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(54) HIGH STRENGTH STEEL SHEET HAVING EXCELLENT BRITTLE CRACK RESISTANCE AND METHOD FOR MANUFACTURING SAME

(57) Provided is a steel plate having excellent resistance to brittle crack initiation in a parent material zone and a weld heat affected zone. More particularly, the present invention relates to a high-strength steel sheet having excellent resistance to brittle crack initiation which includes 0.02 wt% to 0.06 wt% of carbon (C), 0.1 wt% or less of silicon (Si), 1.5 wt% to 2.0 wt% of manganese (Mn), 0.012 wt% or less of phosphorous (P), 0.003 wt% or less of sulfur (S), 0.5 wt% to 1.5 wt% of nickel (Ni), 0.003 wt% to 0.015 wt% of aluminum (Al), 0.005 wt% to 0.02 wt% of titanium (Ti), 0.005 wt% to 0.015 wt% of niobium (Nb), 0.002 wt% to 0.006 wt% of nitrogen (N), and iron (Fe) as well as unavoidable impurities as a remainder, and has a value of C+0.5Si-0.1Ni+6Al+3Nb of 0.1% or less, and a method of manufacturing the high-strength steel sheet.

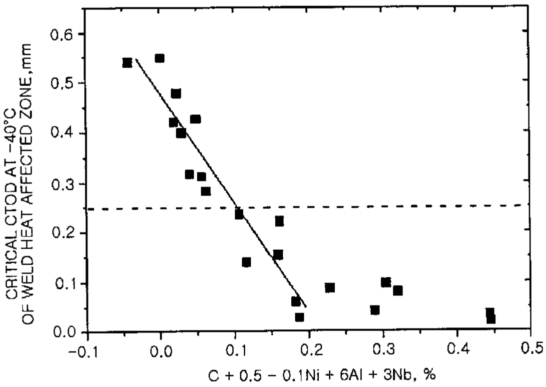

FIG. 1

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Description

[Technical Field]

[0001] The present invention relates to a high-strength steel sheet used in offshore and building structures, and more particularly, to a high-strength steel sheet having excellent resistance to brittle crack initiation in a parent material and in a weld heat affected zone (HAZ) and a method of manufacturing the same.

[Background Art]

[0002] In line with the rapid increase in demand for energy centered on emerging economies such as those of China and India, the development of oil resources has been undertaken in extreme cold regions, in particular, Sakhalin and the Arctic Ocean, which have not previously been developed due to low profitability.

[0003] Steels used in structures built in extreme cold regions are required to have high resistance to brittle crack initiation at low temperatures in order to secure the safety of the structures. A crack tip opening displacement (CTOD) test based on fracture mechanics is mainly used as a method of evaluating resistance to brittle crack initiation at low temperatures.

[0004] The CTOD test has mainly been used to evaluate resistance to brittle crack initiation in a weld heat affected zone so far. Alternatively, an impact test instead of the CTOD test has been used for a parent material zone. However, since high-strength thick steel sheets having a thickness of 50 mm or more are mainly used in offshore structures built in extreme cold regions such as Sakhalin and the Arctic Ocean in consideration of collisions with icebergs, and in addition, there is a possibility that brittle cracks may be generated from fatigue cracks under specific conditions after fatigue cracks initiated in a weld zone propagate into a parent material zone along a direction of applied cyclic stress, a high level of resistance to brittle crack initiation is required for the parent material zone as well as the weld heat affected zone.

[0005] The related art with respect to steel sheets having excellent resistance to brittle crack initiation at low temperatures will be described below.

[0006] Korean Patent Application Laid-Open Publication No. 2002-0028203 discloses a method of preventing the generation of brittle fractures in weld heat affected zones by adding magnesium (Mg) to inhibit grain coarsening generated near a fusion line during welding. However, since this patent guarantees the prevention of brittle fractures at a temperature of -10°C or more, resistance to brittle fractures at a low temperature such as -40°C may not be guaranteed.

[0007] Also, Korean Patent Application Laid-Open Publication No. 2008-0067957 discloses a technique of preventing a rapid decrease in toughness generated in weld heat affected zones by limiting aluminum (Al) or niobium (Nb) below a predetermined limit and securing resistance to brittle crack initiation of weld heat affected zones even at a low temperature of -40°C by using manganese (Mn) having a low effect on the toughness of the weld heat affected zone. However, this patent did not describe a method of securing resistance to brittle crack initiation in a parent material zone different from the weld heat affected zone.

[0008] Meanwhile, Korean Patent Application Laid-Open Publication No. 2006-0090287 discloses a method of manufacturing steels having excellent resistance to brittle crack initiation in a parent material zone and a weld heat affected zone at a low temperature of -40°C, as a technique for securing physical properties of the steel sheet by reducing a carbon (C) content to inhibit the formation of martensitic islands and using precipitation hardening due to copper (Cu) precipitates generated by the addition of 0.8% or more of Cu. However, since this patent requires an additional aging treatment after controlled rolling and accelerated cooling in a state of having a large amount of Cu added thereto in order to obtain Cu precipitates, a manufacturing process may be complicated and manufacturing costs may increase.

[Disclosure]

[Technical Problem]

[0009] An aspect of the present invention provides a high-strength steel sheet having excellent resistance to brittle crack initiation able to inhibit initiation of brittle cracks at low temperatures in both a parent material zone and a weld heat affected zone (HAZ) and having a yield strength of 420 MPa or more, and a method of manufacturing the high-strength steel sheet.

[Technical Solution]

[0010] According to an aspect of the present invention, there is provided a high-strength steel sheet having excellent resistance to brittle crack initiation including: 0.02 wt% to 0.06 wt% of C (carbon); 0.1 wt% or less of Si (silicon); 1.5 wt% to 2.0 wt% of Mn (manganese); 0.012 wt% or less of P (phosphorous); 0.003 wt% or less of S (sulfur); 0.5 wt% to 1.5

wt% of Ni (nickel); 0.003 wt% to 0.015 wt% of Al (aluminum); 0.005 wt% to 0.02 wt% of Ti (titanium); 0.005 wt% to 0.015 wt% of Nb (niobium); 0.002 wt% to 0.006 wt% of N (nitrogen); and Fe (iron) as well as unavoidable impurities as a remainder, wherein a value of C+0.5Si-0.1Ni+6Al+3Nb is 0.1 wt% or less.

[0011] According to another aspect of the present invention, there is provided a method of manufacturing a high-strength steel sheet having excellent resistance to brittle crack initiation including: heating a steel slab satisfying the foregoing composition range within a temperature range of 1000°C to 1100°C; rough rolling the heated slab at a cumulative reduction rate of 40% or more and a temperature of 950°C or more; finish rolling within a temperature range of 700°C to 800°C after the rough rolling; and cooling the rolled steel sheet.

[Advantageous Effects]

[0012] According to an aspect of the present invention, a high-strength steel sheet having a yield strength of 420 MPa or more and simultaneously having excellent resistances to brittle crack initiation at low temperatures of -60°C to -40°C in a parent material and a weld heat affected zone, respectively, and a method of manufacturing the high-strength steel sheet may be provided. The foregoing thick steel sheet may be used in offshore structures, building structures, ships, tankers or the like, operating in extreme environments.

[Description of Drawings]

[0013] The above and other aspects, features and other advantages of the present invention will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings, in which:

[0014] FIG. 1 is a graph showing the results of crack tip opening displacement (CTOD) tests for a weld heat affected zone according to a value of C+0.5Si-0.1Ni+6Al+3Nb; and

[0015] FIG. 2 is a graph showing the results of CTOD tests for a parent material zone according to an effective grain size.

[Best Mode]

[0016] Hereinafter, the present invention will be described in detail.

[0017] The present inventors have recognized that a martensitic island structure generated in a weld heat affected zone is a cause of brittle cracks generated at low temperatures in the weld heat affected zone. In particular, since even a very small amount of martensitic islands existing in a weld heat affected zone may generate brittle fracture in a crack tip opening displacement (CTOD) test at a low temperature such as -40°C, the present inventors have recognized that the inhibition of martensitic islands is very important and have conducted in-depth research into a method of inhibiting the generation of martensitic island structures in weld heat affected zones.

[0018] Also, as a result of investigating a cause of brittle cracks generated in a parent material of a thick steel sheet having a thickness of 50 mm or more, the present inventors found that brittle fractures mainly occur at a center of the sheet in a thickness direction of the steel sheet and brittle cracks are microstructurally initiated at relatively coarse grains among grains in the center of the sheet in the thickness direction, and as a result of in-depth research into a method of inhibiting the brittle cracks, the present inventors completed the present invention.

[0019] Hereinafter, a composition range of the present invention will be described in detail, in terms of weight percentage, (hereinafter, wt%).

[0020] Carbon (C): 0.02% to 0.06%

[0021] Since C is an important alloying element for constituting martensitic islands generated in a weld heat affected zone to initiate brittle fracture, it is essential to primarily limit a content of C in order to inhibit formation of martensitic islands. When the content of C is greater than 0.06%, a target of the present invention may not be achieved due to the insufficient inhibition of martensitic islands. Therefore, an upper limit of C may be limited to 0.06%. However, it may be difficult to secure strength of the steel sheet when the content of C is too low and thus, a lower limit thereof may be 0.02%.

[0022] Silicon (Si): 0.1% or less (excluding 0%)

[0023] Si is an element required for increasing tensile strength of a parent material zone and deoxidization of steel. However, Si greatly contributes to the formation of martensitic islands by preventing the decomposition of untransformed austenites into ferrites and cementites when the untransformed austenites formed by a weld heat cycle are cooled to form a final structure and thus, greatly decreases CTOD toughness in a weld heat affected zone. Therefore, an amount of added Si may be limited to 0.1% or less.

[0024] Manganese (Mn): 1.5% to 2.0%

[0025] Since Mn is a useful element for securing strength, Mn must be added in an amount of 1.5% or more in order to secure the strength of the steel sheet. However, when the addition amount of Mn is excessive, formation of central segregation in a center of the sheet in the thickness direction is promoted and formation of martensitic islands is locally promoted in a portion having the central segregation formed therein to thus greatly deteriorate CTOD characteristics of a weld heat affected zone. Therefore, an upper limit of Mn may be limited to 2.0%.

[0026] Phosphorus (P): 0.012% or less, Sulfur (S): 0.003% or less

[0027] Since P and S are elements generating grain boundary embrittlement in a weld heat affected zone, P and S are required to be minimized. However, since there are difficulties in decreasing P and S to a very low level in a steelmaking process, contents of P and S are limited to 0.012% or less and 0.003% or less, respectively.

[0028] Nickel (Ni): 0.5% to 1.5%

[0029] Ni increases hardenability to promote formation of martensitic islands. However, since an effect of reinforcing toughness of a matrix structure is greater than the foregoing effect, Ni may have an effect of rather improving toughness of a weld heat affected zone different from other alloying elements. Also, since the effect of improving toughness of the matrix phase by Ni is also exhibited in a parent material zone, it is also effective in reinforcing toughness of the parent material zone. In addition, in order to secure the strength of the steel sheet required in the present invention when the amounts of C and Si are extremely limited, Ni is required to be added in an amount of 0.5% or more. However, since the effect of reinforcing toughness of the matrix structure is saturated when an excessive amount of Ni is added, an upper limit thereof may be limited to 1.5%.

[0030] Aluminum (Al): 0.003% to 0.015%

[0031] Similarly to Si, Al is an element contributing to formation of martensitic islands by preventing formation of ferrites and cementites from untransformed austenites during a weld heat cycle. Since Al greatly decreases toughness of a weld heat affected zone when added in an amount of greater than 0.015%, an upper limit thereof may be limited to 0.015%. However, Al is a very effective element for the deoxidization of steel. When a content of Al is also too low in a state in which the Si content in the present invention is limited to 0.1% or less, deoxidization of steel may be insufficiently performed, and thus, cleanliness of the steel may be greatly deteriorated. Therefore, Al may be added in an amount of 0.003% or more.

[0032] Titanium (Ti): 0.005% to 0.02%

[0033] Ti prevents grain coarsening generated near a weld fusion line by forming fine nitrides in combination with nitrogen (N) and thus, improves toughness of a weld heat affected zone. When a content of Ti is too low, the grain coarsening near the weld fusion line may not be prevented because Ti nitrides are insufficiently formed. Therefore, Ti may be added in an amount of 0.005% or more. However, when Ti is added in an amount greater than 0.02%, Ti carbides may be formed together with the Ti nitrides and hardnesses of a parent material zone and the weld heat affected zone may increase due to a precipitate hardening effect of the Ti carbides, and thus, the possibility of brittle crack initiation may be increased. Therefore, an upper limit of Ti may be limited to 0.02%.

[0034] Niobium (Nb): 0.005% to 0.015%

[0035] Nb is an alloying element that decreases resistance to brittle fractures in a weld heat affected zone when added. However, since Nb greatly contributes to refine a structure during a controlled rolling-accelerated cooling process, Nb is an important element for increasing resistance to brittle fractures in a parent material zone. In particular, in a thick steel sheet having a thickness of 50 mm or more, an effective grain size of 30 μm or less required in the present invention may be difficult to obtain unless refinement of the structure by Nb is accompanied, even in the case in which the controlled rolling-accelerated cooling process is performed. Therefore, Nb may be added in an amount of 0.005% or more in order to secure the resistance to brittle fractures in the parent material zone required in the present invention. However, when Nb is excessively added, the generation of martensitic islands may be promoted to deteriorate toughness of the weld heat affected zone, and thus, an upper limit thereof may be limited to 0.015%.

[0036] Nitrogen (N): 0.002% to 0.006%

[0037] N combines with Ti to form TiN particles and thus, prevents grain coarsening near a weld fusion line. Therefore, N may be required to be included in an amount of 0.002% or more in order to obtain the foregoing effect. However, when N is excessively added, toughnesses of parent material zone and weld heat affected zone may deteriorate by free N atoms which are not combined with Ti. Therefore, an upper limit of N may be limited to 0.006%.

[0038] In the present invention, sufficient physical properties may be secured by the foregoing basic composition. However, copper (Cu) may be added in order to further improve characteristics of the steel sheet. A content of Cu may be 0.35% or less. Cu is an alloying element that may secure strength of the steel sheet as well as being relatively less harmful to the toughness of a weld heat affected zone. However, the strength of the steel sheet excessively increases when Cu is excessively added and thus, stable CTOD toughness may not be obtained in a parent material zone and Cu cracks may be initiated on surfaces of slab and steel sheet. Therefore, an upper limit of Cu may be limited to 0.35%.

[0039] Fe and unavoidable impurities are included as a remainder.

[0040] In the present invention, a value of C+0.5Si-0.1Ni+6Al+3Nb in the composition may be 0.1% or less.

[0041] As a result of in-depth research into alloying elements affecting generation of martensitic islands in a weld heat affected zone, the present inventors deduced a method of minimizing the generation of martensitic islands in the weld heat affected zone under a low to medium heat input welding condition having a heat input range of 0.8 kJ/mm to 4.5 kJ/mm.

[0042] In order to deduce a correlation between the alloying elements and the weld heat affected zone based on the results of the following research, the present inventors conducted weld heat affected zone simulation experiments to simulate an intercritically reheated coarse grained heat affected zone which is known as a region, in which the largest amount of martensitic islands is formed in the weld heat affected zone.

[0043] The intercritically reheated coarse grained heat affected zone was simulated in such a manner that small samples having a thickness of 10 mm, a width of 10 mm, and a length of 60 mm were heated to a temperature of 1400°C and then cooled at a cooling rate of 20°C/s within a temperature range of 800°C to 500°C, and intercritically reheated and then cooled at a cooling rate of 20°C/s within a temperature range of a maximum heated temperature to 500°C. Fatigue cracks were introduced at up to 50% of a width of the heat affected zone simulation samples and CTOD tests were then performed at -40°C. From the result of the tests, a correlation between the alloying elements and CTOD toughness of the weld heat affected zone was deduced and the results thereof are presented in FIG. 1.

[0044] FIG. 1 illustrates a relationship between values of C+0.5Si-0.1Ni+6A1+3Nb and critical CTOD test values at -40°C obtained from the heat affected zone simulation samples. It may be understood that the lower the value of C+0.5Si-0.1Ni+6Al+3Nb is, the higher the critical CTOD value at -40°C of the weld heat affected zone is. When the value of C+0.5Si-0.1Ni+6Al+3Nb is greater than 0.2%, brittle fracture occurred in all samples. According to FIG. 1, it may be understood that the value of C+0.5Si-0.1Ni+6Al+3Nb must be 0.1% or less in order that the critical CTOD value measured at -40°C becomes 0.25 mm or more.

[0045] In a formula of C+0.5Si-0.1Ni+6Al+3Nb, C, Si, Al, and Nb alloying elements promote the initiation of brittle cracks in the weld heat affected zone when added, but only Ni has an opposite effect. The reason for this is that the effect of reinforcing toughness of the matrix structure by Ni is greater than that of decreasing toughness by increasing martensitic islands in the weld heat affected zone as a hardening element.

[0046] In the steel sheet of the present invention, an average circle equivalent diameter of grains having a size belong to top 5% of a minimum of 5000 or more grains defined as boundaries having a grain misorientation of 15 degrees or more measured at a center of the sheet in the thickness direction of the steel sheet by an electron back-scattered pattern (EBSP) method may be 30 μm or less. In the present invention, the center of the sheet in the thickness direction is defined such that it is positioned within ± 1 mm in a thickness direction from a position at 1/2 of the thickness of the steel sheet.

[0047] In general, an image analysis method based on an optical microscopic image is used for measuring a grain size. However, in the foregoing image analysis method, relatively accurate analysis may be possible only when a microstructure is composed of polygonal ferrites and pearlites, and an accurate measurement of grain size may be very difficult because grain boundaries are unclear in a microstructure having acicular ferrites or bainites mixed therein.

[0048] As a result, the present inventors used an EBSP method based on Kikuchi patterns in order to more accurately measure a grain size of the center of the sheet in the thickness direction. The EBSP method has advantage in that an intergranular misorientation may be quantitatively analyzed regardless of a microstructure. When a grain is defined by this method, a boundary having a measured intergranular misorientation of 15 degrees or more is defined as a large-angle grain boundary.

[0049] As a result of comparing a distribution of grain sizes at the center of the sheet in the thickness direction obtained by using the EBSP method and CTOD characteristics, it was found that resistance to brittle crack initiation was determined by grains having a size belong to top 5% of an entire grain size distribution rather than grain sizes of entire grains defined as large-angle grain boundaries. That is, it is very important to inhibit a few coarse grains in the microstructure of the center of the sheet in the thickness direction in order to increase the resistance to brittle crack initiation of the parent material zone.

[0050] In the present invention, an average circle equivalent diameter of grains (effective grains) having a size belong to top 5% of a minimum of 5000 or more grains defined as boundaries (large-angle grain boundaries) having a grain misorientation of 15 degrees or more measured at the center of the sheet in the thickness direction of the steel sheet by the EBSP method is defined as an effective grain size.

[0051] In order to deduce a correlation between the effective grain size defined in the present invention and the resistance to brittle fractures in the parent material zone, samples having various grain sizes were prepared from a slab having a composition of 0.05C-0.04Si-1.62Mn-0.95Ni by varying heating and rolling conditions, and CTOD tests were performed at various temperatures by using the samples and 0.25 mm critical CTOD transition temperatures were then obtained. Herein, the 0.25 mm critical CTOD transition temperature is denoted as a transition temperature when the measured critical CTOD value is 0.25 mm. A relationship between the effective grain size and the 0.25 mm critical CTOD transition temperature measured from each sample is shown in FIG. 2.

[0052] According to FIG. 2, it may be understood that a steel sheet having a minimum critical CTOD value of 0.25 mm or more at -60°C may be obtained when the effective grain size defined in the present invention is 30μm or less. When the effective grain size is greater than 30μm, a critical CTOD value at - 60°C of the parent material zone in the steel sheet becomes 0.25 mm or less, and thus, the target of the present invention may not be satisfied.

[0053] Also, at this time, a basic microstructure of the center of the sheet in the thickness direction may include ferrite, bainite, or a composite structure thereof excluding martensite. The reason for this is that a targeted critical CTOD value may not be obtained because hardness of the martensite structure is so high even in the case of having a fine grain size that a pop-in phenomenon is facilitated at an extremely low temperature such as -60°C.

[0054] That is, in the steel sheet of the present invention, since a critical CTOD value at -60°C of the parent material zone is 0.25 mm or more and a critical CTOD value at -40°C of the weld heat affected zone (HAZ) during welding is 0.25 mm or more, excellent low-temperature brittle crack resistance characteristics are obtained in the parent material zone as well as the weld heat affected zone.

[0055] Hereinafter, a manufacturing method of the present invention will be described in detail.

[0056] A steel slab satisfying the foregoing composition is heated to within a temperature range of 1000°C to 1100°C.

[0057] A continuous cast slab may be used as the slab. Since a continuous casting process has a solidification rate of molten steel and a cooling rate after the solidification faster than those of an ingot process, finer TiN particles may be obtained in a material, and thus, resistance to brittle crack initiation of the parent material zone and of the weld heat affected zone may increase.

[0058] A heating temperature of the slab is an important factor affecting a grain size of a final structure. When the heating temperature of the slab is greater than 1100°C, the final structure may be insufficiently refined and TIN particles in the structure become coarse to decrease toughness of the weld heat affected zone. Therefore, an upper limit thereof may be limited to 1100°C. In contrast, when the heating temperature of the slab is less than 1000°C, alloying elements may be insufficiently dissolved and sufficient rolling may be difficult above a recrystallization temperature. Therefore, the heating of the slab may be performed at a temperature of 1000°C or more.

[0059] The slab is heated and rough rolling is then performed at a cumulative reduction rate of 40% or more and a temperature of 950°C or more. Since recrystallization of austenite grains actively occurs at a temperature of 950°C or more, the grain size may decrease. Also, the reason for having a cumulative reduction rate of 40% or more is that mixed grains may be generated in the final structure because the recrystallization of austenite grains occurs insufficiently when the cumulative reduction rate is less than 40%.

[0060] Finish rolling may be performed within a temperature range of 700°C to 800°C. When the finish rolling temperature is greater than 800°C, resistance to brittle crack initiation may not be secured because refinement of a structure at the center of the sheet in the thickness direction is insufficiently completed. The lower the finish rolling temperature is, the finer the structure at the center of the sheet in the thickness direction may be. However, when the finish rolling temperature is too low, rolling productivity becomes too low and thus, it may be difficult to be applied industrially. Therefore, a lower limit thereof may be limited to 700°C.

[0061] Also, the finish rolling may be performed at a minimum cumulative reduction rate of 40% or more in order to further refine the final structure.

[0062] Cooling is performed after the controlled rolling and at this time, a cooling rate and a cooling stop temperature may be in ranges of 3 °C/s to 20 °C/s and 350°C to 550°C, respectively. Since brittle crack initiation is facilitated when the strength is excessively higher than a target value, it is important not to have excessively high strength. From such a point of view, the cooling rate and the cooling stop temperature may be 20 °C/s or less and 350°C or more, respectively. However, since the strength targeted in the present invention may not be obtained when the cooling is insufficient, the cooling rate and the cooling stop temperature for this purpose may be 3 °C/s or more and 550°C or less, respectively.

[Mode for Invention]

[0063] Hereinafter, an embodiment of the present invention will be described in detail. However, the present invention is not limited to the following embodiment.

[0064] (Embodiment)

[0065] Molten steels were prepared in a 300-ton electric furnace according to compositions presented in Table 1 and 300 mm thick slabs were prepared through a continuous casting method. As shown in Table 2, the slabs thus prepared were heated and subjected to rough rolling and finish rolling, and steels were prepared by final accelerated cooling.

[0066] An electron back-scattered pattern (EBSP) apparatus attached to a scanning electron microscope (SEM) was used for measuring effective grain sizes of the prepared steel sheets. The magnifications used were within a range of 300 times to 500 times, a step size was 0.75 μm, and center of the sheet in the thickness directions of cross sections in rolling and thickness directions were observed. In order to obtain statistically meaningful values, a minimum of 5000 or more grains defined as boundaries having a grain misorientation of 15 degrees or more were included. The effective grain sizes defined in the present invention were calculated by using software able to analyze misorientations measured by the EBSP method. Tensile tests were performed on samples collected from the steel sheets prepared by conditions shown in Tables 1 and 2, and CTOD tests were performed for evaluating resistances to brittle fractures in parent material zones. After collecting the samples in such a manner that a direction perpendicular to the rolling direction at a position of 1/4 of a thickness of the steel sheet from a surface became a length direction of the sample, the samples were machined into rod-shaped specimens for the tensile tests. CTOD samples were machined into full-thickness specimens in accordance with the BS7448 standard and a length direction of the specimen is perpendicular to the rolling direction. Fatigue cracks were generated up to 50% of a width of the samples after notches were made in the CTOD samples by electric discharge machining and CTOD tests were then performed three times for each sample at a temperature of -60°C and each sample was evaluated with a minimum value thereof.

[0067] Evaluations were performed in accordance with the API RP 2Z rule in order to evaluate resistances to brittle crack initiation in the weld heat affected zones of the prepared thick steel sheets. Single-opening lines were made according to the API RP 2Z rule and weldings were performed at welding heat inputs of 0.8 kJ/mm and 4.5 kJ/mm by flux cored arc welding and submerged arc welding, respectively. Welded samples were machined into full-thickness specimens in accordance with the BS7448 standard as in the parent material zones and fatigue cracks were introduced into coarse grain regions near weld fusion lines. CTOD tests were then performed three times for each sample at -40°C and each sample was evaluated with a minimum value thereof.

[0068] Yield strengths and tensile strengths of the steel sheets obtained through the tensile tests, and critical CTOD vales of the parent material zones and the weld zones respectively evaluated at -60°C and -40°C are presented in Table 3. Herein, each critical CTOD value presented in Table 3 was the lowest value among three test values and CTOD-60 denotes a CTOD test value at -60°C evaluated on the parent material zone and CTOD-40 denotes a CTOD test value at -40°C evaluated on the weld heat affected zone.

[Table 1]

Category	C	Si	Mn	P	S	Ni	Al	Ti	Nb	N	Cu	C+0.5Si-0.1N+6Al+3Nb
Inventive Example 1	0.039	0.05	1.57	0.003	0.003	1.30	0.007	0.0012	0.0013	0.0058	-	0.014
Inventive Example 2	0.045	0.04	1.80	0.004	0.002	0.68	0.012	0.008	0.006	0.0036	-	0.086
Inventive Example 3	0.023	0.07	1.75	0.005	0.003	1.14	0.010	0.006	0.013	0.0051	-	0.045
Inventive Example 4	0.046	0.04	1.73	0.003	0.003	1.41	0.012	0.007	0.006	0.0055	-	0.015
Inventive Example 5	0.045	0.10	1.59	0.006	0.002	1.14	0.003	0.005	0.014	0.0022	0.15	0.039
Inventive Example 6	0.024	0.03	1.82	0.003	0.001	1.12	0.013	0.010	0.014	0.0056	-	0.047
Inventive Example 7	0.046	0.08	1.77	0.006	0.002	0.82	0.009	0.009	0.010	0.0043	-	0.087
Inventive Example 8	0.025	0.04	1.73	0.006	0.001	1.02	0.006	0.007	0.011	0.0029	0.29	0.014
Inventive Example 9	0.044	0.09	1.76	0.004	0.001	1.45	0.014	0.011	0.005	0.0050	-	0.044
Inventive Example 10	0.037	0.05	1.77	0.003	0.002	0.84	0.009	0.009	0.009	0.0052	-	0.058
Inventive Example 11	0.044	0.07	1.78	0.007	0.002	1.09	0.014	0.007	0.007	0.0031	-	0.077
Inventive Example 12	0.042	0.03	1.55	0.004	0.002	1.31	0.009	0.012	0.012	0.0059	-	0.014
Inventive Example 13	0.050	0.03	1.65	0.003	0.002	1.05	0.006	0.016	0.015	0.0049		0.038
Inventive Example 14	0.056	0.07	1.52	0.003	0.002	1.44	0.013	0.010	0.013	0.0029	-	0.064
Inventive Example 15	0.040	0.06	1.71	0.005	0.001	0.83	0.013	0.007	0.009	0.0047	0.23	0.092
Inventive Example 16	0.020	0.07	1.85	0.005	0.002	1.30	0.011	0.014	0.014	0.0034	-	0.034
Comparative Example 1	0.047	0.07	1.77	0.006	0.001	0.78	0.013	0.009	0.015	0.0041	-	0.127
Comparative Example 2	0.056	0.15	1.88	0.003	0.002	0.85	0.021	0.009	0.009	0.0047	-	0.199
Comparative Example 3	0.047	0.08	1.71	0.003	0.003	0.71	0.013	0.013	0.021	0.0050	-	0.160
Comparative Example 4	0.069	0.05	1.67	0.004	0.001	0.69	0.005	0.008	0.012	0.0051	-	0.093
Comparative Example 5	0.038	0.09	1.72	0.005	0.001	0.38	0.013	0.008	0.012	0.0033	-	0.158
Comparative Example 6	0.037	0.09	1.77	0.007	0.002	1.47	0.007	0.009	0.013	0.0037	-	0.014
Comparative Example 7	0.045	0.03	1.69	0.003	0.003	1.33	0.008	0.009	0.012	0.0059	-	0.012
Comparative Example 8	0.043	0.09	1.70	0.003	0.003	1.08	0.004	0.011	0.014	0.0049	-	0.048
Comparative Example 9	0.055	0.08	1.82	0.006	0.002	0.92	0.015	0.005	0.014	0.0031	-	0.135

[Table 2]

Category	Slab heating temperature (°C)	Rough rolling cumulative reduction rate (%)	Finish rolling temperature (°C)	Finish rolling cumulative reduction rate (%)	Accelerated cooling stop temperature (°C)	Cooling rate (°C/s)	Steel sheet thickness (mm)
Inventive Example 1	1075	55	751	52	493	4.4	92
Inventive Example 2	1074	41	713	53	394	6.0	76
Inventive Example 3	1057	50	715	54	501	4.0	76
Inventive Example 4	1049	48	782	42	522	7.9	70
Inventive Example 5	1050	50	765	42	443	7.3	72
Inventive Example 6	1095	45	759	48	522	6.6	79
Inventive Example 7	1043	49	734	48	411	5.7	83
Inventive Example 8	1048	51	703	42	500	3.7	94
Inventive Example 9	1075	45	736	47	504	6.9	71
Inventive Example 10	1094	47	770	48	411	5.1	72
Inventive Example 11	1090	59	749	44	456	4.0	87
Inventive Example 12	1079	57	755	55	533	4.2	85
Inventive Example 13	1088	42	789	43	474	3.1	83
Inventive Example 14	1078	52	793	50	397	4.6	71
Inventive Example 15	1063	46	760	43	408	7.1	82
Inventive Example 16	1071	41	768	42	391	4.5	95
Comparative Example 1	1057	41	744	54	396	5.0	81
Comparative Example 2	1096	43	775	47	519	4.8	87
Comparative Example 3	1096	59	775	42	527	5.1	82
Comparative Example 4	1048	48	727	50	380	4.9	92

(continued)

Category	Slab heating temperature (°C)	Rough rolling cumulative reduction rate (%)	Finish rolling temperature (°C)	Finish rolling cumulative reduction rate (%)	Accelerated cooling stop temperature (°C)	Cooling rate (°C/s)	Steel sheet thickness (mm)
Comparative Example 5	1057	50	744	48	440	7.3	87
Comparative Example 6	1087	30	734	50	422	3.6	83
Comparative Example 7	1071	42	790	31	642	7.5	85
Comparative Example 8	1156	42	756	45	435	4.1	91
Comparative Example 9	1091	41	709	49	537	2.1	76

[Table 3]

Category	Parent material zone				Weld heat affected zone	
	Effective grain size (μm)	Yield strength (MPa)	Tensile strength (MPa)	CTOD-60 (mm)	0.8 kJ/mm CTOD-40 (mm)	4.5 kJ/mm CTOD-40 (mm)
Inventive Example 1	17	435	533	0.89	0.88	0.64
Inventive Example 2	26	453	557	0.45	0.43	0.28
Inventive Example 3	21	441	558	0.57	0.60	0.41
Inventive Example 4	12	432	547	1.02	0.61	0.57
Inventive Example 5	26	458	551	0.49	0.67	0.55
Inventive Example 6	14	432	539	0.90	0.48	0.50
Inventive Example 7	27	456	553	0.35	0.55	0.26
Inventive Example 8	11	439	547	0.99	0.70	0.56
Inventive Example 9	15	449	548	0.86	0.49	0.34
Inventive Example 10	29	458	566	0.28	0.68	0.42
Inventive Example 11	11	447	543	1.08	0.44	0.41
Inventive Example 12	29	429	531	0.31	0.72	0.62

(continued)

Category	Parent material zone				Weld heat affected zone	
	Effective grain size (μm)	Yield strength (MPa)	Tensile strength (MPa)	CTOD-60 (mm)	0.8 kJ/mm CTOD-40 (mm)	4.5 kJ/mm CTOD-40 (mm)
Inventive Example 13	25	441	547	0.45	0.68	0.46
Inventive Example 14	13	458	566	0.89	0.58	0.41
Inventive Example 15	15	444	553	0.81	0.31	0.30
Inventive Example 16	13	437	536	0.92	0.44	0.47
Comparative Example 1	20	442	549	0.42	0.29	0.14
Comparative Example 2	21	431	528	0.43	0.09	0.05
Comparative Example 3	19	427	532	0.75	0.12	0.07
Comparative Example 4	22	439	541	0.54	0.17	0.10
Comparative Example 5	35	401	487	0.23	0.19	0.04
Comparative Example 6	42	448	548	0.14	0.40	0.60
Comparative Example 7	39	395	509	0.18	0.37	0.43
Comparative Example 8	45	437	535	0.11	0.42	0.29
Comparative Example 9	16	388	491	0.71	0.31	0.14

[0069] In Inventive Examples 1 to 16 corresponding to the composition and manufacturing method of the present invention, effective grain sizes defined in the present invention were 30 μm or less, critical CTOD values of the parent material zones evaluated at -60°C were 0.25 mm or more, and minimum CTOD values at -40°C of the weld heat affected zones under low and medium heat input conditions were also 0.25 mm or more, and thus, very good resistances to brittle crack initiation were obtained.

[0070] In contrast, in Comparative Example 1, a CTOD value of the weld heat affected zone was not greater than 0.25 mm because a value of C+0.5Si-0.1Ni+6Al+3Nb exceeded 0.1%. Si and Al in Comparative Example 2 did not satisfy the scope of the present invention and the value of C+0.5Si-0.1Ni+6Al+3Nb was also high at 0.199%, and thus, CTOD characteristics of the weld heat affected zone at -40°C was very poor.

[0071] In Comparative Example 3, Nb deviated from the scope of the present invention and the value of C+0.5Si-0.1Ni+6Al+3Nb was also 0.1% or more. In Comparative Example 4, the value of C+0.5Si-0.1Ni+6Al+3Nb was 0.1% or less which satisfied the target of the present invention. However, toughness of the weld heat affected zone was insufficient because the content of C is higher than the scope defined in the present invention. In Comparative Example 5, strength of the steel sheet was insufficient due to an insufficient content of Ni and toughnesses of both the parent material zone and the weld heat affected zone were insufficient.

[0072] With respect to Comparative Examples 6 to 8, alloy compositions were belong to the scope of the present invention and the values of C+0.5Si-0.1Ni+6Al+3Nb were 0.1% or less, and thus, toughnesses of the weld heat affected zones were not poor. However, since manufacturing conditions required in the present invention were not satisfied, effective grain sizes were 30 μm or more. Also, in Comparative Example 7, strength also did not reach the level of the present invention. In Comparative Example 9, toughness of the weld heat affected was deteriorated because the value of C+0.5Si-0.1Ni+6Al+3Nb exceeded 0.1% and yield strength of the steel sheet did not reach 420 MPa because the cooling rate among the manufacturing conditions was insufficient.

[0073] While the present invention has been shown and described in connection with the exemplary embodiments, it will be apparent to those skilled in the art that modifications and variations can be made without departing from the spirit and scope of the invention as defined by the appended claims.

Claims

1. A high-strength steel sheet having excellent resistance to brittle crack initiation comprising:

    0.02 wt% to 0.06 wt% of C (carbon);
    0.1 wt% or less of Si (silicon);
    1.5 wt% to 2.0 wt% of Mn (manganese);
    0.012 wt% or less of P (phosphorous);
    0.003 wt% or less of S (sulfur);
    0.5 wt% to 1.5 wt% of Ni (nickel);
    0.003 wt% to 0.015 wt% of Al (aluminum);
    0.005 wt% to 0.02 wt% of Ti (titanium);
    0.005 wt% to 0.015 wt% of Nb (niobium);
    0.002 wt% to 0.006 wt% of N (nitrogen); and
    Fe (iron) as well as unavoidable impurities as a remainder,
    wherein a value of C+0.5Si-0.1Ni+6Al+3Nb is 0.1 wt% or less.

2. The high-strength steel sheet having excellent resistance to brittle crack initiation of claim 1, wherein the steel sheet further comprises 0.35 wt% or less of Cu (copper).

3. The high-strength steel sheet having excellent resistance to brittle crack initiation of claim 1, wherein an average circle equivalent diameter of grains having a size belong to top 5% of a minimum of 5000 or more grains defined as boundaries having a grain misorientation of 15 degrees or more measured at a center of the sheet in the thickness direction of the steel sheet by an electron back-scattered pattern method is 30 μm or less.

4. The high-strength steel sheet having excellent resistance to brittle crack initiation of claim 3, wherein a structure at the center of the sheet in the thickness direction of the steel sheet comprises any one of ferrite, bainite, and a composite structure thereof.

5. The high-strength steel sheet having excellent resistance to brittle crack initiation of claim 1, wherein a critical CTOD (crack tip opening displacement) value at -60°C of a parent material zone of the steel sheet is 0.25 mm or more and a critical CTOD value at -40°C of a weld HAZ (heat affected zone) is 0.25 mm or more.

6. A method of manufacturing a high-strength steel sheet having excellent resistance to brittle crack initiation, the method comprising:

    heating a steel slab including 0.02 wt% to 0.06 wt% of C (carbon), 0.1 wt% or less of Si (silicon), 1.5 wt% to 2.0 wt% of Mn (manganese), 0.012 wt% or less of P (phosphorous), 0.003 wt% or less of S (sulfur), 0.5 wt% to 1.5 wt% of Ni (nickel), 0.003 wt% to 0.015 wt% of Al (aluminum), 0.005 wt% to 0.02 wt% of Ti (titanium), 0.005 wt% to 0.015 wt% of Nb (niobium), 0.002 wt% to 0.006 wt% of N (nitrogen), and Fe (iron) as well as unavoidable impurities as a remainder, and having a value of C+0.5Si-0.1Ni+6Al+3Nb of 0.1% or less within a temperature range of 1000°C to 1100°C;
    rough rolling the heated slab at a cumulative reduction rate of 40% or more and a temperature of 950°C or more;
    finish rolling within a temperature range of 700°C to 800°C after the rough rolling; and
    cooling the rolled steel sheet.

7. The method of claim 6, wherein the steel slab further comprises 0.35 wt% or less of Cu (copper).

8. The method of claim 6, wherein the finish rolling is performed at a cumulative reduction rate of 40% or more.

9. The method of claim 6, wherein a cooling rate and a cooling stop temperature in the cooling are in ranges of 3 °C/s to 20 °C/s and 350°C to 550°C, respectively.

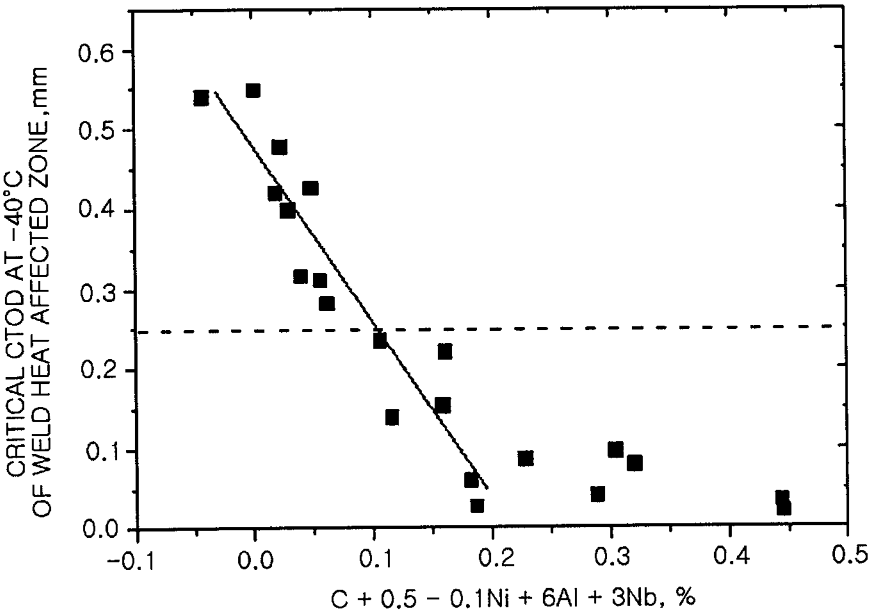
CRITICAL CTOD AT -40°C
OF WELD HEAT AFFECTED ZONE,mm
0.0
0.1
0.2
0.3
0.4
0.5
0.6
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
C + 0.5 - 0.1Ni + 6Al + 3Nb, %

FIG. 1

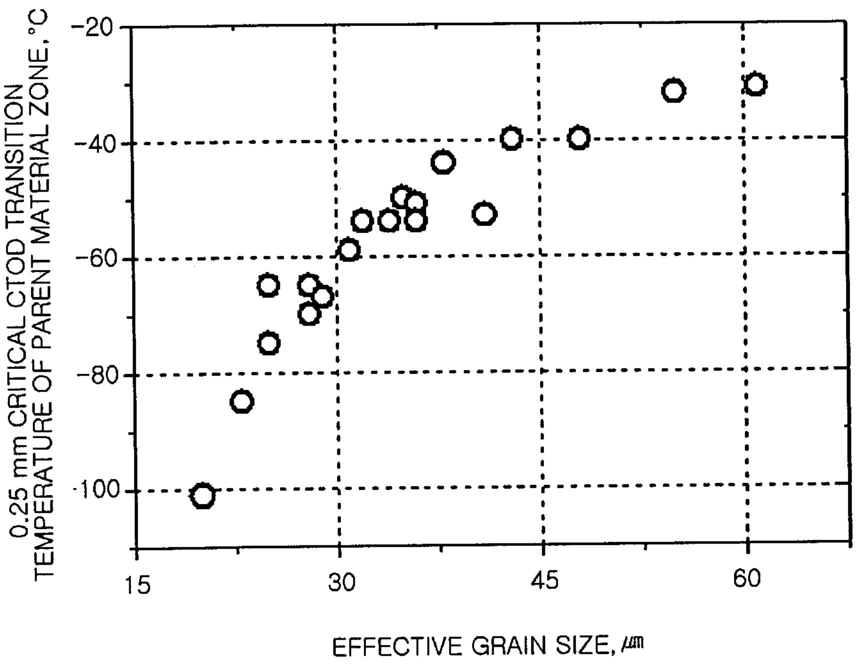
0.25 mm CRITICAL CTOD TRANSITION
TEMPERATURE OF PARENT MATERIAL ZONE, °C
-20
-40
-60
-80
-100
15
30
45
60
EFFECTIVE GRAIN SIZE, ㎛

FIG. 2

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- KR 20020028203 **[0006]**
- KR 20080067957 **[0007]**
- KR 20060090287 **[0008]**