of 0.10% to 2.50%>

[0049] Next, the reasons for setting the Si content in the continuously cast slab for high-strength steel in the range of 0.10% to 2.50% are as follows. Si contained in the continuously cast slab is the element necessary to obtain the residual austenite in the steel sheet in an annealing step for a high-strength steel sheet produced using the continuously cast slab as a raw material. Further, Si contained in the continuously cast slab is the essential additive element as it contributes to increasing the strength of the high-strength steel sheet by solid-solution strengthening. When the Si content is less than 0.10%, the strength required for the high-strength steel sheet cannot be achieved. Therefore, the lower limit of the Si content is 0.10%.

[0050] Meanwhile, when the Si content exceeds 2.50%, the effect of achieving the strength required for the high-strength steel sheet is saturated, and also heavy scale is formed on a hot-rolled sheet that has not yet been processed into a high-strength steel sheet. This deteriorates the appearance and pickling properties of the high-strength steel sheet. Therefore, the upper limit of the Si content is 2.50%.

[0051] From such a perspective, the Si content in the continuously cast slab according to this embodiment is preferably set in the range of 0.10% to 2.50%, more preferably in the range of 0.50% to 2.00%, and further preferably in the range of 1.00% to 1.80%.

<Mn: in the range of 1.00% to 5.00%>

[0052] The Mn content in the continuously cast slab is set in the range of 1.00% to 5.00% , the reason for which is as follows. Mn contained in the continuously cast slab is the element necessary to further increase the strength of the high-strength steel sheet. Specifically, Mn is added to control the strength of the high-strength steel sheet by controlling transformation in the slab during a hot-rolling step for the continuously cast slab. If the Mn content is less than 1.00%, the high-strength steel sheet cannot be sufficiently strengthened. Therefore, the lower limit of the Mn content is 1.00%. Meanwhile, if the Mn content exceeds 5.00%, the degree to which the high-strength steel sheet is sufficiently strengthened is saturated, and the production cost for the high-strength steel sheet increases, which is unfavorable from an economic viewpoint.

[0053] From such a viewpoint, the Mn content in the continuously cast slab according to this embodiment is preferably set in the range of 1.00% to 5.00%, more preferably in the range of 1.50% to 4.50%, and further preferably in the range of 1.80% to 4.00%.

[0054] The continuously cast slab according to this embodiment has the above ingredient composition with the balance consisting of Fe and unavoidable impurities, an appropriate average prior austenite grain size and a microstructure. Provided that the above conditions are satisfied, the continuously cast slab may also contain, 0.100% or less P, 0.0200% or less S, 0.0100% or less N, 0.100% or less Al, and 0.0100% or less O, when other properties are taken into consideration. Examples of the unavoidable impurities include Zn, Pb, and As. Such unavoidable impurities can be included when the total content is 0.100% or less.

[0055] P is segregated at prior austenite grain boundaries and therefore may cause the embrittlement of the grain boundaries, resulting in thermal cracking in the slab in some case. Therefore, the P content is preferably set to 0.100% or less. Note that the lower limit of the P content is not specified. However, since P is a solid solution strengthening element and thus increases the strength of the steel sheet, the P content is preferably set to 0.001% or more. Thus, the P content is preferably set to 0.100% or less. It is preferably 0.001% or more. It is more preferably 0.070% or less.

[0056] S is present as sulfide and causes the embrittlement of the slab. Thus, the S content is preferably set to 0.0200% or less. Note that the lower limit of the S content is not specified. However, the S content is preferably set to 0.0001% or more due to the restrictions of the production technology. Thus, the S content is preferably set to 0.0200% or less. It is preferably 0.0001% or more, and more preferably 0.0050% or less.

[0057] Al affects the fraction of the residual austenite in the slab by suppressing the formation of carbide and promoting the formation of the residual austenite while the slab is cooled. Al is preferably added by 0.005% or more for deoxidation. If the Al content exceeds 0.100%, the slab may become brittle. Therefore, the Al content is preferably set to 0.100% or less. It is more preferably 0.010% or more, further preferably 0.080% or less.

[0058] N is present as nitride and causes the embrittlement of the slab. Therefore, the N content is preferably set to

0.0100% or less. Note that the lower limit of the N content is not specified. However, the N content is preferably set to 0.0001% or more due to the restrictions of the production technology. Thus, the N content is preferably set to 0.0100% or less. It is preferably 0.0001% or more. It is more preferably 0.0050% or less.

[0059] O is present as oxide and causes the embrittlement of the slab. Therefore, the O content is preferably set to 0.0100% or less. Note that the lower limit of the O content is not specified. However, the O content is preferably set to 0.0001% or more due to the restrictions of the production technology. Thus, the O content is preferably set to 0.0100% or less. It is preferably 0.0001% or more. It is more preferably 0.0050% or less.

[0060] The continuously cast slab according to this embodiment may further contain, for a high-strength steel sheet, at least one element selected from the group consisting of Ti: 0.200% or less, Nb: 0.200% or less, V: 0.200% or less, Ta: 0.10% or less, W: 0.10% or less, Cr: 2.00% or less, Mo: 2.00% or less, Ni: 2.00% or less, Cu: 2.00% or less, and B: 0.0100% or less, either alone or in combination in addition to the above ingredient composition.

[0061] Ti, Nb, and V each do not produce coarse precipitates or inclusions in large amounts and thus do not reduce the toughness of the slab when the content of each element is 0.200% or less. Therefore, the content of each of Ti, Nb, and V is preferably set to 0.200% or less. Note that the lower limit of the content of each of Ti, Nb, and V is not specified. However, since Ti, Nb, and V form fine carbide, nitride, or carbonitride during hot rolling or continuous annealing of the continuously cast slab to thus increase the strength of the steel sheet, the content of each element is preferably set to 0.001% or more. When Ti, Nb, and V are contained, the content of each element is set to 0.200% or less. It is more preferably 0.001% or more. It is further preferably 0.100% or less.

[0062] Ta and W each do not produce coarse precipitates or inclusions in large amounts and thus do not reduce the toughness of the slab when the content of each element is 0.10% or less. Therefore, the content of each of Ta and W is preferably set to 0.10% or less. Note that the lower limit of the content of each of Ta and W is not specified. However, since each of Ta and W forms fine carbide, nitride, or carbonitride during hot rolling or continuous annealing of the continuously cast slab to thus increase the strength of the steel sheet, the content of each element is preferably 0.01% or more. Thus, when Ta and W are contained, the content of each element is preferably 0.10% or less. It is more preferably 0.01% or more. It is further preferably 0.08% or less.

[0063] The continuously cast slab according to this embodiment may also contain at least one element selected from the group consisting of Cr, Mo, Ni, and Cu, as appropriate within the range that the object of the present invention can be achieved. Each of Cr, Mo, Ni, and Cu has the effect of increasing the strength of the steel sheet by controlling the structure of the continuously cast slab in hot rolling. This effect becomes remarkable when one or more selected from Cr, Mo, Ni, and Cu are added to reach 0.01% or more each. Therefore, at least one is preferably added to reach 0.01% or more. Meanwhile, if each element is added to exceed the upper limit, the weldability, hot workability, and so on of the steel sheet are deteriorated. Therefore, the upper limit of the content of each of Cr, Mo, Ni, and Cu is set to 1.00%. Thus, when the continuously cast slab contains Cr, Mo, Ni, and Cu, the content of each element is set to 1.00% or less. It is preferably 0.01% or more. It is more preferably 0.80% or less.

[0064] B may be added because it controls the structure transformation of the continuously cast slab during hot rolling and annealing and thus affects the strength through structural strengthening. B does not affect the toughness of the slab when the B content is 0.0100% or less. Therefore, it is preferable to set the B content to 0.0100% or less. Note that the lower limit of the B content is not specified. However, the B content is preferably set to 0.0003% or more because B is segregated at austenite grain boundaries during hot rolling and annealing of the continuously cast slab and thus increases hardenability. Thus, when B is contained, the B content is set to 0.0100% or less. It is more preferably 0.0003% or more. It is further preferably 0.0080% or less.

[0065] Co does not increase coarse precipitates or inclusions and thus does not reduce the toughness of the slab when the Co content is 1.00% or less. Therefore, it is preferable to set the Co content to 1.00% or less. Note that the lower limit of the Co content is not specified. However, it is preferable to set the Co content to 0.001% or more because Co increases hardenability. Thus, when Co is contained, the Co content is set to 1.00% or less. It is more preferably 0.001% or more. It is further preferably 0.80% or less.

[0066] Cu does not increase coarse precipitates or inclusions and thus does not reduce the toughness of the slab when the Cu content is 1.00% or less. Therefore, it is preferable to set the Cu content to 1.00% or less. Note that the lower limit of the Cu content is not specified. However, the Cu content is preferably set to 0.01% or more because Cu increases hardenability. Thus, when Cu is contained, the Cu content is set to 1.00% or less. It is more preferably 0.01% or more. It is further preferably 0.80% or less.

[0067] Sn does not affect the toughness of the slab when the Sn content is 0.200% or less. Therefore, it is preferable to set the Sn content to 0.200% or less. Note that the lower limit of the Sn content is not specified. However, the Sn content is preferably set to 0.001% or more because Sn increases hardenability. Thus, when Sn is contained, the Sn content is set to 0.200% or less. It is more preferably 0.001% or more. It is further preferably 0.100% or less.

[0068] Sb does not increase coarse precipitates or inclusions and thus does not reduce the toughness of the slab when the Sb content is 0.200% or less. Therefore, it is preferable to set the Sb content to 0.200% or less. Note that the lower limit of the Sb content is not specified. However, the Sb content is preferably set to 0.001% or more because Sb suppresses

decarburization and allows the strength of the steel sheet to be adjusted. Thus, when Sb is contained, the Sb content is set to 0.200% or less. It is more preferably 0.001% or more. It is further preferably 0.100% or less.

[0069] Ca, Mg, and REM each do not increase coarse precipitates or inclusions and thus do not reduce the toughness of the slab when the content of each element is 0.0100% or less. Therefore, it is preferable to set the content of each of Ca, Mg, and REM to 0.0100% or less. Note that the lower limit of the content of each of Ca, Mg, and REM is not specified. However, the content of each of Ca, Mg, and REM is preferably set to 0.0005% or more because these elements make the forms of nitride and sulfide spherical and increase the toughness of the slab. Therefore, when Ca, Mg, and REM are contained, the content of each element is set to 0.0100% or less. It is more preferably 0.0005% or more. It is further preferably 0.0050% or less.

[0070] Zr and Te each do not increase coarse precipitates and inclusions and thus do not reduce the toughness of the slab when the content of each element is 0.100% or less. Therefore, it is preferable to set the content of each of Zr and Te to 0.100% or less. Note that the lower limit of the content of each of Zr and Te is not specified. However, the content of each of Zr and Te is preferably set to 0.001% or more because these elements make the forms of nitride and sulfide spherical and increase the toughness of the slab. Thus, when Zr and Te are contained, the content of each element is set to 0.100% or less. It is more preferably 0.001% or more. It is further preferably 0.080% or less.

[0071] Hf does not increase coarse precipitates or inclusions and thus does not reduce the toughness of the slab when the Hf content is 0.10% or less. Therefore, it is preferable to set the Hf content to 0.10% or less. Note that the lower limit of the Hf content is not specified. However, the Hf content is preferably set to 0.01% or more because Hf makes the shapes of nitride and sulfide spherical and improves the ultimate deformability of the steel sheet. Thus, when Hf is contained, the Hf content is set to 0.10% or less. It is more preferably 0.01% or more. It is further preferably 0.08% or less.

[0072] Bi does not increase coarse precipitates or inclusions and thus does not reduce the toughness of the slab when the Bi content is 0.200% or less. Therefore, it is preferable to set the Bi content to 0.200% or less. Note that the lower limit of the Bi content is not specified. However, the Bi content is preferably set to 0.001% or more because Bi reduces segregation. Thus, when Bi is contained, the Bi content is set to 0.200% or less. It is more preferably 0.001% or more. It is further preferably 0.100% or less.

[0073] It should be noted that the elements Ti, Nb, V, Ta, W, B, Cr, Mo, Ni, Co, Cu, Sn, Sb, Ca, Mg, REM, Zr, Te, Hf, and Bi described above may be included as unavoidable impurities, because each element does not impair the advantageous effects of the present invention, when the content of each element is less than its preferred lower limit.

[0074] As described above, the invention according to the second embodiment can achieve the strength required for high-strength steel sheet and can further obtain a continuously cast slab that is excellent in the weldability, workability, and appearance of high-strength steel sheet.

[Third embodiment]

[0075] A method for producing a continuously cast slab according to a third embodiment will be described. The method for producing a continuously cast slab according to this embodiment is a method for producing a continuously cast slab for high-strength steel in which slab thermal cracking due to cooling is suppressed, and includes subjecting a continuously cast slab having the ingredient composition of the continuously cast slab described in the above embodiments to the following:

a first cooling step of cooling the continuously cast slab under a cooling condition that a retention time while a cooling temperature of a center of the wide face at a position 10 mm from a surface layer of the continuously cast slab is in a range of 1200°C to 1450°C is 130 seconds or less;

a second cooling step of cooling the continuously cast slab under a cooling condition that the average cooling rate while the surface temperature at the center of the wide face of the continuously cast slab is in the range of 700°C to 850°C is 25°C/hr or more but 40°C/hr or less, or 50°C/hr or more; and

a third cooling step of cooling the continuously cast slab under a cooling condition that the average cooling rate while the surface temperature at the center of the wide face of the continuously cast slab is in the range of 500°C to 700°C is 15°C/hr or more.

[0076] Herein, the upper limit of each average cooling rate in the second cooling step and the third cooling step is not limited to a particular value. However, the average cooling rates in the temperature range of 700°C to 850°C and in the temperature range of 500°C to 700°C when a single slab is naturally cooled in the atmosphere are at maximum 120°C/hr and 70°C/hr, respectively. If cooling is performed at an average cooling rate higher than such an average cooling rate in each of the second cooling step and the third cooling step, it becomes necessary to spray water onto the slab or blow air onto the slab, for example, which requires a facility for that purpose, and therefore is unfavorable from an economic perspective. Therefore, it is preferable to set the upper limit of the average cooling rate in the temperature range from 700°C to 850°C in the second cooling step to 120°C/hr, and set the upper limit of the average cooling rate in the

temperature range from 500°C to 700°C in the third cooling step to 70°C/hr.

[0077] Note that the method for producing a slab for a high-strength steel sheet according to this embodiment may require re-stacking, depending on various conditions of the production steps. When re-stacking is performed, the cooling rate for the slab may temporarily exceed a predetermined cooling rate. However, since the time required for transformation is as long as 10 hours or more, thermal cracking is not caused by such a handling time of the degree (1 to 2 hours at the longest) required for re-stacking. Therefore, in the present invention, the average cooling rate is defined as a cooling condition instead of the maximum cooling rate.

[0078] Hereinafter, each step included in the method for producing a continuously cast slab according to this embodiment will be described.

(First cooling step)

[0079] The method for producing a continuously cast slab according to this embodiment is a method for producing a continuously cast slab for high-strength steel in which thermal cracking due to cooling is suppressed, and includes a first cooling step of cooling a continuously cast slab having the ingredient composition of the continuously cast slab described in the above embodiments under a cooling condition that a retention time while a cooling temperature of a center of the wide face at a position 10 mm from a surface layer of the continuously cast slab is in a range of 1200°C to 1450°C is 130 seconds or less.

[0080] The first cooling step is a step for controlling the average prior austenite grain size contained in the continuously cast slab according to the above embodiments to be 2.0 mm or less at a predetermined position. In the method for producing a continuously cast slab according to this embodiment, the temperature at which the slab is cooled is a factor that determines the average prior austenite grain size. In the first cooling step, the temperature for cooling the continuously cast slab is in the range from 1450°C to 1200°C. Thus, the method for producing a continuously cast slab according to this embodiment focuses on the cooling temperature of the continuously cast slab in the range of 1450°C to 1200°C, which is a factor that determines the average prior austenite grain size, and thus controls the temperature.

[0081] In the first cooling step, further, the retention time while the continuously cast slab is cooled in the above temperature range is 130 seconds or less. When the retention time of the continuously cast slab in the temperature range is 130 seconds or less, it is possible to control the average prior austenite grain size to be 2.0 mm or less, and thus suppress the occurrence of thermal cracking in the slab, which is preferable. Note that the lower limit of the retention time while the continuously cast slab is retained in the temperature range of 1200°C to 1450°C is not specified. However, if the retention time is too short, there is an increased risk of breakout due to uneven solidification during the continuous casting process. Thus, the retention time is preferably 40 seconds or more, more preferably 60 seconds or more, and further preferably 70 seconds or more.

(Second cooling step)

[0082] The method for producing a continuously cast slab according to this embodiment includes a second cooling step of cooling the continuously cast slab under a cooling condition that the average cooling rate while the surface temperature at the center of the wide face of the continuously cast slab is in the range of 700°C to 850°C is between 25°C/hr and 40°C/hr or 50°C/hr or more. The second cooling step is a step conducted to control the precipitation of grain-boundary ferrite contained in the microstructure of the continuously cast slab according to the above embodiments and to obtain a microstructure of mainly bainite.

[0083] In the second cooling step, the temperature for further cooling the continuously cast slab is in the range of 700°C to 850°C. Thus, the method for producing a continuously cast slab according to this embodiment focuses on the cooling rate in the temperature range of the ferrite transformation range that can control the precipitation of ferrite, and thus controls the temperature.

[0084] In the second cooling step, the average cooling rate for cooling the continuously cast slab in the above temperature range for cooling the continuously cast slab is between 25°C/hr and 40°C/hr or 50°C/hr or more. When the average cooling rate is less than 25°C/hr, ferrite is formed, and then residual austenite is formed in which a solute such as carbon is concentrated in an excessive amount above the solid solubility limit of the ferrite, followed by a large amount of pearlite being precipitated from the residual austenite, which is unfavorable. Meanwhile, when the average cooling rate for the continuously cast slab is more than 40°C/hr but less than 50°C/hr, thin ferrite is precipitated only on the prior austenite grain boundaries depending on the steel ingredient or average prior austenite grain size, causing the embrittlement of the grain boundaries, which is unfavorable.

[0085] From such a viewpoint, the average cooling rate for the continuously cast slab is preferably between 25°C/hr and 40°C/hr, or 50°C/hr or more because such an average cooling rate can optimize the amount of ferrite to be precipitated and suppress the precipitation of pearlite, and thus can suppress the occurrence of thermal cracking in the slab.

[0086] Note that the upper limit of the average cooling rate is not limited to a particular value. However, the average

cooling rate in the temperature range of 700°C to 850°C when a single continuously cast slab is naturally cooled in the atmosphere is 120°C/hr at maximum. If cooling is performed at an average cooling rate higher than such an average cooling rate, it becomes necessary to spray water onto the continuously cast slab or blow air onto the continuously cast slab, for example, which requires a facility for that purpose, and thus is unfavorable from an economic point of view. Therefore, it is preferable to set the upper limit of the average cooling rate in the temperature range of 700°C to 850°C to 120°C/hr.

(Third cooling step)

[0087] The method for producing a continuously cast slab according to this embodiment further includes a third cooling step of cooling the continuously cast slab under a cooling condition that the average cooling rate while the surface temperature of the center of the wide face of the continuously cast slab is in the range of 500°C to 700°C is 15°C/hr or more.

[0088] The third cooling step is a step performed to further suppress the precipitation of pearlite contained in the microstructure of the continuously cast slab according to the above embodiments and form the microstructure mainly of bainite. Specifically, the third cooling step is performed so that the area ratio (%), which is the ratio of the area $S_{(\text{bainite}+\text{ferrite})}$, which is the sum of the area S_{bainite} of bainite and the area S_{ferrite} of ferrite, to the area S_{total} of the microstructure of the continuously cast slab is set to 90% or more.

[0089] In the third cooling step, the temperature for further cooling the continuously cast slab ranges from 500°C to 700°C. Thus, the method for producing a continuously cast slab according to this embodiment focuses on the cooling rate in the temperature range of the pearlite transformation range capable of suppressing the precipitation of pearlite and thus controls the temperature.

[0090] In the third cooling step, the average cooling rate for the continuously cast slab in the above range of the temperature for cooling the continuously cast slab is 15°C/hr or more. If the average cooling rate for the continuously cast slab is less than 15°C/hr, pearlite is precipitated on the structure of mainly bainite. Since the transformation temperature of pearlite is higher than that of bainite, transformation stress is applied to the pearlite portion that has precipitated earlier. Further, since the strength of pearlite is simply lower than that of bainite, strains are concentrated on pearlite due to the difference in strength between pearlite and bainite, promoting cracking.

[0091] From such a viewpoint, the average cooling rate for the continuously cast slab is preferably 15°C/hr or more because such an average cooling rate can avoid the precipitation of a large amount of pearlite and thus suppress the occurrence of thermal cracking in the slab.

[0092] Note that the upper limit of the average cooling rate is not limited to a particular value. However, the average cooling rate in the temperature range of 500°C to 700°C when a single continuously cast slab is naturally cooled in the atmosphere is 70°C/hr at maximum. If cooling is performed at an average cooling rate higher than such an average cooling rate, it becomes necessary to spray water onto the slab or blow air onto the slab, for example, which requires a facility for that purpose, and thus is unfavorable from an economic perspective. Therefore, it is preferable to set the upper limit of the average cooling rate in the temperature range of 500°C to 700°C to 70°C/hr.

[0093] As described above, the method for producing a continuously cast slab according to this embodiment adopts a three-stage cooling step as a cooling step for the continuously cast slab to precisely control the average prior austenite grain size and the microstructure of the continuously cast slab. This makes it possible to provide a continuously cast slab for high-strength steel that can suppress thermal cracking due to cooling.

[0094] As described above, the method for producing a continuously cast slab according to the third embodiment can provide a continuously cast slab for high-strength steel that can suppress thermal cracking during a cooling process by dividing a cooling step into three stages and precisely controlling each cooling step, even if such a slab contains ingredient composition of a continuously cast slab for high-strength steel.

[Other embodiments]

[0095] The invention of the present application has been described with reference to the above embodiments. However, the invention of the present application is not limited thereto. The configuration and details of the invention of the present application may be modified in various ways that can be understood by those skilled in the art, within the technical scope of the invention of the present application. Further, a system or apparatus that includes any combination of the features included in the respective embodiments is encompassed within the technical scope of the present invention.

Examples

[0096] Hereinafter, the advantageous effects of the present invention will be specifically described based on examples. However, the present invention is not limited to such examples. That is, to confirm the advantageous effects of the present invention, the inventors produced a continuously cast slab by using each steel grade as a raw material for each of

Comparative Examples (Test Nos. A-1 to A-4, Test Nos. B-1 to B-8, and Test Nos. C-1 to C-3) and Invention Examples (Test Nos. D-1 to D-20). Table 1 shows steel grades A to F of steel that are the raw materials for the continuously cast slabs used for the Comparative Examples (Test Nos. A-1 to A-4, Test Nos. B-1 to B-8, and Test Nos. C-1 to C-3), and for the examples of the invention (Test Nos. D-1 to D-20).

[Table 1]

Steel Type	C [Mass%]	Si [Mass%]	Mn [Mass%]	P [Mass%]	S [Mass%]	Sol. Al [Mass%]	N [Mass%]	Ti [Mass%]
A	0.11	1.87	2.92	0.011	0.0011	0.052	0.0043	-
B	0.15	0.47	4.98	0.009	0.0015	0.048	0.0039	-
C	0.16	0.70	1.53	0.008	0.0015	0.047	0.0032	-
D	0.18	1.36	2.68	0.007	0.0021	0.048	0.0034	0.02
E	0.25	1.12	3.22	0.007	0.0013	0.050	0.0036	-
F	0.40	0.42	1.57	0.010	0.0008	0.043	0.0030	-

[0097] Herein, each continuously cast slab was cooled by adopting a three-stage cooling step including the following cooling conditions: (I) the retention time [s] in the temperature range of 1200°C to 1450°C, (II) the average cooling rate [°C/hr] in the temperature range of 700°C to 850°C, and (III) the average cooling rate [°C/hr] in the temperature range of 500°C to 700°C, and appropriately changing the condition of each stage.

[0098] Tables 2 to 4 show the cooling conditions (I) to (III) for the continuously cast slabs, the obtained microstructures of the continuously cast slabs, and the evaluation of whether thermal cracking has occurred in the slabs. In Tables 2 to 4, the symbols F, P, and B in the field of the microstructure respectively represent ferrite, pearlite, and bainite, respectively.

[0099] For each of the continuously cast slabs produced in the Comparative Examples and the Invention Examples, the average prior austenite grain size, the calculation of the area ratios of bainite, pearlite, and ferrite, and the evaluation of whether thermal cracking occurred in the continuously cast slabs were performed as follows.

<Measurement of average prior austenite grain size>

[0100] The average prior austenite grain size was measured as follows. A sample was cut out from the position of the center of the wide face of the slab subjected to cooling such that a slab thickness cross section parallel to the width direction of the slab was used as observed face. The observation face was then subjected to mirror polishing with diamond paste, followed by finish polishing with colloidal silica, and was further etched with 3 vol.% Nital to expose the structure on the observation face. The sample was then observed at a position 10 mm from the surface layer of the slab at 10x magnification for five visual fields, using an optical microscope to obtain microstructure images of the continuously cast slab. From the microstructure images for the five visual fields obtained through the observation, the grain sizes of prior austenite were determined by a cutting method according to JIS G 0551:2020. The average value of the grain sizes was then calculated as the average prior austenite grain size.

<Method of measuring area ratio of ferrite>

[0101] For a method of measuring the area ratio of ferrite, an observation face of each slab was prepared as in the above method of measuring the average prior austenite grain size. The observation face was then subjected to mirror polishing with diamond paste, followed by finish polishing with colloidal silica and was further etched with 3 vol.% Nital to expose the structure. Then, the sample was observed at a position 10 mm from the surface layer of the slab at 50x magnification for 10 visual fields, using a SEM (Scanning Electron Microscope) under an accelerating voltage condition of 15 kV. From the obtained microstructure images of the continuously cast slab, the area ratios of ferrite were calculated for the 10 visual fields using PHOTOSHOP (registered trademark) of Adobe Inc. Then, the average of the obtained values was determined as the area ratio of ferrite. Note that ferrite has a larger grain size, a smoother surface, and lower contrast than other structures (i.e., pearlite, bainite, tempered martensite, quenched martensite, and residual austenite), and thus can be easily distinguished at 50x magnification.

<Method of measuring area ratios of pearlite and bainite>

[0102] A method of measuring the area ratios of the pearlite structure and bainite structure involves exposing the

structure on the observation face of each slab as in the above method of measuring the area ratio of ferrite. Then, the slab was observed at a position 10 mm from the surface layer of the slab at 10000x magnification for 10 visual fields, using the SEM under an accelerating voltage condition of 15 kV while ferrite was excluded from the visual fields. From the obtained microstructure images of the continuously cast slab, the area ratios of pearlite and the area ratios of bainite were calculated for the 10 visual fields using PHOTOSHOP (registered trademark) of Adobe Inc. Then, the average of the obtained values was determined as the area ratio of each structure through calculation such that the total area ratio including the area ratio of each structure and the area ratio of ferrite measured with the above method reached 100%. Bainite is a structure of a recessed portion, and pearlite is a structure of a recessed portion that contains lamellar carbide.

[0103] The overall evaluation of the microstructures was conducted. The evaluation criteria are as follows.

- Evaluation of microstructure: Good ... The total area ratio (%) of bainite and ferrite, which is the ratio of $S_{(\text{bainite}+\text{ferrite})}$ to S_{total} , is 90% or more, and the area ratio (%) of ferrite, which is the ratio of $S_{(\text{ferrite})}$ to S_{total} , is 0%, or 3% or more.
- Evaluation of microstructure: Poor ... The total area ratio (%) of bainite and ferrite, which is the ratio of $S_{(\text{bainite}+\text{ferrite})}$ to S_{total} , is less than 90%, or the area ratio (%) of ferrite, which is the ratio of $S_{(\text{ferrite})}$ to S_{total} , is more than 0% but less than 3%.

<Evaluation of thermal cracking in slab>

[0104] As a method for evaluating thermal cracking in each slab, a test based on the penetrant test defined in JIS Z 2343:2017 was conducted to evaluate the presence or absence of a crack in the wide faces and narrow faces of the slab. After a developing solution was applied to each slab, an ooze of a penetrant was visually observed to visually check thermal cracks and flaws in the surface of the slab.

[0105] Note that slab cracks or flaws with a length of 10 mm or less in the slab do not cause the generation of holes during heating in a hot-rolling step, openings, or fractures. Thus, the criteria for evaluating whether thermal cracking had occurred in each slab were determined as follows.

- Thermal cracking in slab: Absent ... A slab with a surface in which neither a crack with a length of 10 mm or more nor a flaw with a length of 10 mm or more was visually seen
- Thermal cracking in slab: Present ... A slab with a surface in which a crack with a length of 10 mm or more or a flaw with a length of 10 mm or more was visually seen

[Table 2]

Test No.	Steel Type	Average Prior Austenite Grain Size [mm]	Microstructure	Ferrite Area Ratio [%]	Pearlite Area Ratio [%]	Bainite Area Ratio [%]	Evaluation of Structure	Retention time[s] from 1450 to 1200°C	Average Cooling Rate [°C /hr] from 850 to 700°C	Average Cooling Rate [°C /hr] from 700 to 500°C	Thermal Crack	Remarks
A-1	D	2.8	Grain Bound-ary F+P+B	9	80	11	Poor	150	27	16	Present	Comparative Example
A-2	D	3.0	F+P+B	16	77	7	Poor	170	20	15	Present	Comparative Example
A-3	D	2.5	F+P+B	10	72	18	Poor	160	28	5	Present	Comparative Example
A-4	D	2.2	F+P	13	87	0	Poor	140	19	7	Present	Comparative Example
A-5	D	2.4	Grain Bound-ary F+B	7	8	85	Good	155	33	24	Present	Comparative Example
B-1	D	1.2	Grain Bound-ary F+P+B	8	28	64	Poor	90	22	16	Present	Comparative Example
B-2	D	2.0	Grain Bound-ary F+P+B	8	46	46	Poor	130	21	15	Present	Comparative Example
B-3	D	1.5	Grain Bound-ary F+P+B	6	13	81	Poor	115	24	20	Present	Comparative Example
B-4	D	1.1	Grain Bound-ary F+P	2	88	10	Poor	98	41	7	Present	Comparative Example
B-5	D	1.2	Grain Bound-ary F+P+B	7	22	71	Poor	105	24	20	Present	Comparative Example
B-6	D	1.7	F+P+B	13	63	24	Poor	118	25	12	Present	Comparative Example
B-7	D	1.6	Grain Bound-ary F+P+B	9	81	10	Poor	128	27	9	Present	Comparative Example
B-8	D	1.5	Grain Bound-ary F+P	9	87	4	Poor	110	25	5	Present	Comparative Example

(continued)

Test No.	Steel Type	Average Prior Austenite Grain Size [mm]	Microstructure	Ferrite Area Ratio [%]	Pearlite Area Ratio [%]	Bainite Area Ratio [%]	Evaluation of Structure	Retention time[s] from 1450 to 1200°C	Average Cooling Rate [°C /hr] from 850 to 700°C	Average Cooling Rate [°C /hr] from 700 to 500°C	Thermal Crack	Remarks
C-1	D	1.5	Grain Bound-ary F+B	2	5	93	Good	109	43	19	Absent	Comparative Example
C-2	D	1.5	Grain Bound-ary F+B	1	3	96	Good	114	41	24	Absent	Comparative Example
C-3	D	1.7	Grain Bound-ary F+B	1	0	99	Good	127	49	27	Absent	Comparative Example

[Table 3]

Test No.	Steel Type	Average Prior Austenite Grain Size [mm]	Microstructure	Ferrite Area Ratio [%]	Pearlite Area Ratio [%]	Bainite Area Ratio [%]	Evaluation of Structure	Retention time[s] from 1450 to 1200°C	Average Cooling Rate [°C/hr] from 850 to 700°C	Average Cooling Rate [°C/hr] from 700 to 500°C	Thermal Crack	Remarks
D-1	D	1.3	B	0	3	97	Good	92	51	18	Absent	Invention Example
D-2	D	1.7	Grain Boundary F+B	3	0	97	Good	108	36	17	Absent	Invention Example
D-3	D	1.5	Grain Boundary F+B	8	0	92	Good	105	27	16	Absent	Invention Example
D-4	D	1.7	B	0	4	96	Good	125	53	23	Absent	Invention Example
D-5	D	1.4	B	0	0	100	Good	85	57	26	Absent	Invention Example
D-6	D	0.8	Grain Boundary F+B	3	7	90	Good	66	25	18	Absent	Invention Example
D-7	D	1.2	B	0	0	100	Good	82	105	65	Absent	Invention Example
D-8	A	1.9	F+B	12	0	88	Good	118	26	15	Absent	Invention Example
D-9	A	2.0	Grain Boundary F+B	7	2	91	Good	130	27	16	Absent	Invention Example
D-10	B	1.6	B	0	0	100	Good	120	30	16	Absent	Invention Example
D-11	B	1.8	Grain Boundary F+B	4	0	96	Good	118	31	18	Absent	Invention Example
D-12	B	1.4	B	0	0	100	Good	100	39	24	Absent	Invention Example
D-13	C	1.9	F+B	42	7	51	Good	122	52	29	Absent	Invention Example

(continued)

Test No.	Steel Type	Average Prior Austenite Grain Size [mm]	Microstructure	Ferrite Area Ratio [%]	Pearlite Area Ratio [%]	Bainite Area Ratio [%]	Evaluation of Structure	Retention time[s] from 1450 to 1200°C	Average Cooling Rate [°C/hr] from 850 to 700°C	Average Cooling Rate [°C/hr] from 700 to 500°C	Thermal Crack	Remarks
D-14	C	1.2	F+B	32	0	68	Good	85	37	24	Absent	Invention Example
D-15	C	1.0	F+B	28	0	72	Good	72	31	20	Absent	Invention Example
D-16	E	1.6	B	0	0	100	Good	109	40	21	Absent	Invention Example
D-17	E	1.5	Grain Boundary F+B	4	0	96	Good	95	33	15	Absent	Invention Example

[Table 4]

Test No.	Steel Type	Average Prior Austenite Grain Size [mm]	Microstructure	Ferrite Area Ratio [%]	Pearlite Area Ratio [%]	Bainite Area Ratio [%]	Evaluation of Structure	Retention time[s] from 1450 to 1200°C	Average Cooling Rate [°C/hr] from 850 to 700°C	Average Cooling Rate [°C/hr] from 700 to 500°C	Thermal Crack	Remarks
D-18	E	1.1	B	0	0	100	Good	80	52	31	Absent	Invention Example
D-19	F	1.5	F+B	13	7	80	Good	107	60	39	Absent	Invention Example
D-20	F	1.7	F+B	10	5	85	Good	109	72	41	Absent	Invention Example

<Comparative Examples (Test Nos. A-1 to A-5)>

[0106] A slab microstructural structure satisfied by the continuously cast slabs produced in Test Nos. A-1 to A-5 is regarded as Condition A. In the Condition A, the average prior austenite grain size at a position 10 mm from the surface layer of the slab in the thickness direction was more than 2.0 mm. In such cases, the toughness of prior austenite grain boundaries was reduced due to an increase in the density of precipitates at the prior austenite grain boundaries. As a result, thermal cracking in the slab could not be suppressed even though the slow cooling conditions for the slab after removal from the continuous casting machine were varied.

<Comparative Examples (Test Nos. B-1 to B-8)>

[0107] A slab microstructural structure satisfied by each of the continuously cast slabs produced as Test Nos. B-1 to B-8 is regarded as a Condition B. The Condition B is of an example that the average prior austenite grain size at a position 10 mm from the surface layer of the slab was 2.0 mm or less, while 10% or more pearlite was precipitated, thus not suppressing the occurrence of thermal cracking in the slab.

<Comparative Examples (Test Nos. C-1 to C-3)>

[0108] A slab microstructural structure satisfied by the continuously cast slabs produced in Test Nos. C-1 to C-3 is regarded as a Condition C. The Condition C is of an example that the average prior austenite grain size was 2.0 mm or less at the position 10mm from the surface layer of the slab and the area ratio of bainite and ferrite is 90% or more, while the area ratio of ferrite was 1% or 2% and thin ferrite was precipitated at the grain boundaries, thus not suppressing the occurrence of cracks in the slab.

<Invention Examples (Test Nos. D-1 to D-20)>

[0109] A slab microstructural structure satisfied by the continuously cast slabs produced in Test Nos. D-1 to D-20 is regarded as a Condition D. The Condition D is the condition of the invention examples of the present invention. Each of the continuously cast slabs produced in the examples of the present invention had an average prior austenite grain size within the range of 0.5 mm to 2.0 mm at a position 10 mm from the surface layer of the slab and a microstructure of a bainite phase alone or a structure of bainite + ferrite. That is, thermal cracking did not occur in the slab after slab cooling by increasing the toughness of the slab in terms of reducing the prior austenite grain size and optimizing the microstructure.

[0110] Tables 2 to 4 show that it is possible to suppress the occurrence of thermal cracking in each slab during cooling by satisfying the following conditions: the average prior austenite grain size at a position 10 mm from the surface layer of the slab in the thickness direction is 2.0 mm or less; and the total of the area ratio of bainite and the area ratio of ferrite is 90% or more in the microstructure of the continuously cast slab, and the area ratio of ferrite is 0%, or 3% or more.

[0111] Fig. 3 is a magnified micrograph of the continuously cast slab produced in the Invention Example (Test No. D-2) of the continuously cast slab, observed with an optical microscope. A metallographic structure contained in the continuously cast slab was identified based on the enlarged photograph of the continuously cast slab observed with the optical microscope shown in Fig. 3. Then, the ratio of the area $S_{(\text{bainite}+\text{ferrite})}$, which is the sum of the area S_{bainite} of bainite and the area S_{ferrite} of ferrite, to the area S_{total} of the microstructure of the continuously cast slab was calculated as the area ratio (%). Consequently, it was found that in the continuously cast slab of the example of the present invention, the average prior austenite grain size at a position 10 mm from the surface layer of the slab in the thickness direction is in the range of 0.5 mm to 2.0 mm and that the total of the area ratio of bainite and the area ratio of ferrite is 90% or more in the microstructure of the slab, and the area ratio of ferrite is 0%, or 3% or more.

[0112] As described above, the continuously cast slab of the present invention has features such that the average prior austenite grain size at a position 10 mm from the surface layer of the slab is in the range of 0.5 mm to 2.0 mm, the total of the area ratio of bainite and the area ratio of ferrite in the microstructure of the slab is 90% or more, and the area ratio of ferrite is 0%, or 3% or more. Thus, it is possible to provide a slab for high-alloy, high-strength steel that is unlikely to cause thermal cracking after casting, and avoid the occurrence of problems such as the formation of holes during rolling. That is, according to the Invention Examples and Comparative Examples, it was found to be possible to suppress the occurrence of thermal cracking in a slab during cooling by satisfying the following conditions that the average prior austenite grain size of the slab at a position 10 mm from the surface layer in the thickness direction is in the range of 0.5 mm to 2.0 mm, the total area ratio of bainite and ferrite in the microstructure of the slab is 90% or more, and the area ratio of ferrite is 0%, or 3% or more.

[0113] To obtain such a microstructure of the slab for a high-strength steel sheet, it is preferable to adopt, for example, three-stage cooling that includes cooling the slab to attain a slab surface temperature in the range of 1450°C to 1200°C within a retention time of 130 seconds, and then cooling the slab at a cooling rate of 25°C/hr to 40°C/hr, or 50°C/hr or more

when the surface temperature of the center of the wide face of the slab is in the range of 850°C to 700°C, and further cooling the slab at an average cooling rate of 15°C/hr or more when the surface temperature of the center of the wide face of the slab is in the range of 700°C to 500°C. Note that the method for producing a continuously cast slab that has the microstructure of a slab for a high-strength steel sheet is not limited thereto.

Industrial Applicability

[0114] The continuously cast slab of the present invention has features such that the average prior austenite grain size at a position 10 mm from the surface layer of the slab is in the range of 0.5 mm to 2.0 mm, the total of the area ratio of bainite and the area ratio of ferrite in the microstructure of the slab is 90% or more, and the area ratio of ferrite is 0% or 3% or more. Thus, a slab for high-strength steel that is unlikely to cause thermal cracking after casting can be provided, and the occurrence of problems such as the formation of holes during rolling can be avoided. Thus, the present invention is industrially advantageous.

Claims

1. A continuously cast slab for high-strength steel, **characterized in that:**

an average prior austenite grain size at a position 10 mm from a surface layer of the continuously cast slab is in a range of 0.5 mm to 2.0 mm;
a total of an area ratio of bainite and an area ratio of ferrite in a microstructure of the slab is 90% or more; and
the area ratio of ferrite is 0%, or 3% or more.

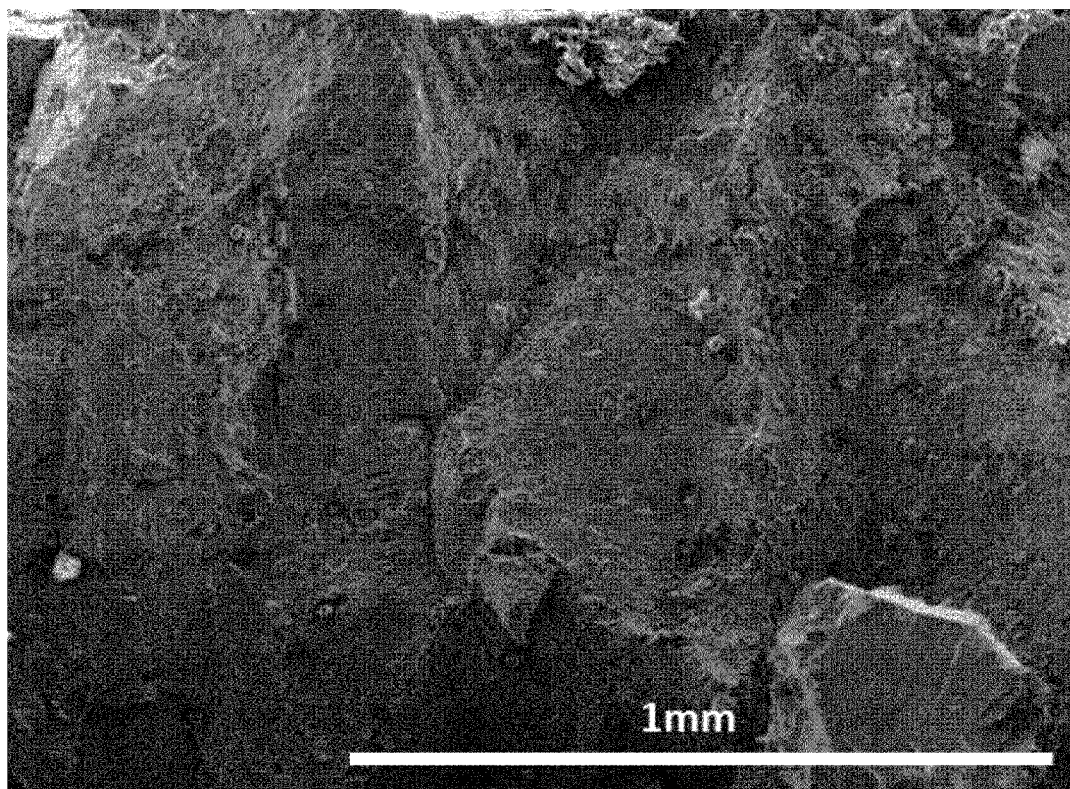
2. The continuously cast slab according to claim 1, comprising, in mass%:

C: in a range of 0.10% to 0.40%,
Si: in a range of 0.10% to 2.50%, and
Mn: in a range of 1.00% to 5.00%.

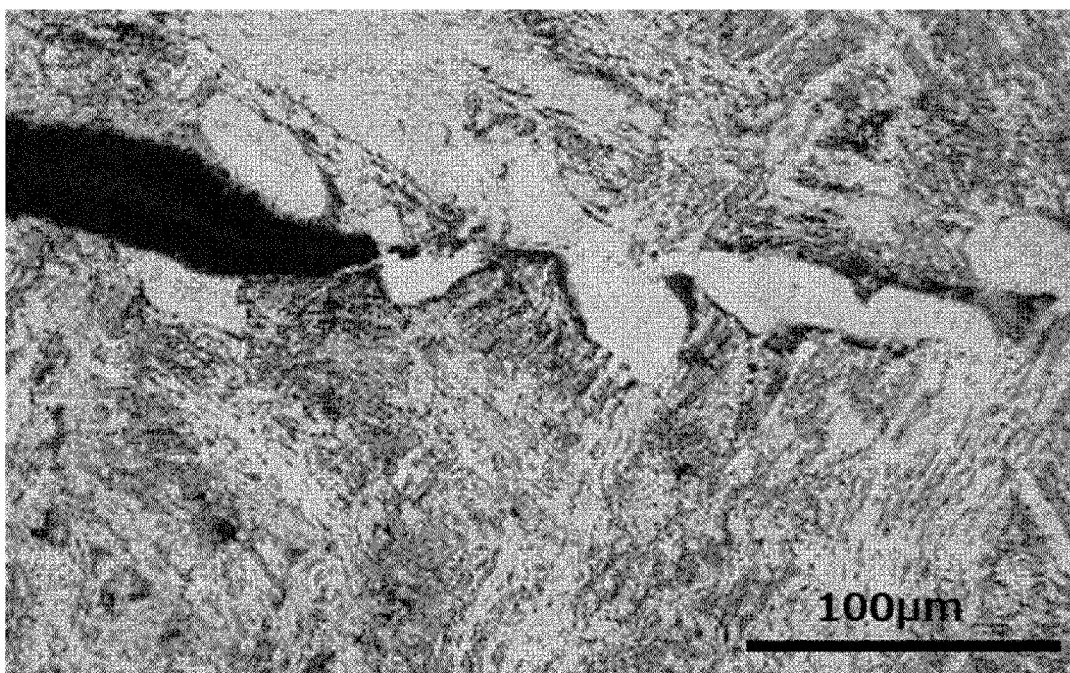
3. A method for producing a continuously cast slab for high-strength steel, the continuously cast slab preventing thermal cracking due to cooling, comprising subjecting the continuously cast slab having the ingredient composition according to claim 2 to the following:

a first cooling step of cooling the continuously cast slab under a cooling condition that a retention time while a cooling temperature of a center of a wide face at a position 10 mm from a surface layer of the continuously cast slab is in a range of 1200°C to 1450°C is 130 seconds or less;
a second cooling step of cooling the continuously cast slab under a cooling condition that an average cooling rate when a surface temperature at the center of the wide face of the continuously cast slab is in a range of 700°C to 850°C is between 25°C/hr and 40°C/hr, or 50°C/hr or more; and
a third cooling step of cooling the continuously cast slab under a cooling condition that an average cooling rate when the surface temperature at the center of the wide face of the continuously cast slab is in a range of 500°C to 700°C is 15°C/hr or more.

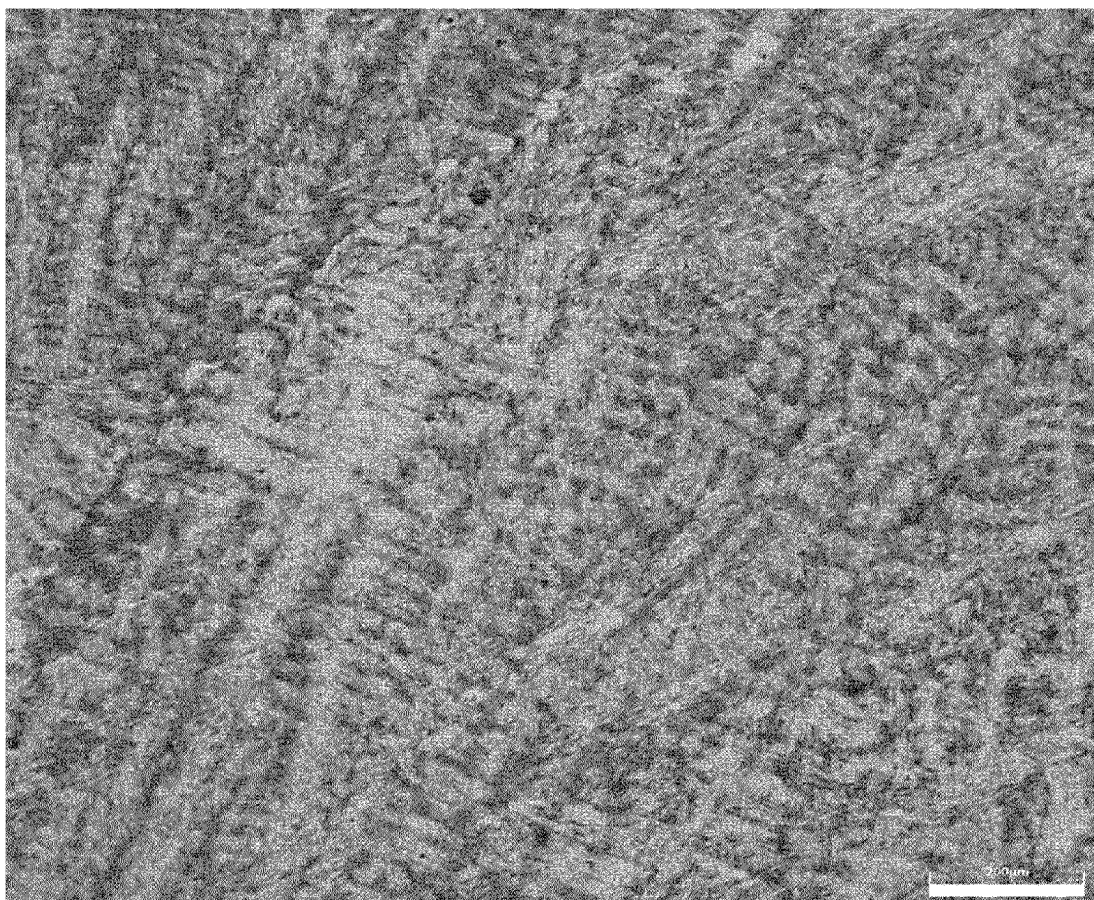
[Fig. 1]



[Fig. 2]



[Fig. 3]



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2023/012744

A. CLASSIFICATION OF SUBJECT MATTER C22C 38/00 (2006.01)i; C21D 1/00 (2006.01)i; C21D 9/00 (2006.01)i; C22C 38/04 (2006.01)i; C22C 38/60 (2006.01)n FI: C22C38/00 301A; C21D1/00 118B; C21D9/00 101Y; C22C38/04; C22C38/60 According to International Patent Classification (IPC) or to both national classification and IPC															
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) C22C38/00-38/60; C21D1/00; C21D9/00; B22D11/00-11/22 Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Published examined utility model applications of Japan 1922-1996 Published unexamined utility model applications of Japan 1971-2023 Registered utility model specifications of Japan 1996-2023 Published registered utility model applications of Japan 1994-2023 Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)															
C. DOCUMENTS CONSIDERED TO BE RELEVANT <table border="1"> <thead> <tr> <th>Category*</th> <th>Citation of document, with indication, where appropriate, of the relevant passages</th> <th>Relevant to claim No.</th> </tr> </thead> <tbody> <tr> <td>A</td> <td>JP 2007-181861 A (SUMITOMO METAL INDUSTRIES, LTD.) 19 July 2007 (2007-07-19)</td> <td>1-3</td> </tr> <tr> <td>A</td> <td>JP 2019-167560 A (NIPPON STEEL CORP.) 03 October 2019 (2019-10-03)</td> <td>1-3</td> </tr> <tr> <td>A</td> <td>JP 2019-167559 A (NIPPON STEEL CORP.) 03 October 2019 (2019-10-03)</td> <td>1-3</td> </tr> <tr> <td>A</td> <td>JP 2020-139210 A (KABUSHIKI KAISHA KOBE SEIKO SHO (KOBELCO CORP.)) 03 September 2020 (2020-09-03)</td> <td>1-3</td> </tr> </tbody> </table>	Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.	A	JP 2007-181861 A (SUMITOMO METAL INDUSTRIES, LTD.) 19 July 2007 (2007-07-19)	1-3	A	JP 2019-167560 A (NIPPON STEEL CORP.) 03 October 2019 (2019-10-03)	1-3	A	JP 2019-167559 A (NIPPON STEEL CORP.) 03 October 2019 (2019-10-03)	1-3	A	JP 2020-139210 A (KABUSHIKI KAISHA KOBE SEIKO SHO (KOBELCO CORP.)) 03 September 2020 (2020-09-03)	1-3
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A	JP 2020-139210 A (KABUSHIKI KAISHA KOBE SEIKO SHO (KOBELCO CORP.)) 03 September 2020 (2020-09-03)	1-3													
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Information on patent family members

International application No.
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