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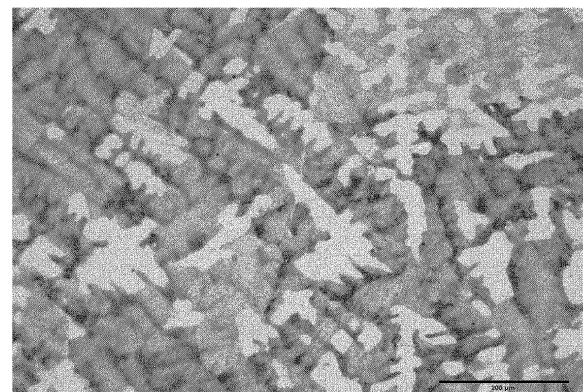
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(54) **CONTINUOUS CASTING SLAB AND METHOD FOR MANUFACTURING SAME**

(57) Provided are a continuously cast slab that is unlikely to cause 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 10 mm from the surface layer of the continuously cast slab is in the range of 0.5 mm to 2.0 mm; and a total of an area ratio of ferrite and an area ratio of pearlite in the microstructure of the slab is 90% or more, and the area ratio of ferrite is less than 5% or 10% or more.

[Fig. 3]



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 does not cause problems such as the formation of holes during rolling, 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 remove the cracks in the slab completely. 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 cracking in slabs.

25 **[0004]** Fig. 1 is a micrograph 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 austenite
30 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 the prior austenite
35 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 with lower stress. In such a case, when the prior austenite grains are coarse, grain-boundary ferrite that is linearly thin and elongated
40 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 occurred in the slab in the above
45 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 from austenite to ferrite occurs, thereby reducing the stress generated due to the transformation expansion. That is, Patent
50 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 based on the finding that internal stress in the high tensile strength steel depends on its cooling rate.

55 **[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 prior austenite grain size 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, causing a problem such as formation of holes during rolling.

[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, nor does it cause problems such as the formation of holes during rolling, even when the toughness of the continuously cast slab 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 thereof and to avoid problems such as the formation of holes during rolling, 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 the range of 0.5 mm to 2.0 mm; a total of an area ratio of ferrite and an area ratio of pearlite in the microstructure of the slab is 90% or more; and the area ratio of ferrite is less than

5% or 10% 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 1.00%, Si: in a range of 0.10% to 2.50%, and Mn: in a range of 0.40% 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 20°C/hr or less; 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 10°C/hr or less.

Advantageous Effects of Invention

[0017] The present invention can provide a continuously cast slab that causes neither thermal cracking during cooling nor problems such as the formation of holes during rolling, 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 micrograph 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-9) 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) a total of an area ratio of ferrite and an area ratio of pearlite in a microstructure of the slab is 90% or more, and (iii) the area ratio of ferrite is less than 5% or 10% 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 neither causes thermal cracking during cooling nor problems such as the formation of holes during rolling, even when 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 described above, 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 prior austenite grain size, and a ferrite structure at the grain boundary which is a factor for embrittlement of the grain boundary. A high-alloy, high-strength steel sheet is made from a continuously cast slab with extremely low toughness, and furthermore, if the continuously cast slab has such an embrittlement factor, it is impossible to suppress the occurrence of thermal cracking in the slab even if the slab is slowly cooled to reduce stress. 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. A grain boundary has a feature such that precipitates tend to concentrate thereon because the solute component tends to condense thereon. This means that the larger the average prior austenite grain size, the smaller the ratio of grain boundaries per unit volume. The density of precipitates thus increases, reducing 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, precipitates that are concentrated on prior austenite grain boundaries can be dispersed, which is preferable because the toughness of the continuously cast slab is not reduced.

[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 breakout due to uneven solidification. Therefore, the lower limit of the average prior austenite grain size is preferably 0.5 mm or more. Note that the lower limit of the average prior austenite grain size is preferably 0.8 mm or more, and more preferably 1.0 mm or more.

[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 γ 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, it is preferable to control the retention time within 130 seconds 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.

[0029] When the retention time in the temperature range of 1450°C to 1200°C 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. Controlling the average prior austenite grain size to be small in such a manner can disperse precipitates and grain-boundary ferrite, increasing the toughness of the slab and suppressing the occurrence of thermal cracking in the slab, which is preferable.

[0030] 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.

[0031] 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.

[0032] That is, if the retention time of the continuously cast slab in the temperature range of 1450°C to 1200°C is less than 40 seconds, cracking may occur due to uneven solidification, resulting in a risk of breakout. Thus, the retention time is preferably set to 40 seconds or more. From such a viewpoint, the retention time of the continuously cast slab in the temperature range of 1450°C to 1200°C is more preferably 60 seconds or more, and further preferably 70 seconds or more.

[0033] 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 flux 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.

[0034] By controlling such cooling conditions, the average prior austenite grain size at a position 10 mm below 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 >

[0035] The continuously cast slab according to this embodiment has features such that (ii) a total of an area ratio of ferrite and an area ratio of pearlite in a microstructure of the slab is 90% or more, and (iii) the area ratio of ferrite is less than 5% or 10% 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 ferrite and pearlite 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 (ii) that a total of an area ratio of ferrite and an area ratio of pearlite in a microstructure of the slab is 90% or more, and the condition (iii) that the area ratio of ferrite is less than 5% or 10% or more. Note that the area ratio of ferrite and the area ratio of pearlite 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, ferrite and pearlite contained in the microstructure of the continuously cast slab can be identified using an observation means such as an optical microscope.

[0036] From the results of identifying the microstructure of the continuously cast slab, the area S_{total} of the microstructure of the continuously cast slab and the area $S_{(\text{ferrite}+\text{pearlite})}$, which is the sum of the area S_{ferrite} of ferrite and the area S_{pearlite} of pearlite, are calculated. Then, the ratio of the area $S_{(\text{ferrite}+\text{pearlite})}$, which is the sum of the area S_{ferrite} of ferrite and the area S_{pearlite} of pearlite, to the area S_{total} of the microstructure of the continuously cast slab is calculated as the area ratio (%).

[0037] The continuously cast slab according to this embodiment has a feature such that (ii) a total of an area ratio of ferrite and an area ratio of pearlite 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 $S_{(\text{ferrite}+\text{pearlite})}$, which is the sum of the area S_{ferrite} of ferrite and the area S_{pearlite} of pearlite, to the area S_{total} of the microstructure of the continuously cast slab is 90% or more, it is possible to reduce thermal stress and transformation stress to be applied to the slab due to bainite/martensitic transformation while the slab is slowly cooled, and to allow such generated stress to be dispersed in ferrite and pearlite existing in large amounts within the microstructure, and thus 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.

[0038] Further, the continuously cast slab according to this embodiment has a feature such that (iii) the area ratio of ferrite is less than 5% or 10% or more. That is, in the continuously cast slab according to this embodiment, when the area ratio of ferrite is 5% or more but less than 10%, the slab is in such a state that thin ferrite is present at grain boundaries and stress is concentrated on the soft ferrite portions, resulting in the development of cracks, which is unfavorable. As long as the area ratio of ferrite is less than 5%, even if cracks have started to develop, the development stops soon, which is preferable. Meanwhile, when the area ratio of ferrite is 10% or more, the stress is unlikely to be concentrated in the ferrite portions, and cracks do not develop, which is preferable.

[0039] 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 in 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 pearlite, it is possible to significantly increase the toughness of the continuously cast slab by suppressing the formation of grain-boundary ferrite.

[0040] Note that ferrite contains a maximum carbon content of 0.02 mass% and thus is a structure close to pure iron. Ferrite is a ferromagnetic material from room temperature to 780°C, and is the softest of all structures of steel, with excellent ductility. Pearlite is a structure obtained when austenite is slowly cooled. Pearlite includes ferrite layers and cementite layers and is formed with such layers alternately arranged.

[0041] The precipitation of grain-boundary ferrite is largely influenced by the cooling rate in the ferrite transformation range. If the cooling rate is lower than the critical rate, the precipitation of ferrite occurs, so that the cooling rate needs to be controlled in the temperature range of 850°C to 700°C. If the cooling rate in the ferrite transformation range is lower than the critical rate but a sufficient precipitation time cannot be secured, ferrite is preferentially precipitated at grain boundaries where precipitation is likely to occur. Therefore, the stress applied by subsequent pearlite transformation or bainite/martensitic transformation is concentrated on the soft ferrite portions, resulting in thermal cracking in the slab, which is unfavorable. As a countermeasure, it is possible to grow the ferrite precipitated at the grain boundaries into polygonal ferrite by reducing the cooling rate in the ferrite transformation range and thus securing a sufficient time for the precipitation of ferrite. Forming polygonal ferrite in such a manner can suppress excessive stress concentration, and thus can increase the toughness of the slab.

[0042] To suppress the occurrence of thermal cracking in the slab, it is important not only to suppress the embrittlement of prior austenite grain boundaries but also to reduce the stress during transformation. Thus, controlling the cooling rate in the pearlite transformation range (the temperature range of 700°C to 500°C) in various manners can also control the microstructure of the continuously cast slab.

[0043] 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.

[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 both thermal cracking of the slab during a cooling process and the occurrence of problems such as the formation of holes during a rolling 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 1.00%, Si: in the range of 0.10% to 2.50%, and Mn: in the range of 1.50% 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 1.00%>

[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 1.00% 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 1.00%, sufficient weldability or workability of the high-strength steel sheet cannot be obtained, 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 1.00%, more preferably within the range of 0.12% to 0.40%, and particularly more preferably within the range of 0.15% to 0.40%.

<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 0.40% to 5.00%>

[0052] The Mn content in the continuously cast slab is set in the range of 0.40% 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 0.40%, the high-strength steel sheet cannot be sufficiently strengthened. Therefore, the lower limit of the Mn content is 0.40%. 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 0.40% to 5.00%, more preferably in the range of 1.20% to 4.50%, and further preferably in the range of 1.40% 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, and an appropriate average prior austenite grain size and 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 causes the grain boundaries to become embrittled, resulting in thermal cracking in the slab in some cases. Therefore, the P content is preferably set to 0.100% or less. Meanwhile, 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. 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 large amounts of coarse precipitates or inclusions 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 large amounts of coarse precipitates or inclusions 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 set to 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 is 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 or annealing and thus affects the strength through structural strengthening. B has no effect on 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 or 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 ingredient 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 or 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 and can further obtain a continuously cast slab that is excellent in the weldability, workability, and appearance of high-strength steel.

[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 component 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 of the center of the wide face of the continuously cast slab is in the range of 700°C to 850°C is 20°C/hr or less; 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 10°C/hr or less.

[0076] The lower limit of each average cooling rate in the second cooling step and 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 plurality of slabs are stacked and a heat-insulating cover is further used are 2°C/hr and 1°C/hr, respectively, at minimum. If cooling is performed at an average cooling rate lower than the average cooling rate in each of the second cooling step and the third cooling step, it becomes necessary to place the slab in a heating furnace and apply heat thereto, for example, which requires a facility for that purpose and therefore is unfavorable from an economic

viewpoint. Therefore, it is preferable to set the lower limit of the average cooling rate in the temperature range of 700°C to 850°C in the second cooling step to 2°C/hr, and to set the lower limit of the average cooling rate in the temperature range of 500°C to 700°C in the third cooling step to 1°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 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 the 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. Controlling the average prior austenite grain size to be 2.0 mm or less can reduce the density of precipitates on the grain boundaries of prior austenite, and can also suppress the precipitation of harmful grain-boundary ferrite, which can increase the toughness of the slab.

[0081] 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 ranges from 1450°C to 1200°C. Thus, the method for producing a continuously cast slab according to this embodiment focuses on the cooling temperature within the range of 1450°C to 1200°C, which is a factor that determines the average prior austenite grain size of the continuously cast slab, and thus controls the temperature.

[0082] 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)

[0083] 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 20°C/hr or less. The second cooling step is a step conducted to suppress the precipitation of grain-boundary ferrite contained in the microstructure of the continuously cast slab according to the above embodiments and to set the area ratio of ferrite to less than 5% or 10% or more.

[0084] 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.

[0085] 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 20°C/hr or less. If the average cooling rate is more than 20°C/hr, thin ferrite is precipitated only on the prior austenite grain boundaries, causing the embrittlement of the grain boundaries, which is unfavorable. When the average cooling rate for cooling the continuously cast slab is 20°C/hr or less, it is possible to obtain a sufficient retention time of the continuously cast slab in the ferrite transformation temperature range, thus allowing the grain-boundary ferrite to grow into polygonal ferrite. This can suppress the stress concentration on the grain-boundary ferrite, which is preferable.

[0086] Note that the lower limit of the average cooling rate is not specified. However, since it is necessary to separately provide an energy source needed to control the cooling rate, the average cooling rate is preferably 2°C/hr or more. More preferably, the average cooling rate is in the range of 5°C/hr to 18°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 10°C/hr or less.

[0088] The third cooling step is a step performed so that the continuously cast slab according to the above embodiments has a microstructure mainly of pearlite and the internal stress can be reduced. Specifically, the third cooling step is a step performed so that the area ratio (%), which is the ratio of the area $S_{(\text{ferrite}+\text{pearlite})}$, which is the sum of the area S_{ferrite} of ferrite and the area S_{pearlite} of pearlite 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 and thus controls the temperature.

[0090] In the third cooling step, the average cooling rate for cooling the continuously cast slab in the above temperature range for cooling the continuously cast slab is 10°C/hr or less. If the average cooling rate for the continuously cast slab is more than 10°C/hr, bainite and martensite are precipitated on the microstructure of mainly pearlite, causing large stress, which is unfavorable. The transformation temperatures of bainite and martensite are lower than the transformation temperature of pearlite. Thus, the transformation stress of bainite and martensite is applied to the pearlite portion that has already completed the transformation, promoting cracking.

[0091] From such a viewpoint, the average cooling rate for cooling the continuously cast slab is preferably 10°C/hr or less because such an average cooling rate can suppress bainite transformation, and thus can obtain a structure of mainly pearlite, thereby reducing internal stress.

[0092] Note that the lower limit of the average cooling rate is not strictly defined. However, since it is necessary to separately provide an energy source needed to control the cooling rate, the average cooling rate is preferably 1°C/hr or more. More preferably, the average cooling rate is 5°C/hr or more.

[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 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 and avoid problems including the formation of holes during a rolling process.

[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 and avoid problems such as the formation of holes during a rolling 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-24). Table 1 shows steel grades A to I 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 Invention Examples (Test Nos. D-1 to D-24).

[Table 1]

Steel Type	C [Mass%]	Si [Mass%]	Mn [Mass%]	P [Mass%]	S [Mass%]	Sol. Al [Mass%]	N [Mass%]	Ti [Mass%]	Nb [Mass%]
A	0.10	2.50	3.51	0.011	0.0011	0.052	0.0043	-	-
B	0.12	0.51	5.00	0.009	0.0015	0.048	0.0039	0.024	0.010
C	0.16	0.74	1.49	0.008	0.0015	0.047	0.0032	-	-
D	0.18	1.37	2.74	0.007	0.0021	0.048	0.0034	0.021	-
E	0.25	1.08	3.23	0.007	0.0013	0.050	0.0036	-	0.034
F	0.50	1.97	3.02	0.010	0.0008	0.043	0.0030	-	-
G	0.42	0.24	1.55	0.019	0.0043	0.041	0.0042	-	-
H	0.55	0.19	0.69	0.021	0.0045	0.025	0.0035	-	-
I	1.00	0.23	0.40	0.020	0.0025	0.002	0.0031	-	-

[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.

[0099] For each of the continuously cast slabs produced as the Comparative Examples and the Invention Examples, the average prior austenite grain size, the calculation of the area ratios of ferrite and pearlite, 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. Then, the sample was observed at a position 10 mm below 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. Then, the average value of the grain sizes was 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 below 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 ratio of pearlite>

[0102] A method of measuring the area ratio of the pearlite 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 below 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. The average of the obtained values was determined as the area ratio of each structure by 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%. Pearlite is a eutectoid of ferrite and cementite, and has a structure in which flake-shaped layers of ferrite and cementite exhibit a glow like pearls when observed with the above scanning electron microscope.

[0103] The microstructure of the continuously cast slab according to the present invention is a structure of mainly pearlite and without grain-boundary ferrite. However, it would be difficult to strictly distinguish between grain-boundary ferrite and polygonal ferrite. Thus, the inventors have conducted intensive studies on the slabs in which thermal cracking had occurred, and found that there is a large amount of grain-boundary ferrite when the area ratio of ferrite is more than 5% but less than 10%. That is, the continuously cast slab according to the present invention has a structure in which the area ratio of ferrite + pearlite is 90% or more, and the area ratio of ferrite is less than 5% or 10% or more.

<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 cracking in the surface of the slab.

[0105] Note that if a slab has a crack of 50 mm or more in length, there is a high risk of the slab fracture during handling or in a heating furnace. This may also lead to a high possibility of problems such as the formation of holes during a rolling process. Thus, the criteria for evaluating whether thermal cracking had occurred in each slab were determined as follows.

- Thermal cracking in slab: Absent ... A slab without a crack with a length of 50 mm or more in its surface
- Thermal cracking in slab: Present ... A slab with a crack with a length of 50 mm or more in its surface.

[Table 2]

Test No.	Steel Type	Average Prior Austenite Grain Size [mm]	Ferrite + Pearlite Area Ratio [%]	Ferrite Area Ratio [%]	Bainite Area Ratio [%]	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 Cracking in Slab	Remarks
A-1	D	2.8	85	10	15	150	24	14	Present	Comparative Example
A-2	D	3.0	89	11	11	170	20	13	Present	Comparative Example
A-3	D	2.5	100	10	0	160	28	5	Present	Comparative Example
A-4	D	2.2	92	12	8	140	19	7	Present	Comparative Example
B-1	D	1.2	70	5	30	90	41	36	Present	Comparative Example
B-2	D	2.0	82	6	18	130	40	18	Present	Comparative Example
B-3	D	1.5	91	5	9	115	38	10	Present	Comparative Example
B-4	D	1.1	95	8	5	98	36	7	Present	Comparative Example
B-5	D	1.2	80	6	20	105	24	20	Present	Comparative Example

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(continued)

Test No.	Steel Type	Average Prior Austenite Grain Size [mm]	Ferrite + Pearlite Area Ratio [%]	Ferrite Area Ratio [%]	Bainite Area Ratio [%]	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 Cracking in Slab	Remarks
B-6	D	1.7	89	5	11	122	25	12	Present	Comparative Example
B-7	D	1.6	91	8	9	128	27	9	Present	Comparative Example
B-8	D	1.5	100	9	0	110	25	5	Present	Comparative Example
C-1	D	1.3	89	12	11	102	18	12	Present	Comparative Example
C-2	D	1.4	85	15	15	95	10	19	Present	Comparative Example
C-3	D	1.9	89	25	11	130	4	12	Present	Comparative Example

[Table 3]

Test No.	Steel Type	Average Prior Austenite Grain Size [mm]	Ferrite + Pearlite Area Ratio [%]	Ferrite Area Ratio [%]	Bainite Area Ratio [%]	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 Cracking in Slab	Remarks
D-1	D	1.7	93	11	7	118	20	7	Absent	Invention Example
D-2	D	1.8	100	12	0	125	19	5	Absent	Invention Example
D-3	D	1.2	100	11	0	95	20	2	Absent	Invention Example
D-4	D	1.4	100	11	0	98	17	4	Absent	Invention Example
D-5	D	1.7	100	13	0	115	15	3	Absent	Invention Example
D-6	D	1.4	92	14	8	105	9	7	Absent	Invention Example
D-7	D	1.5	99	12	1	100	8	5	Absent	Invention Example
D-8	D	1.6	100	11	0	115	10	2	Absent	Invention Example
D-9	D	1.9	100	26	0	120	5	3	Absent	Invention Example
D-10	A	1.9	100	30	0	118	2	1	Absent	Invention Example
D-11	A	2.0	91	14	9	130	15	9	Absent	Invention Example

(continued)

Test No.	Steel Type	Average Prior Austenite Grain Size [mm]	Ferrite + Pearlite Area Ratio [%]	Ferrite Area Ratio [%]	Bainite Area Ratio [%]	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 Cracking in Slab	Remarks
D-12	B	1.6	97	16	3	120	8	6	Absent	Invention Example
D-13	B	1.8	100	21	0	118	5	3	Absent	Invention Example
D-14	B	1.4	91	12	9	100	19	8	Absent	Invention Example
D-15	C	1.9	100	22	0	122	6	2	Absent	Invention Example
D-16	C	1.2	100	15	0	85	8	2	Absent	Invention Example
D-17	E	1.6	97	14	3	109	9	4	Absent	Invention Example

[Table 4]

Test No.	Steel Type	Average Prior Austenite Grain Size [mm]	Ferrite + Pearlite Area Ratio [%]	Ferrite Area Ratio [%]	Bainite Area Ratio [%]	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 Cracking in Slab	Remarks
D-18	E	1.5	95	18	5	95	10	8	Absent	Invention Example
D-19	F	1.5	100	3	0	107	12	6	Absent	Invention Example
D-20	F	1.7	100	4	0	109	3	2	Absent	Invention Example
D-21	F	1.8	100	2	0	112	18	9	Absent	Invention Example
D-22	G	1.4	100	1	0	100	20	7	Absent	Invention Example
D-23	H	1.2	100	4	0	85	5	3	Absent	Invention Example
D-24	I	1.5	100	0	0	107	10	9	Absent	Invention Example

< Comparative Examples (Test Nos. A-1 to A-4) >

[0106] A slab microstructural structure satisfied by the continuously cast slabs produced in Test Nos. A-1 to A-4 is regarded as a Condition A. In the Condition A, the average prior austenite grain size at a position 10 mm below the surface layer of the slab 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 the continuously cast slabs produced in Test Nos. B-1 to B-8 is regarded as a Condition B. In the Condition B, the average prior austenite grain size at a position 10 mm below the surface layer of the slab was 2.0 mm or less, but grain-boundary ferrite was precipitated at prior austenite grain boundaries. In such cases, the toughness of the prior austenite grain boundaries was reduced due to the grain-boundary ferrite. Thus, the occurrence of thermal cracking in the slab could not be suppressed even by varying the subsequent cooling rate to change the configuration of the microstructure.

< 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 and the precipitation of grain-boundary ferrite was suppressed, while 10% or more bainite was precipitated, thus not suppressing the occurrence of cracks in the slab. It is considered that the occurrence of cracks in the slab was not suppressed because bainite transformation occurs at a temperature lower than that of pearlite transformation, and thus the difference in density between bainite and austenite is large, and also because the transformation stress is high.

< Invention Examples (Test Nos. D-1 to D-24) >

[0109] A slab microstructure satisfied by the continuously cast slabs produced in Test Nos. D-1 to D-24 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 invention examples of the present invention had an average prior austenite grain size of 2.0 mm or less and a microstructure containing less grain-boundary ferrite and a small amount of bainite. That is, it was possible to prevent thermal cracking in the slab during cooling by controlling the prior austenite grain boundaries to be small and dispersing precipitates to thus increase toughness, also by suppressing precipitation of grain-boundary ferrite to increase toughness, and further by suppressing precipitation of bainite to reduce internal stress.

[0110] From Tables 2 to 4, it was found that the occurrence of thermal cracking can be suppressed in each slab during a cooling process therefor by satisfying the following conditions: (i) an 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, (ii) a total of an area ratio of ferrite and an area ratio of pearlite in a microstructure of the continuously cast slab is 90% or more, and (iii) the area ratio of ferrite is less than 5% or 10% or more.

[0111] That is, 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 ferrite and the area ratio of pearlite in the microstructure of the slab is 90% or more, and the area ratio of ferrite is less than 5% or 10% or more, making it possible to provide a slab for high-alloy, high-strength steel which suppress the occurrence of cracking after casting and prevents the occurrence of problems such as the formation of holes during a rolling process. That is, according to the Invention Examples and the Comparative Examples, the occurrence of thermal cracking can be suppressed in each slab during a cooling process therefor by satisfying the following conditions: 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 an area ratio of ferrite and an area ratio of pearlite in the microstructure of the slab is 90% or more, and the area ratio of ferrite is less than 5% or 10% or more.

[0112] Fig. 3 is a magnified micrograph of the continuously cast slab produced in the Invention Example (Test No. D-9) of the continuously cast slab, observed with an optical microscope. A metallographic structure contained in the continuously cast slab was identified based on the magnified micrograph of the continuously cast slab observed with the optical microscope shown in Fig. 3. Then, the ratio of the area $S_{(\text{ferrite}+\text{pearlite})}$, which is the sum of the area S_{ferrite} of ferrite and the area S_{pearlite} of pearlite, 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 present Invention Example, 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 and that the total of an area ratio of ferrite and an area ratio of pearlite in the microstructure of the slab is 90% or more. Further, it was found that in the continuously cast slab of the present Invention Example, the area ratio of ferrite is less than 5% or 10% or more.

[0113] To obtain such a microstructure of the continuously cast slab, it is preferable to adopt, for example, a three-stage cooling consisting of a step of cooling the slab such that a retention time while a temperature at a position 10 mm below the slab surface layer is in a range of 1450°C to 1200°C is 130 seconds or less; another step of cooling the slab at a cooling rate of 20°C/hr or less 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 the other step of further cooling the slab at an average cooling rate of 10°C/hr or less when the surface temperature of the center of the wide face of the slab is in the range of 700°C to 500°C.

[0114] Note that if the continuously cast slab is strongly cooled in the temperature range of 1450°C to 1200°C, there is a risk of cracking in the slab surface due to uneven solidification. In that case, for example, it is possible to achieve a finer prior austenite grain size by using austenite reverse transformation, by rapidly cooling the slab surface to the BS point or lower when the center of the wide face of the slab at a position of 10 mm below the surface layer of the slab is at a temperature in the range of 900°C to 1200°C and then stopping the cooling, so that the temperature reaches to the AC3 point or higher. After that, the slab is cooled at a cooling rate of 20°C/hr or less 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 then, the slab is cooled at a cooling rate of 10°C/hr or less when the surface temperature of the center of the wide face of the slab is in the temperature range of 700°C to 500°C so that a continuously cast slab with the above microstructure can be obtained. The method for producing a continuously cast slab with the above microstructure of the continuously cast slab is not limited thereto.

Industrial Applicability

[0115] The continuously cast slab of the present invention has features such that an 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; a total of an area ratio of ferrite and an area ratio of pearlite in the microstructure of the slab is 90% or more; and the area ratio of ferrite is less than 5% or 10% or more. Thus, a slab for high-strength steel that is unlikely to cause 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 the range of 0.5 mm to 2.0 mm;
a total of an area ratio of ferrite and an area ratio of pearlite in a microstructure of the slab is 90% or more; and
the area ratio of ferrite is less than 5% or 10% or more.

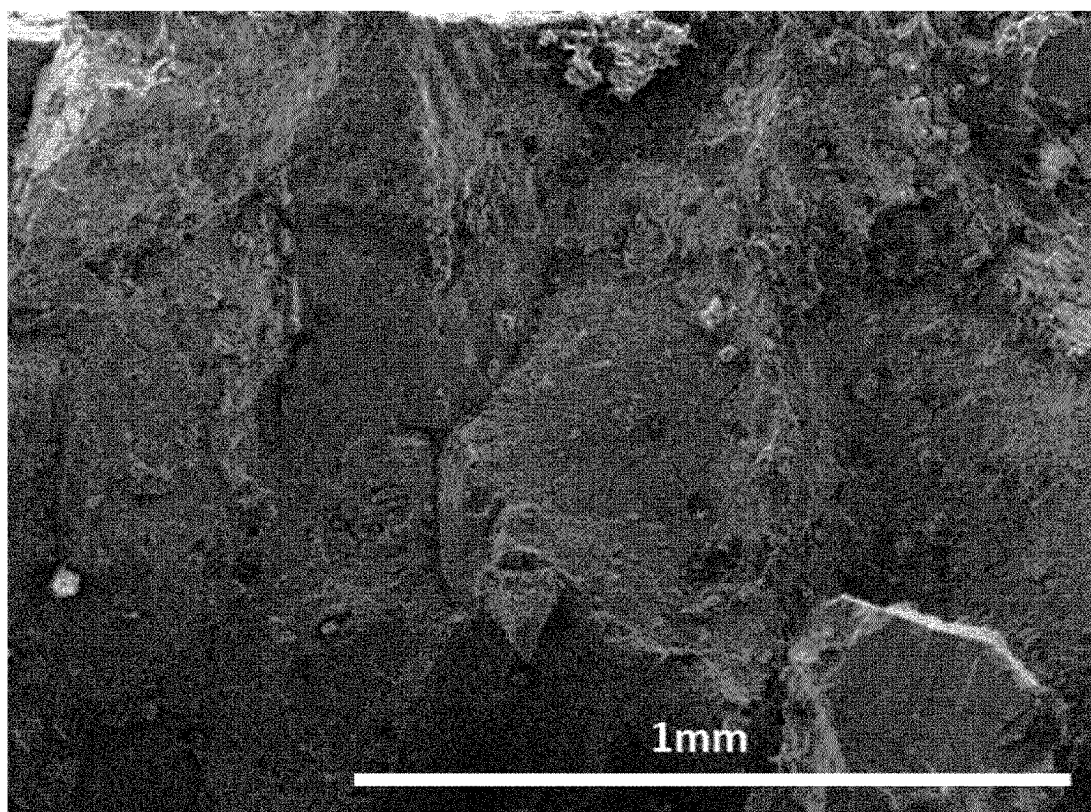
2. The continuously cast slab according to Claim 1, comprising, in mass%:

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

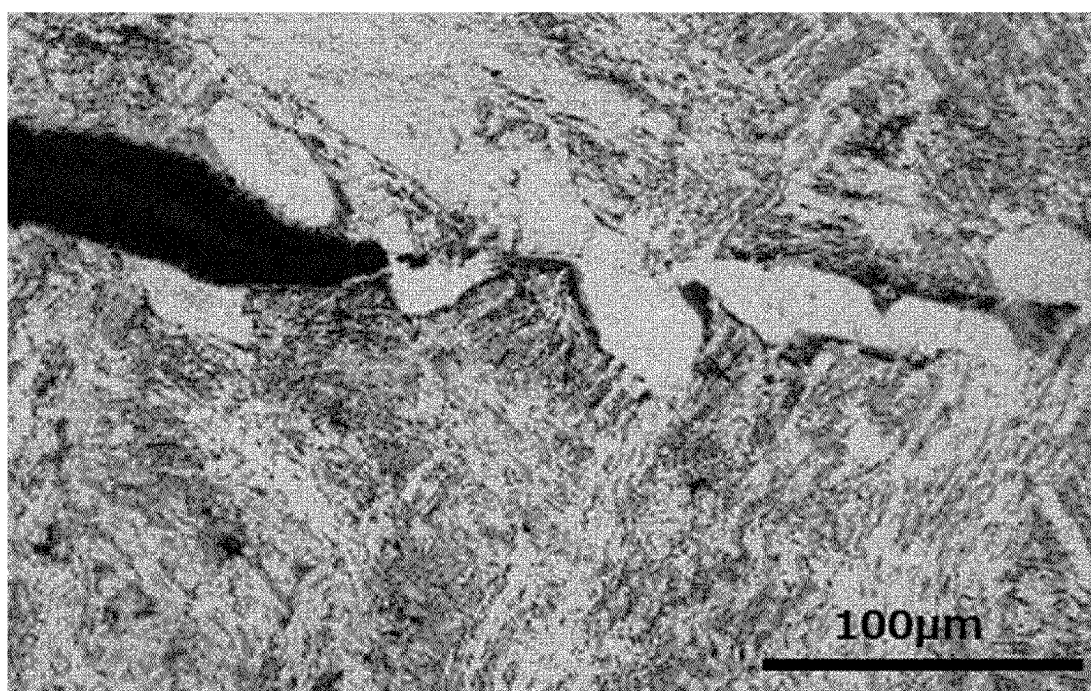
3. A method for producing a continuously cast slab for high-strength steel, the continuously cast slab preventing thermal cracking due to cooling, comprising subjecting the continuously cast slab having the ingredient composition according to Claim 2 to the following:

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 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 20°C/hr or less; 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 10°C/hr or less.

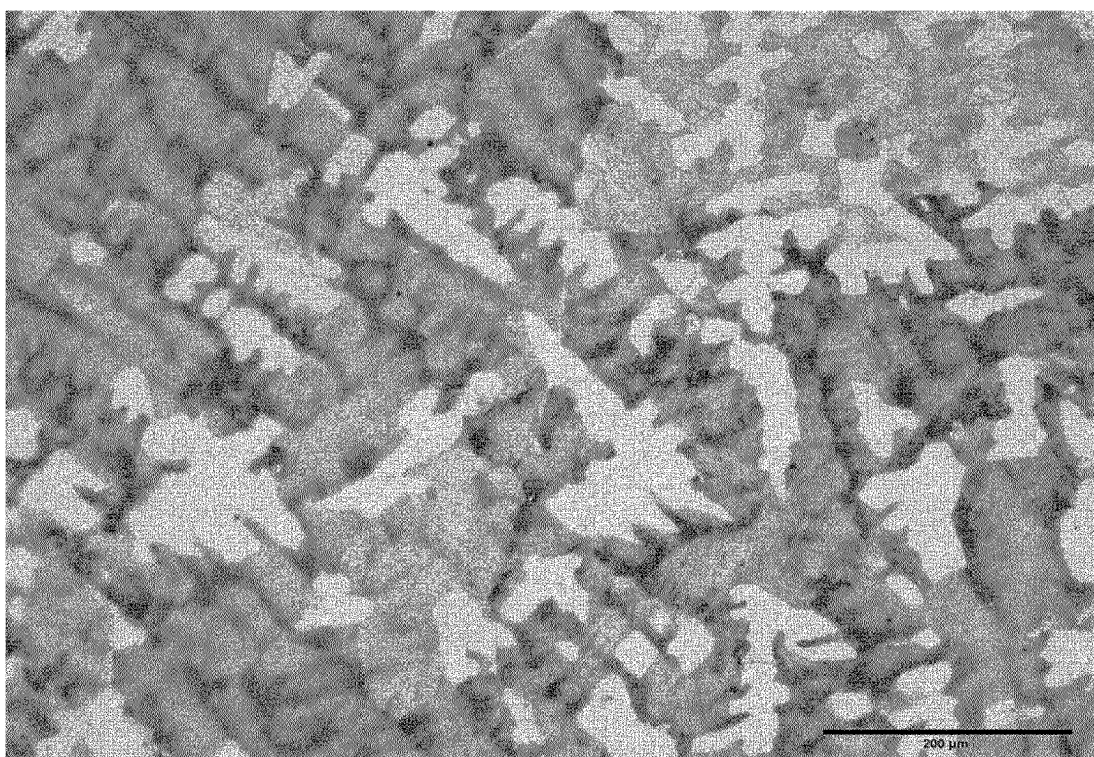
[Fig. 1]



[Fig. 2]



[Fig. 3]



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2023/012746

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

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 STEEL, LTD.)) 03 September 2020 (2020-09-03)	1-3

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

08 June 2023

Date of mailing of the international search report

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2023/012746

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
JP	2007-181861	A	19 July 2007	(Family: none)	
JP	2019-167560	A	03 October 2019	(Family: none)	
JP	2019-167559	A	03 October 2019	(Family: none)	
JP	2020-139210	A	03 September 2020	(Family: none)	

REFERENCES CITED IN THE DESCRIPTION

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