

(19)



Europäisches Patentamt

European Patent Office

Office européen des brevets



(11)

EP 1 312 690 A1

(12)

EUROPEAN PATENT APPLICATION

(43) Date of publication:

21.05.2003 Bulletin 2003/21

(51) Int Cl.7: **C22C 38/04**, C22C 38/40,
C22C 38/44, C22C 38/42,
C22C 38/48, C22C 38/46,
C22C 38/54, C22C 38/50,
C21D 8/02

(21) Application number: **02025246.6**

(22) Date of filing: **12.11.2002**

(84) Designated Contracting States:

**AT BE BG CH CY CZ DE DK EE ES FI FR GB GR
IE IT LI LU MC NL PT SE SK TR**

Designated Extension States:

AL LT LV MK RO SI

(30) Priority: **14.11.2001 JP 2001349220**

09.05.2002 JP 2002134471

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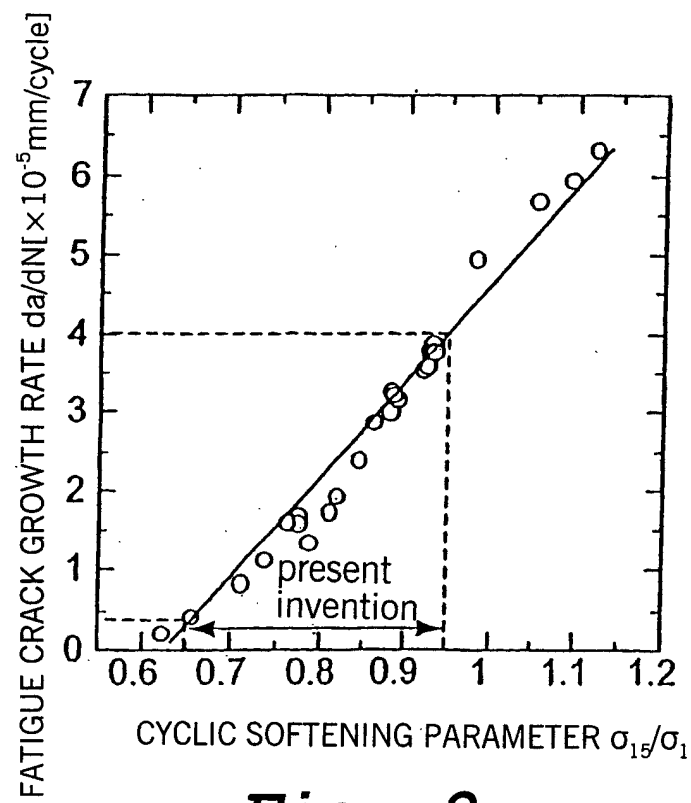
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(54) **Steel material having improved fatigue crack driving resistance and manufacturing process therefor**

(57) The present invention provides a structural steel material and a manufacturing process therefor, which makes it possible to perform material design using a quantitative assessment of fatigue resistance in steel materials which undergo cyclic softening. The steel material according to the present invention has a cyclic softening parameter of at least 0.65 and at most 0.95, the cyclic softening parameter being represented by the ratio (σ_{15}/σ_1) of the stress at the maximum strain in the first cycle (σ_1) to that in the 15th cycle (σ_{15}) measured when a waveform of incremental and decremental cyclic loads is applied 15 times with a maximum tensile and compressive strain of ± 0.012 , a frequency of 0.5 Hz, and the number of waves to the maximum strain being 12. The structural steel material comprises C: 0.02-0.20%, Si: at most 0.60%, Mn: 0.50 - 2.0%, Al: 0.003 - 0.10%, and optionally a small amount of one or more elements of Cu, Ni, Cr, Mo, V, Nb, Ti, B, and Ca, and has a value of carbon equivalent, Ceq, represented by the following formula of from 0.28 - 0.65:

$$\text{Ceq (\%)} = \text{C} + \text{Si}/24 + \text{Mn}/6 + \text{Ni}/40 + \text{Cr}/5 + \text{Mo}/4 + \text{V}/14.$$

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**Fig. 2**

DescriptionTechnical Field

5 **[0001]** This invention relates to a steel material which has improved fatigue crack driving resistance and which is suitable for use in applications where a steel material is expected to undergo repeated loads, such as boats and ships, marine structures, bridges, buildings, tanks, and industrial or construction equipment, for example, and it also pertains to a process for manufacturing the steel material.

10 Background Art

15 **[0002]** For steel materials which are used in boats and ships, marine structures, bridges, buildings, tanks, and industrial or construction equipment, it is necessary to pay attention to fatigue properties in order to guarantee their safety, since repeated loads are often applied thereto. It is known that fatigue fracture of a steel material is greatly influenced by environmental conditions and that when a steel material undergoes repeated loads in a corrosive environment such as in seawater, its strength decreases.

20 **[0003]** The fatigue process of a steel material should be considered by dividing it into two stages, i.e., generation of a crack in an area where stress concentration occurs and subsequent growth of the crack, which are different in nature from each other. In usual machine parts, generation of a macroscopic crack is considered to be the working limit, so they are almost never designed to accept crack growth. However, with a structure having a high redundancy, generation of a fatigue crack does not soon lead to a fracture of the structure. Therefore, even if a fatigue crack is found in a structure by a routine inspection before final fracture occurs, in the case where the cracked portion is repaired or the crack does not grow during the service life of the structure to a length sufficient to cause final fracture, the structure still endures to use adequately in spite of the fatigue crack.

25 **[0004]** In a welded structure, since there are many toes of weld which become stress-concentrated areas, it is nearly impossible from a technical standpoint and also not advisable from an economical viewpoint to completely prevent the generation of fatigue cracks. Therefore, it is important to retard crack growth as much as possible so as to greatly extend the fatigue life (remaining life) from a state in which cracks exist.

30 **[0005]** With respect to a technique designed to retard fatigue crack growth and extend fatigue life of a steel material, JP P05-185441A discloses an approach in which microcracks are formed at the tip of a fatigue crack. However, the effectiveness of this approach is limited to a crack in which the stress intensity factor range ΔK (the difference between the maximum and minimum stress intensity factor) is small, that is, the case where the crack is not long and the stress level is low. It is thought that this approach is less effective for a crack having a medium level of ΔK range, which originates from a weld and has a considerable length.

35 **[0006]** JP P04-337026A proposes a method for manufacturing a high-strength hot-rolled steel plate having improved fatigue strength and fatigue crack propagating resistance in which the phosphorus and copper contents are controlled such that the steel has dual phases of ferrite with a grain size of 5 - 25 μm and a second phase comprising 10% - 30% by volume. In that patent application, the fatigue crack propagating resistance indicates the threshold stress intensity factor (ΔK_{th}) for fatigue crack growth. Thus, the proposed technique has an effect of increasing the threshold stress intensity factor that is the lower limit for causing a fatigue crack to grow but it is not effective in retarding fatigue crack growth.

40 **[0007]** Japanese Patent No. 2,692,134 discloses a steel plate having a fatigue crack growth inhibiting effect which comprises a hard phase-forming matrix and a soft phase dispersed in the matrix, the difference in hardness between the two phases being at least 150 in terms of Vickers hardness. However, that patent does not disclose the mechanical properties of the steel. Moreover, that technique is applicable only in situations in which the hard and soft phases of the structure are clearly distinguishable from each other. In general, since the structure should be made fine in order to improve the strength and toughness of the steel, the hard and soft phases are not always clearly distinguishable from each other to such an extent that the difference in hardness can be measured.

45 **[0008]** JP P2001-41868A discloses a method for assessing the fatigue crack growth rate of a steel material containing at least 20% of bainite on the basis of the amount of softening (cyclic softening parameter) determined when repeated loads are applied to the steel with a controlled strain having a stress ratio of -4 to -0.25 and an alternating waveform. According to that method, as long as a master curve showing the correlation between the amount of cyclic softening and the fatigue crack growth rate has been prepared, the fatigue crack growth rate can be assessed quickly and efficiently from the amount of cyclic softening.

50 **[0009]** However, that method is merely an assessment method and it is not a measure which is capable of providing an excellent steel which is worth while assessing by the method. There is no disclosure as to whether the steel described therein has adequate strength, toughness, and weldability as a structural steel.

55 **[0010]** It has been known that under conditions in which a cyclic strain is imposed, a steel having a hardened structure

becomes softer (i.e, shows cyclic softening), while an annealed steel becomes harder. For steel materials showing cyclic softening, since the nature of fatigue properties has not been elucidated, they do not have an established criterion of industrial design. As a result, such steel materials have not been employed in those applications which exploit their fatigue properties.

Disclosure of Invention

[0011] It is an object of the present invention to provide a structural steel material which makes it possible to perform material design by using fatigue properties as a quantitative parameter, particularly in a steel material showing cyclic softening, and a process for manufacturing such a steel material.

[0012] The present invention provides a steel material having improved fatigue crack driving resistance and a manufacturing method therefor on the basis of investigations on fatigue properties of steel materials including softening behavior under conditions in which a cyclic strain is imposed. The steel material also has strength, toughness, and weldability which are optimal for structural steel for use in boats and ships, marine structures, bridges, buildings, tanks, industrial or construction equipment, and the like.

[0013] A steel material having improved fatigue crack driving resistance according to the present invention has a cyclic softening parameter of at least 0.65 and at most 0.95, the cyclic softening parameter being represented by the ratio (σ_{15}/σ_1) of the stress at the maximum strain in the first cycle (σ_1) to that in the 15th cycle (σ_{15}) measured when a waveform of incremental and decremental cyclic loads is applied 15 times with a maximum tensile and compressive strain of ± 0.012 , a frequency of 0.5 Hz, and the number of waves to the maximum strain being 12.

[0014] The steel material preferably has a composition by mass% which comprises C: 0.02 - 0.20%, Si: at most 0.60%, Mn: 0.50 - 2.0%, Al: 0.003 - 0.10%, and optionally one or more elements selected from (A) one or more of Cu: at most 1.5%, Ni: at most 1.5%, Cr: at most 1.20%, Mo: at most 1.0%, and V: at most 0.10%, (B) one or two of Nb: at most 0.10% and Ti: at most 0.10%, (C) B: 0.0003 - 0.0020%, and (D) Ca: 0.0005 - 0.010%, and which has a value of carbon equivalent, Ceq, represented by the following formula of from 0.28 - 0.65:

$$\text{Ceq (\%)} = \text{C} + \text{Si}/24 + \text{Mn}/6 + \text{Ni}/40 + \text{Cr}/5 + \text{Mo}/4 + \text{V}/14.$$

[0015] The steel material having improved fatigue crack driving resistance according to the present invention can be manufactured by any of the following processes:

(a) a process comprising subjecting a hot-rolled steel material of the above-described composition to heat treatment one or more times, the heat treatment comprising reheating to a temperature above the A_{c1} point followed by cooling to 550°C or below at a cooling rate of at least 5°C/s;

(b) a process comprising cooling a hot-rolled steel material of the above-described composition from a temperature range of at least (A_{r3} point - 100)°C and at most (A_{r3} point + 150)°C to 550°C or below at a cooling rate of at least 5°C/s; and

(c) a process comprising cooling a hot-rolled steel material of the above-described composition from a temperature range of at least (A_{r3} point - 100)°C and at most (A_{r3} point + 150)°C to 550°C or below at a cooling rate of at least 5°C/s and subsequently subjecting it to heat treatment one or more times, the heat treatment comprising reheating to a temperature above the A_{c1} point followed by cooling to 550°C or below at a cooling rate of at least 5°C/s.

[0016] In any of the above-described processes, a final heat treatment may be performed by tempering with heating to a temperature below the A_{c1} point.

Brief Description of Drawings

[0017]

Figure 1 is a diagram showing an incremental and decremental strain waveform;

Figure 2 is graph showing the cyclic softening parameter and the fatigue crack growth rate; and

Figure 3 is a graph showing the amount of strain at the tip of a fatigue crack determined by the finite element method.

Detailed Description of the Invention

[0018] Now the present invention will be described in detail. In the following description, all percentages are mass% unless otherwise indicated.

[0019] The present invention relates to assessment of a steel material with respect to the degree of softening under conditions that a cyclic strain is imposed, so a steel material to which the present invention pertains has a structure which becomes softer when subjected to cyclic strain (i.e., a hardened structure).

[0020] A steel material having a hardened structure becomes softer by loading with a cyclic strain to give a cyclic softening parameter σ_{15}/σ_1 . It has been found that the value of the cyclic softening parameter σ_{15}/σ_1 has a correlation with the fatigue crack growth rate (da/dN) in a stress intensity factor range (ΔK) of $20 \text{ MPa}\cdot\text{m}^{0.5}$ which is ordinarily used and thus can be used for assessment of fatigue crack growth rate.

[0021] If a steel material has a cyclic softening parameter of less than 0.65, it will have a low crack growth rate, but its toughness and weldability will be deteriorated and its use as a structural steel will be significantly limited. On the other hand, if it has a cyclic softening parameter of greater than 0.95, not only does the crack growth rate become high, but the strength is decreased. Thus, the cyclic softening parameter is made at least 0.65 and at most 0.95. It is preferably at least 0.70 and at most 0.90.

[0022] The cyclic softening parameter σ_{15}/σ_1 used herein will be described.

[0023] The waveform of the strain which is imposed on a steel material to determine the cyclic softening parameter is an alternating waveform in which tensile and compressive loads are applied alternately in order to assess the amount of cyclic softening of the steel material. The waveform is an incremental and decremental waveform with a frequency of 0.5 Hz and a strain range of 0.024 during strain incrementation (a maximum tensile and compressive strain of ± 0.012). The frequency of 0.5 Hz was selected in view of suppressing internal heat build-up. The strain range of 0.024 was selected since the stress intensity factor range (ΔK) which is ordinarily employed is $20 \text{ MPa}\cdot\text{m}^{0.5}$. In the incremental stage, the strain reaches a maximum value in 12 waves, and in the decremental stage, it returns to zero in 12 waves. A combination of a single incremental stage and a single decremental stage constitutes a set, which is hereafter referred to as a "block".

[0024] Figure 1 shows a diagram of strain waveform in which the abscissa is time (sec) and the ordinate is the amount of strain. Only the first and second blocks are shown in the figure, but the number of blocks is fifteen or the incremental and decremental strain waveform is repeated 15 times. Fifteen repetitions for the block were selected since it is thought that the softening effect attained by cyclic strain will almost saturate by 15 blocks.

[0025] The ratio σ_{15}/σ_1 is defined as a cyclic softening parameter, where σ_1 is the stress corresponding to the maximum strain in the first block and σ_{15} is the stress corresponding to the maximum strain in the 15th block.

[0026] Figure 2 is a graph showing the relationship between the cyclic softening parameter defined above and the fatigue crack growth rate. As described above, a certain correlation can be observed between these parameters.

[0027] The mechanism thereof is considered to be as follows.

[0028] Application of a cyclic load with alternating tensile and compressive or positive and negative forces to a steel material causes inversion movement of dislocations at the tip of a fatigue crack, and the dislocations move or disappear to cause the material to soften. The softening relaxes the strain at the tip of the fatigue crack, thereby decreasing the driving force of fatigue crack growth.

[0029] The strain relaxation phenomenon at the tip of a fatigue crack was analyzed by the finite element method. The mechanical properties of the steel which underwent cyclic softening (cyclically softened material) were divided into analysis elements to describe a softened zone around a fatigue crack, and a model to which a load is applied such that the stress intensity factor range at the crack tip or front is $20 \text{ MPa}\cdot\text{m}^{0.5}$ was presumed.

[0030] Figure 3 shows a result of the analysis in terms of the strain at the tip of a fatigue crack of a homogeneous steel material compared to that of a cyclically softened material. It was confirmed that the strain of a cyclically softened material at the tip of a fatigue crack is smaller than that of a homogeneous material. Thus, in a cyclically softened steel material, it is thought that relaxation of strain imposed on the crack tip contributes to suppression of fatigue crack growth.

[0031] A target in the present invention is that a steel material has a fatigue crack growth rate (da/dN) of at most $4.0 \times 10^{-5} \text{ mm/cycle}$ with a stress intensity factor range of $20 \text{ MPa}\cdot\text{m}^{0.5}$ in a fatigue test in air.

[0032] In a preferred embodiment, a steel material according to the present invention has the chemical composition described above for the following reasons.

Carbon: 0.02 - 0.20%

Carbon (C) is an element which is effective in order to provide a structural steel with strength. With a carbon content of less than 0.02%, it is difficult to achieve the strengthening effect. On the other hand, a carbon content of greater than 0.20% decreases the weldability of a steel and makes it difficult to process the steel by welding, thereby limiting its working range as a structural steel. In order to attain a high strength with good weldability, the carbon content is preferably in the range of 0.04 - 0.15%.

Silicon: at most 0.60%

Silicon (Si) has a deoxidizing effect. However, an Si content of greater than 0.60% deteriorates the toughness of a steel. Preferably, the Si content is 0.05 - 0.5%.

Manganese: 0.50 - 2.0%

Manganese (Mn) is also an element which has an effect of providing a steel with strength. With an Mn content

of less than 0.50%, its effect is not sufficient. An Mn content of greater than 2.0% deteriorates the toughness of a steel. Preferably, the Mn content is 0.70 - 1.8%.

Aluminum: 0.003 - 0.10%

[0033] Aluminum (Al) has a deoxidizing effect. With an Al content of less than 0.003%, its effect is not sufficient. An Al content of greater than 0.10% deteriorates the toughness of a steel. Preferably, the Al content is 0.010 - 0.050%.

[0034] The steel material according to the present invention may further contain at least one element selected from the following groups, in addition to the above-described elements:

(A) at least one of Cu, Ni, Cr, Mo, and V;

(B) Nb and/or Ti;

(C) B; and

(D) Ca.

Copper: at most 1.5%

[0035] Copper (Cu) is an element which is effective in order to improve the strength and corrosion resistance of a steel, but a Cu content of greater than 1.5% causes the steel to have a deteriorated toughness. A preferable content of Cu, when added, is 0.10 - 1.0%.

Nickel: at most 1.5%

Nickel (Ni) is an element which is effective in order to improve the strength and toughness of a steel. However, when Ni is added in an amount of greater than 1.5%, not only are these effects saturated, but costs are increased. A preferable content of Ni, when added, is 0.050 - 1.3%.

Chromium: at most 1.2%

Like Cu, chromium (Cr) is an element which is effective in order to improve the strength and corrosion resistance of a steel. However, a Cr content of greater than 1.5% causes the steel to have a deteriorated toughness. A preferable content of Cr, when added, is 0.10 - 1.0%.

Molybdenum: at most 1.0%

Molybdenum (Mo) is an element which is effective in order to improve the hardenability and strength of a steel. However, when the Mo content is greater than 1.0%, not only is the toughness deteriorated, but costs are increased. A preferable content of Mo, when added, is 0.050 - 0.80%.

Vanadium: at most 0.10%

Vanadium (V) has an effect of increasing the strength of a steel and may be added in order to secure a high strength as a structural steel. However, the addition of V in an amount of greater than 0.10% deteriorates the toughness of the steel. A preferable content of V, when added, is 0.010 - 0.080%.

Niobium; at most 0.10%

Niobium (Nb) is an element which is effective in order to improve the toughness of a steel. However, the addition of Nb in an amount of greater than 0.10% results in a decrease in toughness to the contrary. A preferable content of Nb, when added, is 0.020 - 0.050%.

Titanium: at most 0.10%

Like Nb, titanium (Ti) is also an element which has an effect of improving the toughness of a steel. However, to the contrary, the addition of Ti in an amount of greater than 0.10% results in a decrease in toughness. A preferable content of Ti, when added, is 0.010 - 0.050%.

Boron: 0.00030 - 0.020%

Boron (B) is an element which is effective in improving the hardenability of a steel and controlling the ferrite content thereof. These effects are not exhibited sufficiently with a B content of less than 0.00030%. On the other hand, a B content of greater than 0.00020% causes the toughness of the steel to deteriorate. A preferable content of B, when added, is 0.00080 - 0.0015%.

Calcium: 0.00050 - 0.010%

Calcium (Ca) is an element which has an effect of spheroidizing non-metallic inclusions and improving the toughness of a steel. Such an effect is not achieved with a Ca content of less than 0.00050%. When the Ca content is greater than 0.010%, a large amount of inclusions such as CaO and CaS are formed, leading to a deterioration in toughness. A preferable content of Ca, when added, is 0.0010 - 0.0050%.

Carbon equivalent (Ceq): 0.28 - 0.65%

$$\text{Ceq (\%)} = \text{C} + \text{Si}/24 + \text{Mn}/6 + \text{Ni}/40 + \text{Cr}/5 + \text{Mo}/4 + \text{V}/14$$

[0036] The carbon equivalent, Ceq, which has the above formula, is an index to assess the hardenability and weldability of a steel material and is widely used. However, Ceq has been used merely as an index to obtain a steel material

having desired mechanical properties and weldability, and there has been found no research which investigates C_{eq} in relation to fatigue crack driving resistance.

[0037] In order to suppress fatigue crack growth and satisfy the strength properties generally desired for a structural steel, i.e., a tensile strength, TS, of at least 500 N/mm² and Charpy absorbed energy value at 0°C, vE_0 , of at least 27 J, a steel material should have a fine (not coarsened) microstructure. The present inventors have found that with a steel having a fine microstructure, the value of C_{eq} has a relation not only to the mechanical properties and weldability of the steel, but to the fatigue crack growth rate thereof.

[0038] Namely, with a steel having a value of C_{eq} of less than 0.28%, not only is its strength low, but the fatigue crack growth is not sufficiently suppressed due to its low level of cyclic softening. On the other hand, with a steel having a value of C_{eq} of greater than 0.65%, although the fatigue crack growth of the steel is suppressed, its weldability is deteriorated, and it is difficult to work the steel material by welding, leading to a severe limitation in its use.

[0039] Next, a method of manufacturing a steel material according to the present invention will be described.

[0040] A mass of a steel having a composition as described above which has been prepared by continuous casting, for example, is hot-rolled. The resulting hot-rolled steel plate is then cooled at a controlled cooling rate and/or subjected to heat treatment so as to obtain a steel material having a cyclic softening parameter adjusted to at least 0.65 and at most 0.95.

[0041] The hot rolling process is not critical and may be performed in a conventional manner. A steel material according to the present invention is generally in the form of a hot-rolled plate, but it may be in another form such as shape steel, bar, pipe, or the like depending on the use thereof. Thus, the hot-rolling process may be replaced by other hot-working process.

[0042] Following the hot rolling, heat treatment is performed by reheating to a temperature above the Ac_1 point followed by rapid cooling, or the steel plate as hot-rolled is cooled rapidly, or a combination of these is employed, as described below, thereby resulting in the formation of a steel material having a hardened structure in which the cyclic softening parameter is between 0.65 and 0.95. Thereafter, the steel material may be further subjected to tempering as described below.

Heat Treatment (Reheating and Rapid Cooling):

[0043] The temperature at which the hot-rolled steel material is reheated is above the Ac_1 point of the steel. If the temperature for reheating is less than the Ac_1 point, no austenite transformation occurs, so a steel material having the desired cyclic softening parameter cannot be obtained and the steel material has deteriorated fatigue crack growth properties. A preferable temperature range for reheating is between 100°C and 300°C above the Ac_1 point.

[0044] Following reheating, rapid cooling is performed at a cooling rate of at least 5°C/s. If the cooling rate is less than 5°C/s, cooling is so slow that the resulting steel material has an increased fatigue crack growth rate and a decreased strength and toughness. The cooling rate after reheating is preferably at least 10°C/s. Although there is no particular upper limit on the cooling rate, it depends on the size of the steel material (the thickness if it is a steel plate). For example, it is possible for a steel plate having a thickness of 10 mm or smaller to achieve a cooling rate of 50°C or higher.

[0045] The temperature at which the rapid cooling is stopped is 550°C or lower. If the cooling is stopped at a temperature above 550°C, the steel material has an increased fatigue crack growth rate and hence deteriorated cyclic softening properties. A preferable temperature at which the rapid cooling is stopped is 450°C or below.

[0046] The above-described heat treatment by reheating and subsequent rapid cooling may be performed two or more times as required. In order to maintain the hardened structure thus formed, after the heat treatment, the steel material is not subjected to additional heat treatment except for the after-mentioned tempering.

Rapid Cooling Following Hot Rolling:

[0047] A steel material having a cyclic softening parameter of 0.65 - 0.95 can be produced merely by rapidly cooling the steel material as hot-rolled from a temperature range of from (Ar_3 point - 100)°C to (Ar_3 point + 150)°C.

[0048] The cooling rate just after hot rolling is at least 5°C/s and the temperature at which the rapid cooling is stopped is 550°C or below for the same reasons described above for cooling after reheating.

[0049] If the temperature at which the rapid cooling is started is lower than (Ar_3 point - 100)°C, the cyclic softening properties and strength are deteriorated. On the other hand, if it is higher than (Ar_3 point + 150)°C, the austenite grains in the steel are coarsened, thereby deteriorating the toughness. A preferable temperature at which rapid cooling is started is in the range of from (Ar_3 point - 50)°C to (Ar_3 point + 100)°C.

[0050] After the hot-rolled steel plate is rapidly cooled in the above-described manner, the aforementioned heat treatment by reheating and subsequent rapid cooling may be performed one or more times.

Tempering:

[0051] The steel material which has been rapid cooled after hot rolling and/or reheating in the above-described manner may be finally subjected to tempering. Particularly, when the rapid cooling is performed at a higher cooling rate (e.g., 50°C or higher), it is preferable to perform tempering, since a significant improvement in toughness can be attained by tempering. The tempering temperature is below the Ac_1 point of the steel. If it is higher than the Ac_1 point, tempering causes austenite transformation, thereby deteriorating the cyclic softening properties and decreasing the strength and toughness. The tempering temperature is preferably 550°C or below.

[0052] A steel material according to the present invention has a cyclic softening parameter in the range of from 0.65 to 0.95. It should be understood by those skilled in the art from the foregoing description that the cyclic softening parameter can be adjusted by the conditions for heat treatment and cooling and/or Ceq .

[0053] In accordance with the present invention, it is possible to quantitatively assess the fatigue properties of a steel material and hence to perform material design using the assessment. It also becomes feasible to provide a steel material having improved fatigue crack driving resistance by use of the material design. The steel material exhibits excellent properties even in an environment containing chlorine or chloride ions. Therefore, it is suitable for use in various structures including boats and ships, marine structures, bridges, buildings, tanks, and industrial or construction equipment.

Examples

(Example 1)

[0054] Steels each having a composition and a value of Ceq as shown in Table 1 were prepared by melting in a test furnace in a conventional manner. Table 1 also shows the values of the Ar_3 and Ac_1 points of each steel.

[0055] Each steel was made in the form of a slab 150 mm in thickness by normal hot forging. The slab was heated to 1150°C and hot-rolled to produce a steel plate having a thickness shown in Table 1.

[0056] These steel sheets were subjected to the following procedures.

[0057] For Steels 1, 2, and 13 which had a thickness of 10 mm or smaller, each hot-rolled steel plate was subjected to heat treatment once by reheating to 200°C above its Ac_1 point followed by cooling to room temperature at a cooling rate of 60°C/s, and finally tempering was performed at 400°C.

[0058] For Steels 3 - 12 and 14 - 28, immediately after hot-rolling, each steel plate was cooled to 450°C starting from the temperature that was equal to 50°C above its Ar_3 point. The cooling rate was 30°C/s for a plate thickness of 15 mm, 20°C/s for a plate thickness of 25 mm, 10°C/s for a plate thickness of 40 mm, or 5 - 8°C/s for a plate thickness of 50 mm. Tempering was not performed.

[0059] Appropriate test pieces or specimens were taken from these steel plates so as to evaluate a central portion along the thickness of each plate and were used for a cyclic softening test, a fatigue crack growth test, a tensile test, and a Charpy impact test.

[0060] The cyclic softening test was conducted in air at room temperature with a purely alternating strain waveform using a test bar having a diameter of 6 - 8 mm and a parallel length of 15 mm, which had been taken from a central portion of the steel plate in its thickness direction in such a manner that the longitudinal direction of the test bar was coincident with the rolling direction. An extensometer having a gauge length of 12.5 mm was attached to the parallel zone of the test bar, and an axial force was applied to the test bar while controlling the strain by use of the extensometer as a sensor. The testing machine used was an electro-hydraulic closed-loop fatigue testing machine, and the strain waveform was an incremental step waveform of the incremental and decremental type. The waveform had a frequency of 0.5 Hz and a strain range of 0.024, and the strain reached the maximum strain in 12 waves during a strain incremental stage and returned to zero in 12 waves in a strain decremental stage (see Figure 1).

[0061] As described previously, a set of such an incremental and a decremental stage is referred to as a "block". The stress corresponding to the maximum strain in the first block was measured and taken as σ_1 , while that corresponding to the maximum strain in the 15th block was measured and taken as σ_{15} , and the ratio σ_{15}/σ_1 was determined as a cyclic softening parameter.

[0062] In the fatigue crack growth test, a CT (compact) specimens was taken in such a manner that the crack growing direction was perpendicular to the rolling direction of the plate. The test was performed in air at room temperature under loading conditions of a frequency of 25 Hz and stress ratio (minimum stress/maximum stress) of 0.1 in accordance with ASTM Specifications (E647).

[0063] The fatigue crack growth rate was determined to be the growth rate at the point that the stress intensity factor range ΔK at the crack tip was 20 MPa·m^{0.5}. In view of the fatigue crack growth rate of conventional materials which is within the range of 5 to 6×10⁻⁵ mm/cycle, the target fatigue crack growth rate was set at 4.0×10⁻⁵ mm/cycle or lower.

[0064] The tensile test was performed with a No. 4 test piece specified in JIS Z2201 (1998), which was taken from

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a central portion of the steel plate in its thickness direction in such a manner that the longitudinal direction of the test piece was perpendicular to the rolling direction of the plate.

[0065] The Charpy impact test was carried out with a V-notched impact test piece specified in JIS Z2202 (1998), which was taken from a central portion of the steel plate in its thickness direction in such a manner that the longitudinal direction of the test piece was coincident with the rolling direction of the plate. The test was repeated three times at each test temperature, and the brittle-ductile fracture transition temperature (vTrs) was determined.

[0066] The results of these tests are shown in Table 2. In the table, the marks "○", "Δ", and "×" in the tensile test and the Charpy impact test indicate the following.

[0067] In the tensile test, the mark "○" indicates that the tensile strength is 500 MPa or higher and the mark "Δ" indicates that it is lower than 500 MPa.

[0068] In the Charpy impact test, the mark "○" indicates that the brittle-ductile fracture transition temperature (vTrs) is -20°C or lower, the mark "Δ" indicates that it is higher than -20°C and up to 0°C, and the mark "×" indicates that it is higher than 0°C. When the value of vTrs of a material is -20°C or lower, the absorbed energy is, on the average, at least 150 J at 0°C and at least 100 J at -20°C.

Table 1
(Balance: Fe)

Steel No.	C (%)	Si (%)	Mn (%)	Cu (%)	Ni (%)	Cr (%)	Mo (%)	V (%)	Nb (%)	Ti (%)	Al (%)	B (%)	Ca (%)	Ceq (%)	Thick-ness (mm)	Ar ₃ point (°C)	Ac ₁ point (°C)
1	0.09	0.23	1.10	—	—	—	—	—	—	—	0.027	—	—	0.283	8	794	694
2	0.10	0.30	1.30	—	—	—	—	—	—	—	0.031	—	—	0.329	10	776	691
3	0.09	0.22	1.46	—	—	—	—	—	0.014	0.018	0.025	—	—	0.343	15	768	688
4	0.06	0.44	1.51	—	—	0.16	—	—	0.025	0.018	0.024	—	—	0.362	25	774	688
5	0.06	0.45	1.50	—	—	0.16	0.15	—	0.026	0.012	0.031	—	—	0.398	50	772	687
6	0.08	0.30	1.54	—	—	—	0.14	0.057	0.034	0.017	0.024	—	—	0.388	40	762	685
7	0.06	0.18	1.38	0.26	0.27	0.12	0.29	0.039	0.039	0.018	0.025	—	—	0.404	40	747	682
8	0.05	0.11	1.47	0.32	0.29	—	—	—	0.011	—	0.025	0.0010	—	0.307	25	761	681
9	0.07	0.13	1.62	0.28	0.21	—	—	0.045	0.031	0.015	0.021	—	0.0024	0.354	25	748	681
10	0.05	0.05	1.55	—	—	0.92	0.58	—	—	0.013	0.025	0.0011	—	0.641	50	725	691
11	0.12	0.12	0.95	—	—	0.73	0.25	0.041	—	0.019	0.022	0.0009	—	0.495	50	781	704
12	0.14	0.17	1.08	—	—	0.63	0.34	0.035	0.016	0.022	0.035	0.0010	—	0.541	50	758	700
13	0.05	0.12	1.02	—	—	—	—	—	—	—	0.032	—	—	0.225	10	814	695
14	0.11	0.42	1.53	—	—	0.92	0.55	—	—	0.022	0.035	0.0011	—	0.704	50	710	693
15	0.01	0.43	1.55	—	—	—	—	—	—	—	0.035	—	—	0.286	25	789	685
16	0.25	0.45	1.22	—	—	—	—	—	—	—	0.027	—	—	0.472	25	741	695
17	0.10	0.72	1.23	—	—	—	—	—	—	—	0.027	—	—	0.335	25	787	692
18	0.14	0.35	0.40	23	0.23	0.13	0.35	—	—	—	0.033	—	—	0.341	25	793	701
19	0.11	0.43	2.13	—	—	—	—	—	—	—	0.035	—	—	0.483	25	711	676
20	0.07	0.51	1.47	—	—	—	—	—	—	—	0.115	—	—	0.336	25	777	687
21	0.09	0.22	1.45	—	—	—	—	—	0.120	0.018	0.025	—	—	0.341	25	772	688
22	0.08	0.42	1.38	—	—	—	—	—	0.025	0.110	0.032	—	—	0.328	25	781	689
23	0.11	0.44	0.83	—	—	1.25	—	—	0.025	0.018	0.024	—	—	0.517	25	797	714
24	0.10	0.45	0.75	—	—	0.16	1.10	—	0.026	0.012	0.031	—	—	0.551	25	735	692
25	0.05	0.22	0.65	1.60	0.83	—	—	—	0.011	—	0.025	0.0010	—	0.188	25	771	686
26	0.10	0.30	0.91	—	—	—	0.15	0.112	0.034	0.017	0.024	—	—	0.310	25	800	696
27	0.07	0.21	1.12	0.32	0.29	—	—	—	0.011	—	0.025	0.0025	—	0.273	25	782	688
28	0.07	0.13	1.42	0.23	0.21	—	—	0.058	0.028	0.012	0.023	—	0.011	0.321	25	765	684

Table 2

Steel No.	Cyclic softening parameter σ_{15}/σ_1	Fatigue crack growth rate (x10 ⁻⁵ mm/cycle)	Tensile Test	Charpy impact test
1	0.935	3.84	○	○
2	0.927	3.77	○	○
3	0.889	3.16	○	○
4	0.863	2.87	○	○
5	0.820	1.92	○	○
6	0.845	2.38	○	○
7	0.811	1.72	○	○
8	0.931	3.88	○	○
9	0.881	2.99	○	○
10	0.657	0.42	○	○
11	0.738	1.12	○	○
12	0.712	0.83	○	○
13	0.869	3.64	Δ	○
14	0.624	0.21	○	Δ
15	0.980	4.95	Δ	○
16	0.788	1.34	○	Δ
17	0.921	3.54	○	Δ
18	1.092	5.95	Δ	○
19	0.776	1.68	○	Δ
20	0.882	3.25	○	Δ
21	0.886	3.22	○	Δ
22	0.925	3.57	○	×
23	0.775	1.58	○	Δ
24	0.764	1.60	○	Δ
25	1.120	6.32	○	×
26	0.930	3.78	○	Δ
27	1.052	5.67	○	Δ
28	0.934	3.76	○	Δ

[0069] As is shown in Table 2, Steels Nos. 15, 18, 25, and 27 had a cyclic softening parameter which is beyond the range defined in the present invention, and they had a large fatigue crack growth rate in air. Steel No. 14 had an excessively small cyclic softening parameter and hence poor impact properties. Steels Nos. 13, 16, 17, 19 - 24, 26, and 28 had a good cyclic softening parameter and also a good fatigue crack growth rate, but their strength or impact properties were slightly poor.

(Example 2)

[0070] Using Steel No. 4 in Example 1 (Ac₁ point: 688°C, Ar₃ point: 774°C) in which all of the cyclic softening parameter, fatigue crack growth rate, tensile strength, and vTrs reached their respective target values, the effects of manufacturing conditions were surveyed.

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[0071] A 150 mm-thick steel slab was heated to 1150°C and hot-rolled to produce a 25 mm-thick steel plate. The cooling stage following hot rolling and/or heat treatment (reheating and cooling) after completion of hot rolling were performed under the conditions shown in Table 3. The same tests as described in Example 1 were carried out using the respective test pieces for these tests taken from the resulting steel plates. Table 4 shows the cyclic softening parameter, fatigue crack growth rate, tensile strength, and Charpy impact test result (vTrs).

Table 3

Mark	Manufacturing conditions
A	Reheating to 900°C and then cooling to RT at a rate of 20°C/s
B	Reheating to 900°C, then cooling to RT at a rate of 20°C/s, and tempering with heating to 500 °C
C	Reheating to 900°C, then cooling to RT at a rate of 20°C/s, reheat-int to 750°C, and cooling to RT at a rate of 15°C/s
D	Reheating to 900°C, then cooling to RT at a rate of 20°C/s, reheat-int to 780°C, cooling to RT at a rate of 20°C/s, and tempering with heating to 450°C
E	Following hot rolling, cooling from 830°C to 500°C at a rate of 20°C/s
F	Following hot rolling, cooling from 800 °C to 450°C at a rate of 25°C/s and then tempering with heating to 400°C
G	Following hot rolling, cooling from 750°C to RT at a rate of 30°C/s
H	Following hot rolling, cooling from 800°C to RT at a rate of 30°C/s and then reheating to 750°C and cooling to RT at a rate of 25°C/s
I	Reheating to 650°C and then cooling to RT at a rate of 20°C/s
J	Reheating to 900°C, then cooling to RT at a rate of 3°C/s, and tempering with heating to 450°C
K	Reheating to 900°C, then cooling to RT at a rate of 20°C/s, reheat-int to 660°C, and cooling to RT at a rate of 15°C/s
L	Reheating to 900°C, then cooling to RT at a rate of 20°C/s, reheat-int to 780°C, cooling to RT at a rate of 3°C/s, and tempering with heating to 400°C
M	Following hot rolling, cooling from 830°C to 600°C at a rate of 20°C/s
N	Following hot rolling, cooling from 800°C to 450°C at a rate of 25°C/s and then tempering with heating to 700°C
O	Following hot rolling, cooling from 650°C to RT at a rate of 30°C/s
P	Following hot rolling, cooling from 750°C to RT at a rate of 30°C/s and then reheating to 650°C and cooling to RT at a rate of 25°C/s

Table 4

Manufacturing conditions	Cyclic softening parameter σ_{15}/σ_1	Fatigue crack growth rate (x10 ⁻⁵ mm/cycle)	Tensile Test	Charpy impact test
A	0.852	2.42	○	○
B	0.911	3.21	○	○
C	0.831	1.98	○	○
D	0.912	3.05	○	○
E	0.875	2.61	○	○
F	0.891	2.97	○	○
G	0.860	2.85	○	○
H	0.855	2.47	○	○

Table 4 (continued)

Manufacturing conditions	Cyclic softening parameter σ_{15}/σ_1	Fatigue crack growth rate ($\times 10^{-5}$ mm/cycle)	Tensile Test	Charpy impact test
I	1.105	6.24	Δ	$\times$
J	1.011	5.03	Δ	Δ
K	0.976	4.98	$\bigcirc$	$\times$
L	0.987	5.01	Δ	$\times$
M	0.979	4.95	$\bigcirc$	$\bigcirc$
N	0.981	4.96	Δ	$\times$
O	0.993	5.02	Δ	$\bigcirc$
P	0.984	4.88	$\bigcirc$	$\times$

[0072] As can be seen from Table 4, Steel Plates A to H in which the manufacturing conditions fell within the range defined in the present invention had a cyclic softening parameter which was in the proper range of 0.65 - 0.95 and a fatigue crack growth rate which was below the target maximum value of 4.0×10^{-5} mm/cycle. Their tensile strength and impact properties were also good.

[0073] In contrast, Steel Plates I to P in which the manufacturing conditions were outside the range defined in the present invention had a cyclic softening parameter of greater than 0.95, and their fatigue crack growth rate did not reach the target value. In addition, except for Steel Plate M, they were not adequate at least one of tensile strength and impact strength.

(Example 3)

[0074] A corrosion fatigue crack growth test and a corrosion fatigue were performed on nine steels in Table 2, i.e., Steels Nos. 3, 4, 5, 7, 12, 15, 18, 25, and 27.

[0075] The corrosion fatigue crack growth test was conducted in seawater at room temperature. The test pieces used in this test were CT specimens having the same shape as described in Example 1. The difference from the fatigue crack growth test in air was that the cycle rate was 0.17 Hz in order to match with the cycle of waves in the sea. The stress ratio was set at 0.1, which was the same as in the fatigue crack growth test in air.

[0076] The corrosion fatigue test was performed in five environments: sea water at room temperature, seawater at 60°C, an aqueous saturated chlorine solution at room temperature, a 1% saline solution (aqueous sodium chloride solution) at room temperature, and a 3% saline solution at room temperature. The seawater used herein means artificial seawater prescribed in ASTM specifications. Room temperature indicates that the test was conducted without temperature control, while 60°C indicates that the temperature was controlled so as to maintain that temperature by means of a thermostat. The two saline environments were prepared in order to show the effect of sodium chloride alone on corrosion fatigue strength, and the 3% saline environment corresponds to a seawater environment containing about 3.5% sodium chloride.

[0077] With respect to the environment of seawater at room temperature which was selected as the standard testing environment for a corrosion fatigue test, the test was also performed in different load modes or with a test piece having a differently worked test surface to evaluate the effects of these parameters.

[0078] Like a corrosion fatigue crack growth rate, corrosion fatigue strength also greatly depends on the cycle rate, and the lower the cycle rate, the more significantly the corrosion fatigue strength decreases. Therefore, the cycle rate of repeated loads in the corrosion fatigue test was the same rate of 0.17 Hz in all the test runs so as to match with the cycle of wave loads in the sea. The stress ratio was set at 0.1, which is the standard value most widely employed in a fatigue test.

[0079] The load modes used in the corrosion fatigue test were three modes of axial force, bending, and torsion, in which axial force load was the standard load mode.

[0080] A plate test piece was used in the axial force load mode and bending load mode of the corrosion fatigue test. The width of the test piece was 80 mm in the grip portions and 25 mm in the test portion, the width decreasing smoothly in a curve of R100 from the grip portions to the test portion. The thickness of the test piece was 12 mm in the grip portions and 6 mm in the test portion, the thickness decreasing smoothly in a curve of R40 from the grip portions to the test portion.

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[0081] The test pieces used in the torsional load mode were in the shape of an axially symmetrical round bar which had a diameter of 12 mm in the grip portions and 6 mm in the test portion.

[0082] The test surface was worked by machining, plasma arc cutting, or laser cutting, with machining being the standard.

[0083] When the corrosion fatigue strength was evaluated by causing a fatigue crack on a machined surface, the finish machining of a test surface was performed in such a way that the maximum height of surface roughness was between 1.6 and 6.3 μm along a length of 8 mm.

[0084] In the case of evaluating the corrosion fatigue strength originating at a plasma arc-cut surface, the plasma arc cutting technique was applied when the flat surface of a test piece was cut out. In order to ensure that a fatigue crack originated at the plasma arc-cut surface, the corners in the cross section of the test piece had been chamfered with a curve of R1 with a baby grinder. The plasma arc cutting was performed under the following conditions:

Conditions for plasma arc cutting:

[0085]

electric current: 240 A, voltage: 110 V, cutting speed: 1000 mm/minute, electrodes: tungsten electrodes, gas: mixed $\text{H}_2\text{-N}_2\text{-Ar}$ gas.

[0086] When the corrosion fatigue strength was evaluated on a laser-cut surface, the cut surface was prepared by laser cutting under the following conditions. Also in this case, in order to ensure that a fatigue crack originated at the cut surface, the same chamfering as in the plasma arc-cut surface was employed.

Conditions for laser cutting:

[0087]

CO2 laser, output: 40 kW (continuous), position: lateral, cutting speed: 2.5 m/min, focal distance: 381 mm (parabolic condensing), defocusing amount: +8 mm.

[0088] In the corrosion fatigue test, for each test run, i.e., for each combination of a steel and a testing condition, 6 to 8 test pieces were tested to prepare an S-N curve (fatigue strength diagram), on which the corrosion fatigue strength was determined to be the fatigue strength $\Delta\sigma$ (stress range: maximum stress minus minimum stress) at a finite life of 1×10^6 cycles at fatigue fracture.

[0089] The results of the corrosion fatigue crack growth test and the corrosion fatigue test are shown in Tables 5 and 6, respectively. For reference, the values of cyclic softening parameter and fatigue crack growth rate in air shown in Table 2 are also included in Table 5.

Table 5

Steel No.	Cyclic softening parameter σ_{15}/σ_1	Fatigue crack growth rate ($\times 10^{-5}$ mm/cycle)		Environmental acceleration of fatigue crack growth rate	Remarks
		Air	Seawater		
3	0.889	3.16	17.38	5.5	Inventive
4	0.863	2.87	17.79	6.2	"
5	0.820	1.92	9.22	4.8	"
7	0.811	1.72	9.98	5.8	"
12	0.712	0.83	4.23	5.1	"
15	0.980*	4.95	24.26	4.9	Comparative
18	1.092*	5.95	36.30	6.1	"

*Outside the range defined herein.

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Table 5 (continued)

Steel No.	Cyclic softening parameter σ_{15}/σ_1	Fatigue crack growth rate ($\times 10^{-5}$ mm/cycle)		Environmental acceleration of fatigue crack growth rate	Remarks
		Air	Seawater		
25	1.120*	6.32	34.76	5.5	"
27	1.052*	5.67	33.45	5.9	"

*Outside the range defined herein.

Table 6

Test Environment	Seawater	Seawater	Seawater	Seawater	Seawater	Seawater	Seawater	Sat. Cl ₂	1% Saline	3% Saline
Test Temperature	RT	RT	RT	60°C	RT	RT	RT	RT	RT	RT
Test Surface	Machined	Machined	Machined	Machined	Plasma	Laser	Machined	Machined	Machined	Machined
Load Mode	Axial	Bending	Torsion	Axial	Axial	Axial	Axial	Axial	Axial	Axial
Steel No.	3	450	630	360	440	430	410	400	460	450
	4	420	—	—	410	410	410	410	440	420
	5	410	—	—	—	400	400	410	—	—
	7	420	—	—	—	400	410	—	—	—
	12	430	—	—	—	420	430	—	—	—
	15*	290	—	—	—	250	—	—	—	—
	18*	290	—	—	—	240	—	—	—	—
	25*	270	380	220	260	220	210	230	280	270
27*	300	—	—	—	240	220	—	—	—	

(Unit : MPa)

Asterisked steels are comparative steels.

[0090] As can be seen from Table 5, although the growth rate of corrosion fatigue cracks (fatigue crack growth rate in seawater) was higher than the fatigue crack growth rate in air for all the steel materials, the degree of acceleration of growth rate of corrosion fatigue cracks relative to the fatigue crack growth rate in air (i.e., environmental acceleration of fatigue crack growth rate) was almost constant and scarcely depended on the steel type. Thus, it was confirmed

that the growth rate of corrosion fatigue cracks of a steel can be suppressed by suppressing its fatigue crack growth rate in air.

[0091] From the results of the corrosion fatigue test in Table 6, it can be seen that the axial force fatigue crack strength originating at the machined surface in seawater at room temperature was over 400 MPa and was thus excellent for Steels Nos. 3, 4, 5, and 7 according to the present invention, but it was as low as 310 MPa for Steels Nos. 15, 18, 25, and 27 which were comparative examples having a cyclic softening parameter of greater than 0.95. Comparing those steels having the full data (No. 3 and 25), the corrosion fatigue strength of the steel according to the present invention (No. 3) was significantly superior to that of the comparative steel (No. 25) in all the testing environments, in all the test surfaces, and in all the load modes.

[0092] Upon observation of the fracture surface and its neighborhood of each test piece after the corrosion fatigue test, no apparent differences in the shape and size of corrosion pits were found between the steels according to the present invention and the comparative steels. However, by measuring the micro hardness in the vicinity of the bottom of a corrosion pit, all the steels according to the present invention had a lower micro hardness than the comparative steels. It is thought that due to its cyclic softening properties, a steel according to the present invention has a decreased hardness, which favorably affects the formation of fatigue cracks in a corrosive environment.

Claims

1. A structural steel material, which has a cyclic softening parameter of at least 0.65 and at most 0.95, the cyclic softening parameter being represented by the ratio (σ_{15}/σ_1) of the stress at the maximum strain in the first cycle (σ_1) to that in the 15th cycle (σ_{15}) measured when a waveform of incremental and decremental cyclic loads is applied 15 times with a maximum tensile and compressive strain of ± 0.012 , with a frequency of 0.5 Hz, and with the number of waves to the maximum strain being 12.

2. A steel material according to claim 1, wherein the steel has the following composition by mass%:

C: 0.02 - 0.20%, Mn: 0.50 - 2.0%, Cu: 0 - 1.5%, Cr: 0 - 1.20%, V: 0 - 0.10%, Ti: 0 - 0.10%, Ca: 0 - 0.010%, and	Si: at most 0.60%, Al: 0.003 - 0.10%, Ni: 0 - 1.5%, Mo: 0 - 1.0%, Nb: 0 - 0.10%, B: 0 - 0.0020%, balance: Fe and incidental impurities,
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and a value of carbon equivalent, Ceq, represented by the following formula of from 0.28 - 0.65:

$$\text{Ceq (\%)} = \text{C} + \text{Si}/24 + \text{Mn}/6 + \text{Ni}/40 + \text{Cr}/5 + \text{Mo}/4 + \text{V}/14.$$

3. A steel material according to claim 2 wherein the steel contains one or both of B: 0.0003 - 0.0020% and Ca: 0.0005 - 0.010%.

4. A process for manufacturing a structural steel material, comprising subjecting a hot-rolled steel material having a composition as set forth in claim 2 or 3 to heat treatment one or more times, said heat treatment comprising reheating to a temperature above the A_{c1} point followed by cooling to 550°C or below at a cooling rate of at least 5°C/s.

5. A process for manufacturing a structural steel material, comprising cooling a hot-rolled steel material having a composition as set forth in claim 2 or 3 from a temperature range of at least (A_{r3} point - 100)°C and at most (A_{r3} point + 150)°C to 550°C or below at a cooling rate of at least 5°C/s.

6. A process for manufacturing a structural steel material, comprising cooling a hot-rolled steel material having a composition as set forth in claim 2 or 3 from a temperature range of at least (A_{r3} point - 100)°C and at most (A_{r3} point + 150)°C to 550°C or below at a cooling rate of at least 5°C/s and subsequently subjecting it to heat treatment one or more times, said heat treatment comprising reheating to a temperature above the A_{c1} point followed by cooling to 550°C or below at a cooling rate of at least 5°C/s.

7. A process according to any of claims 4 to 6, which further comprises finally performing tempering with a heating temperature below the Ac_1 point.

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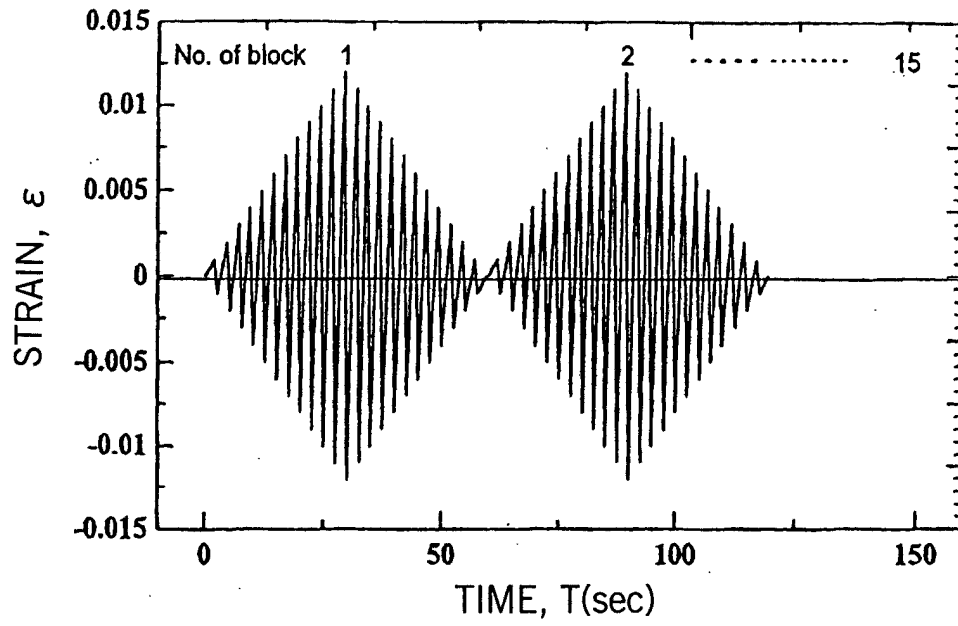


Fig. 1

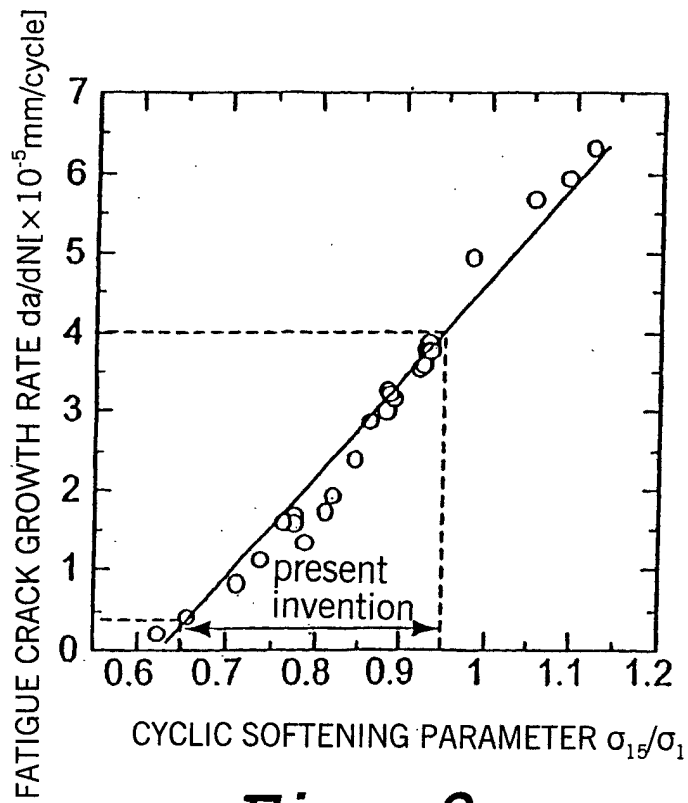


Fig. 2

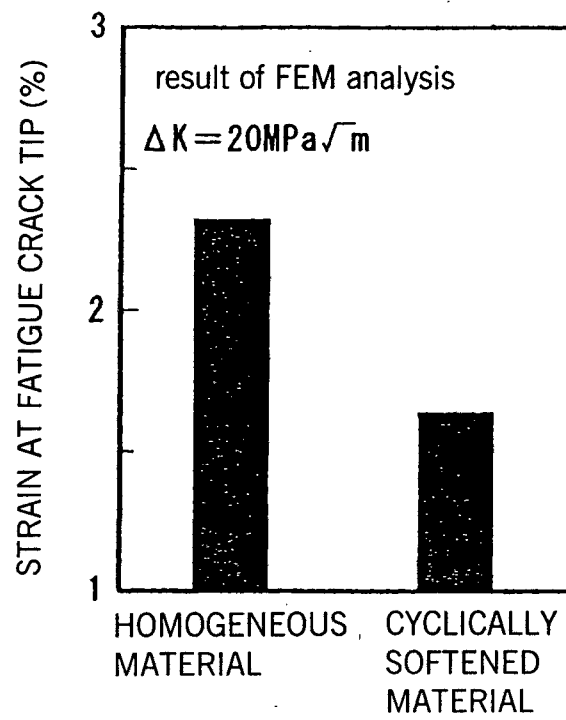


Fig. 3



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EUROPEAN SEARCH REPORT

Application Number
EP 02 02 5246

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
X	WO 98 38345 A (FUJIWARA KAZUKI ;HAMADA MASAHIKO (JP); KOMIZO YU ICHI (JP); OKAGUC) 3 September 1998 (1998-09-03) * page 5, line 17-28; tables 1,2,5,6 * * page 20, line 22 - page 24, line 25; tables 3,4 *	1-3,5	C22C38/04 C22C38/40 C22C38/44 C22C38/42 C22C38/48 C22C38/46 C22C38/54 C22C38/50 C21D8/02
X,D	--- PATENT ABSTRACTS OF JAPAN vol. 2000, no. 19, 5 June 2001 (2001-06-05) -& JP 2001 041868 A (SUMITOMO METAL IND LTD), 16 February 2001 (2001-02-16) * abstract * * paragraphs [0015]-[0026],[0043],[0044],[0056] *	1-3,5	
X	--- EP 0 861 915 A (SUMITOMO METAL IND) 2 September 1998 (1998-09-02) * figures 1-5; examples 1-6 *	2,3,5,7	
X	--- US 5 900 075 A (KOO JAYOUNG ET AL) 4 May 1999 (1999-05-04) * tables 1-3 *	2,3,5,7	TECHNICAL FIELDS SEARCHED (Int.Cl.7) C22C C21D
X	--- PATENT ABSTRACTS OF JAPAN vol. 012, no. 482 (C-553), 15 December 1988 (1988-12-15) -& JP 63 199821 A (KOBE STEEL LTD), 18 August 1988 (1988-08-18) * abstract; examples 9-12; table 1 *	2,3,5	
X	--- US 4 572 748 A (SUGA MASATAKA ET AL) 25 February 1986 (1986-02-25) * tables 1-3 *	2,3,5,7	
The present search report has been drawn up for all claims			
Place of search MUNICH		Date of completion of the search 22 January 2003	Examiner Catana, C
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

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**ANNEX TO THE EUROPEAN SEARCH REPORT
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22-01-2003

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
WO 9838345	A	03-09-1998	JP 10237583 A	08-09-1998
			AU 726316 B2	02-11-2000
			AU 6656698 A	18-09-1998
			BR 9807805 A	22-02-2000
			CN 1249006 T	29-03-2000
			EP 0972087 A1	19-01-2000
			JP 2000513050 T	03-10-2000
			WO 9838345 A1	03-09-1998
			US 6245290 B1	12-06-2001

JP 2001041868	A	16-02-2001	NONE	

EP 0861915	A	02-09-1998	CA 2230396 A1	25-08-1998
			DE 69800029 D1	25-11-1999
			DE 69800029 T2	20-07-2000
			EP 0861915 A1	02-09-1998
			JP 10298707 A	10-11-1998
			NO 980776 A	26-08-1998
			US 6045630 A	04-04-2000
			US 6183573 B1	06-02-2001

US 5900075	A	04-05-1999	US 5876521 A	02-03-1999
			US 5545269 A	13-08-1996
			WO 9902747 A1	21-01-1999
			BR 9509968 A	25-11-1997
			CA 2207382 A1	13-06-1996
			CN 1168700 A ,B	24-12-1997
			DE 69527801 D1	19-09-2002
			DE 69527801 T2	16-01-2003
			EP 0796352 A1	24-09-1997
			JP 10509768 T	22-09-1998
			RU 2152450 C1	10-07-2000
			WO 9617964 A1	13-06-1996

JP 63199821 8	A		NONE	

US 4572748	A	25-02-1986	DE 3401406 A1	25-07-1985
			JP 1018968 B	10-04-1989
			JP 1537713 C	16-01-1990
			JP 59100214 A	09-06-1984
			CA 1221895 A1	19-05-1987
			FR 2536765 A1	01-06-1984
			GB 2132225 A ,B	04-07-1984
			SE 451599 B	19-10-1987
			SE 8307123 A	23-06-1985
			ZA 8308886 A	25-07-1984

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82