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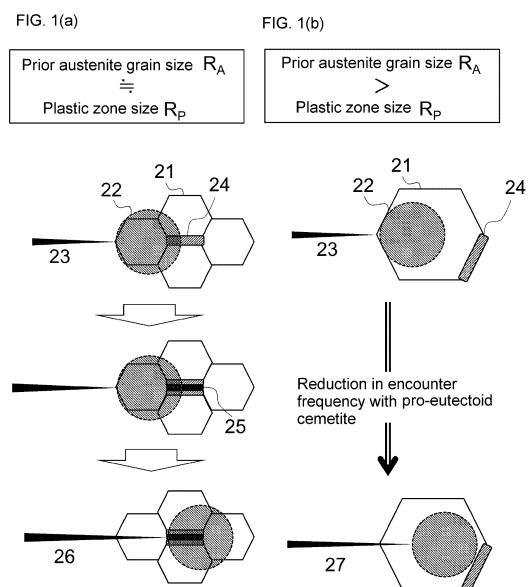
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(54) **RAIL HAVING EXCELLENT FATIGUE CRACK PROPAGATION RESISTANCE CHARACTERISTICS, AND METHOD FOR PRODUCING SAME**

(57) Proposed is a rail having excellent fatigue damage resistance, particularly excellent fatigue crack propagation resistance characteristics and a preferable method for producing the same. The rail has a component composition comprising, on a mass basis, C: 0.80 to 1.30%, Si: 0.10 to 1.20%, Mn: 0.20 to 1.80%,  $P \leq 0.035\%$ , S: 0.0005 to 0.012%, Cr: 0.20 to 2.50% and the remainder being Fe and inevitable impurities and has  $CP = X/R_A$  of not more than 2500 (where  $X = \{(10 \times [\%C]) + ([\%Si]/12) + ([\%Mn]/24) + ([\%Cr]/21)\}^5$ , and  $[\%Y]$  is a content of an element Y (mass%), and  $R_A$  is a prior austenite grain size ( $\mu m$ )). In the production method of the rail, a raw steel material is heated to not higher than  $1350^\circ C$  and then hot-rolled such that a finish temperature is not lower than  $900^\circ C$ .



**Description**

## Technical Field

**[0001]** This invention relates to a rail and a method for producing the same, and more particularly to a rail having an improved fatigue crack propagation resistance characteristics and a method for advantageously producing the rail.

## Background

**[0002]** In a high-axle load railway mainly used for transporting ores and the like, a load applied to an axle shaft of a freight car is much higher than that applied to a passenger carriage, causing a severer usage environment of a rail. The rail used under such an environment has used steel mainly having a pearlite microstructure with an emphasis on wear resistance. In recent years, however, with an increase in the load weight of a freight car to enhance transportation efficiency by rail, further improvement of the wear resistance and fatigue damage resistance of a rail has been demanded. Note that the high-axle load railway means a railway in which a load capacity per one freight car in a train or goods train is large (for example, the load capacity is not less than about 150 tons).

**[0003]** In this regard, various studies have been made to further improve the wear resistance. For example, the C content is increased to more than 0.85 mass% but not more than 1.20 mass% in Patent Literatures 1 and 2. In Patent Literatures 3 and 4, the C content is made to more than 0.85 mass% but not more than 1.20 mass% and the head portion of the rail is subjected to a heat treatment. In these techniques, the C content is increased to increase the cementite fraction, thus improving the wear resistance.

**[0004]** Rolling stress by a wheel and slippage by centrifugal force is applied to a rail laid in the curved section of the high-axle load railway, causing severer wearing of the rail and fatigue damage resulting from the slippage. Patent Literature 5 proposes a technique for suppressing the formation of pro-eutectoid cementite by adding Al and Si to improve fatigue damage resistance.

Also, Patent Literature 6 proposes a technique of controlling a lamellar spacing of pearlite in a proper range to decrease the fatigue crack propagation rate.

## Citation List

## Patent Literatures

**[0005]**

Patent Literature 1: JP-A-H8-109439

Patent Literature 2: JP-A-H8-144016

Patent Literature 3: JP-A-H8-246100

Patent Literature 4: JP-A-H8-246101

Patent Literature 5: JP-A-2002-69585

Patent Literature 6: JP-A-2010-185106

## Summary of Invention

## Technical Problem

**[0006]** The prior arts of the above Patent Literatures have the following problems to be solved.

**[0007]** In the techniques disclosed in Patent Literatures 1 to 4, when simply controlling the C content to more than 0.85 mass% but not more than 1.20 mass%, the pro-eutectoid cementite is formed depending on heat treatment conditions, also causing an increase in the amount of cementite layer having a brittle pearlite lamellar structure, so that the improvement of the fatigue damage resistance cannot be expected. The technique disclosed in Patent Literature 5, in which an oxide as a starting point of fatigue damage is formed by adding Al, has difficulty in suppressing the fatigue cracking. In the technique disclosed in Patent Literature 6, the pro-eutectoid cementite may be formed depending on the combination between the ingredients and production conditions, and consequently, fatigue crack propagation rate is increased, so that it cannot be said that the material control is sufficient.

**[0008]** The invention is made to advantageously solve the aforementioned problems, and an object thereof is to provide a rail having excellent fatigue damage resistance, particularly fatigue crack propagation resistance characteristics and a preferable method for producing the same.

## Solution to Problem

**[0009]** In order to solve the above problem, the inventors prepared rails with varying contents of C, Si, Mn, and Cr and carefully studied each structure and fatigue crack propagation resistance characteristic of the rails and thus derived an ingredient parameter X corresponding to a pro-eutectoid cementite amount and a parameter CP from a prior austenite grain size  $R_A$ . The inventors have also found, by controlling the parameter CP within a certain range, excellent fatigue crack propagation resistance characteristics can be obtained, even if there is a large amount of pro-eutectoid cementite present.

**[0010]** This invention is developed to solve the above problem and achieve the above object and provides a rail having excellent fatigue crack propagation resistance characteristics, characterized by having a component composition comprising C: 0.80 to 1.30 mass%, Si: 0.10 to 1.20 mass%, Mn: 0.20 to 1.80 mass%, P: not more than 0.035 mass%, S: 0.0005 to 0.012 mass%, Cr: 0.20 to 2.50 mass% and the remainder being Fe and inevitable impurities and satisfying CP represented by the following equation (1) being not more than 2500:

$$CP = X/R_A \quad \dots (1)$$

and

$$X = \{(10 \times [\%C]) + ([\%Si]/12) + ([\%Mn]/24) + ([\%Cr]/21)\}^5 \dots (2).$$

**[0011]** Note that, [%Y] is the content of an element Y (mass%), and  $R_A$  is a prior austenite grain size ( $\mu\text{m}$ ).

**[0012]** The rail having excellent fatigue crack propagation resistance characteristics according to the invention is considered to have more preferable solution means as follows:

- a. the component composition further contains at least one selected from V: not more than 0.30 mass%, Cu: not more than 1.0 mass%, Ni: not more than 1.0 mass%, Nb: not more than 0.05 mass%, and Mo: not more than 2.0 mass%; and
- b. the component composition further contains at least one selected from Al: not more than 0.07 mass%, W: not more than 1.0 mass%, B: not more than 0.005 mass%, Ti: not more than 0.05 mass%, and Sb: not more than 0.05 mass%.

**[0013]** A method for producing a rail having excellent fatigue crack propagation resistance characteristics according to the invention is developed to solve the task and achieve the object and characterized by heating a raw steel material having any one of the aforementioned component compositions to not higher than 1350°C and hot rolling the material such that the finish temperature is not lower than 900°C.

**[0014]** The method for producing a rail having excellent fatigue crack propagation resistance characteristics according to the invention is considered to have more preferable means as follows. That is, it is preferable that, after the hot rolling, accelerated cooling is conducted at a cooling rate of 0.4 to 3°C/s from 900°C to 750°C and at a cooling rate of 1 to 10°C/s from 750°C to a cooling stop temperature of 400 to 600°C.

## Advantageous Effects of Invention

**[0015]** The rail and the method for producing the rail according to the invention can stably produce a rail with fatigue damage resistance that has excellent fatigue crack propagation resistance characteristics. Such a rail contributes to increasing the service life of a rail for a high axle load railway and preventing a railway accident, bringing about a beneficial effect in the industry.

**[0016]** Moreover, the fatigue damage resistance can be improved by properly controlling the heat treating conditions after the hot rolling.

## Brief Description of Drawings

**[0017]**

FIG. 1 is a schematic view showing the influence of pro-eutectoid cementite on fatigue crack propagation rate. FIG.

1(a) is a case where a prior austenite grain size is approximately equal to a plastic zone size, and FIG. 1(b) is a case where a prior austenite grain size is larger than a plastic zone size.

FIG. 2 is a view showing a position where a test specimen for observing a prior austenite grain size was taken out.

FIG. 3 is a view showing a position where a test specimen for fatigue crack propagation was taken out.

FIG. 4 is a view showing the shape of a test specimen used in the fatigue crack propagation test, where FIG. 4(a) is a front view, FIG. 4(b) is a side view, and FIG. 4(c) is an enlarged front view of a notch portion.

FIG. 5 is a view illustrating the shape of a test specimen used in a fatigue damage resistance test, where FIG. 5(a) is a side view, and FIG. 5(b) is a front view.

FIG. 6 is a view showing a position where a test specimen for fatigue damage resistance test was taken out.

#### Description of Embodiment

**[0018]** One embodiment of the present invention will be concretely described below. First, the reason for limiting the component composition of the steel as a raw material of the rail into the above range will be described. Note that "%" means "mass%" hereinafter in the following description unless otherwise noted.

C: 0.80 to 1.30%

**[0019]** C is an essential element to secure the strength of pearlite microstructure, i.e., fatigue damage resistance. When the C content is less than 0.80%, it is difficult to obtain excellent fatigue crack propagation resistance characteristics. When it exceeds 1.30%, a large amount of a pro-eutectoid cementite is formed in an austenite grain boundary during the cooling after hot rolling, bringing about an increase in a fatigue crack propagation rate. Although the pro-eutectoid cementite is present even when the C content is not more than 1.30%, the influence thereof can be avoided by controlling the prior austenite grain size, based on a relation expression mentioned below. Therefore, the C content should range from 0.80 to 1.30%. The upper limit of the C content is preferably 1.00%, more preferably 0.90%.

Si: 0.10 to 1.20%

**[0020]** In addition to the effect as a deoxidizer, Si contributes to the reduction of fatigue crack propagation rate by increasing the pearlite equilibrium transformation temperature and reducing the lamellar spacing. Thus, the Si content needs to be not less than 0.10%. However, when it exceeds 1.20%, the weldability is deteriorated due to the high bonding force of Si with oxygen. Further, Si acts to move the eutectoid precipitation point to the low C content side, so that an excessive addition of Si contributes to the formation of pro-eutectoid cementite and increases the fatigue crack propagation rate. Therefore, the Si content should range from 0.10 to 1.20 %. The lower limit of the Si content is preferably 0.20 %, and the upper limit of the Si content is preferably 0.80 %, more preferably 0.60%.

Mn: 0.20 to 1.80%

**[0021]** Mn contributes to the reduction of the fatigue crack propagation rate by lowering the pearlite transformation temperature and increasing the lamellar spacing. However, an Mn content of less than 0.20% does not have a sufficient effect. On the other hand, when the Mn content exceeds 1.80%, the martensitic microstructure is likely to be formed, which causes hardening and embrittlement during heat treatment and welding of the rail, leading to material deterioration. Furthermore, as Mn has the effect of moving the eutectoid precipitation point towards the low C content side, the excessive addition contributes to the formation of pro-eutectoid cementite and increases the fatigue crack propagation rate. Therefore, the Mn content should range from 0.20 to 1.80%. The lower limit of the Mn content is preferably 0.30%, while the upper limit of the Mn content is preferably 1.00%, more preferably 0.60%.

P: not more than 0.035%

**[0022]** The P content exceeding 0.035% deteriorates ductility. Therefore, the P content should be not more than 0.035%, preferably not more than 0.020%. On the other hand, the lower limit of the P content is not particularly limited and may be 0%; more than 0% is usual industrially. Moreover, reducing the P content excessively causes an increase in the refining cost. Therefore, the P content is preferable to be not less than 0.001% from the viewpoint of economic efficiency.

S: 0.0005 to 0.012%

**[0023]** S is present in steel mainly in the form of A-based inclusion (subjected to viscous deformation by working). The

S content exceeding 0.012% remarkably increases the amount of the inclusion and, at the same time, forms coarse inclusion, deteriorating the cleanness of the steel material. Meanwhile, less than 0.0005% S increases the refining cost. Therefore, the S content should range from 0.0005 to 0.012%. The upper limit of the S content is preferably 0.010%, more preferably 0.008%.

Cr: 0.20 to 2.50%

**[0024]** Cr increases the pearlite equilibrium transformation temperature to reduce the lamellar spacing, contributing to decreasing the fatigue crack propagation rate. However, less than 0.20% Cr cannot suppress the progress of the fatigue crack sufficiently, while the Cr content exceeding 2.50% increases the hardenability of steel, thus often producing martensite. In the production where martensite is not produced, the pro-eutectoid cementite is produced in the prior austenite grain boundary, and as a result, the fatigue crack propagation rate is increased. Therefore, the Cr content should range from 0.20 to 2.50%. The lower limit of the Cr content is preferably 0.40%, more preferably 0.50%, while the upper limit of the Cr content is preferably 1.50%, more preferably 1.00%.

**[0025]** In the invention, it is insufficient that each element only satisfies the above range. It is also important to control the CP value represented by the following equation (1) derived from ingredient parameter X corresponding to a pro-eutectoid cementite amount shown in the following equation (2) and prior austenite grain size  $R_A$  to not more than 2500.

$$CP = X/R_A \quad \dots (1)$$

$$X = \{ (10 \times [\%C]) + ([\%Si]/12) + ([\%Mn]/24) + ([\%Cr]/21) \}^5 \quad \dots (2)$$

**[0026]** Note that [%Y] is a content of element Y (mass%), and  $R_A$  is a prior austenite grain size ( $\mu m$ ).

**[0027]** The inventors have examined the cause of the increased fatigue crack propagation rate due to the presence of pro-eutectoid cementite. As a result, they have found that the preceding brittle fracture of pro-eutectoid cementite 24 at the tip of the fatigue crack 23 is the cause of the increase 26 in the fatigue crack propagation rate, as shown in the schematic view of FIG. 1(a). Furthermore, they have found that the progress of brittle crack can be suppressed by adjusting the prior austenite grain size to be a formation site of the structure in correspondence to the amount of the pro-eutectoid cementite formed to thus decrease an encountering frequency of the pro-eutectoid cementite with a plastic zone 22 formed in the tip of the fatigue crack. Specifically, even when a large amount of the pro-eutectoid cementite is present, as shown in FIG. 1(b), the CP value can be controlled to not more than 2500 by sufficiently coarsening the prior austenite grain size 21 larger than the size of the plastic zone 22 at the crack tip. Thus, the effect of suppressing the fatigue crack propagation rate can be obtained stably. Moreover, the CP value is preferable to be not more than 2000.

**[0028]** The component composition used in the rail according to the invention may arbitrarily contain any one selected from at least one selected from following Group A, at least one selected from following Group B, and both thereof, in addition to the aforementioned ingredients.

Group A: V: not more than 0.30%, Cu: not more than 1.0%, Ni: not more than 1.0%, Nb: not more than 0.05%, and Mo: not more than 2.0%

Group B: Al: not more than 0.07%, W: not more than 1.0%, B: not more than 0.005%, Ti: not more than 0.05%, and Sb: not more than 0.05%

**[0029]** The reason for specifying the contents of the elements belonging to Groups A and B will be described below.

V: not more than 0.30%

**[0030]** V forms carbonitride in steel, which is dispersed and precipitated into the base to improve the wear resistance of steel. However, when the content exceeds 0.30%, the workability of steel is deteriorated to increase the production cost. The V content exceeding 0.30% also increases the alloying cost, causing an increase in the production cost for a high internal hardness type rail. Therefore, V is preferable to be contained up to 0.30% as an upper limit. Moreover, V is preferable to be contained by not less than 0.001% to develop the above effect of improving the wear resistance. The upper limit of the V content is more preferably 0.15%.

Cu: not more than 1.0%

**[0031]** Cu is an element capable of further increasing the strength of steel by solid-solution strengthening like Cr. When the content exceeds 1.0 %, however, a Cu-induced crack is easily caused. Therefore, when the component composition includes Cu, the content should be not more than 1.0%. The lower limit and upper limit of the Cu content should be 0.005% and 0.5%, respectively.

Ni: not more than 1.0%

**[0032]** Ni is an element capable of increasing the strength of steel without deteriorating its ductility. Also, the Cu-induced crack can be suppressed by composite addition with Cu, so that it is desirable to contain Ni when Cu is included in the component composition. When the Ni content exceeds 1.0%, however, the hardenability of steel is further improved, increasing the production amount of martensite and bainite, which often causes deterioration of the wear resistance and the fatigue damage resistance. Therefore, when Ni is included, the Ni content is preferably not more than 1.0%. Moreover, the lower limit of the Ni content is more preferably 0.005%, while the upper limit of the Ni content is more preferably 0.5%.

Nb: not more than 0.05%

**[0033]** Nb bonds to C in steel during and after the hot rolling for shaping the rail to form precipitates as a carbide, which acts effectively to fine the size of pearlite colony. As a result, Nb largely improves the wear resistance, fatigue damage resistance, and ductility and largely contributes to the prolonged service life of the high internal hardness type rail. When the Nb content exceeds 0.05%, the effect of improving the wear resistance and fatigue damage resistance is saturated, failing to be commensurate with the increase of the content. Therefore, Nb may be contained by up to 0.05%. When the Nb content is less than 0.001%, the effect of prolonging the service life of the rail is hard to be obtained. When Nb is included, therefore, the Nb content is preferably not less than 0.001%. Moreover, the upper limit of the Nb content is more preferably 0.03%.

Mo: not more than 2.0%

**[0034]** Mo is an element capable of further increasing the strength of steel by solid-solution strengthening. Mo also moves the eutectoid precipitation point toward the high C content side to suppress the formation of the pro-eutectoid cementite. However, when it exceeds 2.0%, the amount of bainite produced in steel increases to thus deteriorate the wear resistance. Therefore, when Mo is included in the component composition of the rail, the Mo content is preferably not more than 2.0%. Moreover, the lower limit of the Mo content is more preferably 0.005%, while the upper limit of the Mo content is more preferably 1.0%.

Al: not more than 0.07%

**[0035]** Al can be added as a deoxidizing agent. However, when the Al content exceeds 0.07%, a large amount of an oxide-based inclusion is produced in steel due to a high bonding force of Al with oxygen, resulting in deterioration in the ductility of steel. Therefore, the Al content is preferably not more than 0.07%. On the other hand, the lower limit of the Al content is not particularly limited but is preferable to be not less than 0.001% for deoxidization. Moreover, the upper limit of the Al content is more preferably 0.03%.

W: not more than 1.0%

**[0036]** W forms precipitates as carbide during and after hot rolling for shaping into a rail form and improves the strength and ductility of the rail by precipitation strengthening. When the W content exceeds 1.0%, however, martensite is produced in steel to deteriorate the ductility. Therefore, when W is added, the W content is preferably not more than 1.0%. Although the lower limit of the W content is not particularly limited, it is preferably not less than 0.001% to develop the action of improving the strength and ductility. The lower limit of the W content is more preferably 0.005%, while the upper limit of the W content is more preferably 0.5%.

B: not more than 0.005%

**[0037]** B forms precipitates as nitride in steel during and after hot rolling for the shaping into a rail form and improves the strength and ductility of steel by precipitation strengthening. When the B content exceeds 0.005%, however, martensite is formed, resulting in a decrease in the steel ductility. Thus, when B is included, the B content is preferably not more

than 0.005%. Although the lower limit of the B content is not particularly limited, it is preferably not less than 0.001% to develop the action of improving the strength and ductility. Moreover, the upper limit of the B content is more preferably 0.003%.

5 Ti: not more than 0.05%

10 **[0038]** Ti forms precipitates as carbide, nitride, or carbonitride in steel during and after hot rolling for shaping into a rail form to improve the strength and ductility of steel by precipitation strengthening. When the Ti content exceeds 0.05%, the coarse carbide, nitride, or carbonitride is produced, resulting in the deterioration of the ductility of steel. Therefore, when Ti is included, the Ti content is preferably not more than 0.05%. Although the lower limit of the Ti content is not particularly limited, it is preferably not less than 0.001% to develop the action of improving the strength and ductility. The lower limit of the Ti content is more preferably 0.005%, while the upper limit of the Ti content is more preferably 0.03%.

15 Sb: not more than 0.05%

**[0039]** Sb has a remarkable effect of preventing decarburization of steel during reheating of steel material for a rail conducted in a heating furnace before the hot rolling. However, when the Sb content exceeds 0.05%, the ductility and toughness of steel are adversely affected. Thus, when Sb is included, the Sb content is preferably not more than 0.05%. Although the lower limit of the Sb content is not particularly limited, it is preferably not less than 0.001% to develop the effect of mitigating a decarburized layer. Moreover, the lower limit of the Sb content is more preferably 0.005%, while the upper limit of the Sb content is more preferably 0.03%.

20 **[0040]** The component composition of the raw steel material to be the material of the rail according to the invention comprises the above ingredients and the remainder being Fe and inevitable impurities. Also, a rail containing a trace amount of other elements in place of part of Fe in the component composition according to the invention within the scope of substantially having no influence upon the action and effects of the invention belongs to the invention. Here, N, O, and so on are mentioned as the inevitable impurity, where N is acceptable up to 0.008% and O is acceptable up to 0.004%.

25 **[0041]** Moreover, the structure other than pearlite in the microstructure of the rail according to the invention is not particularly limited. The structure hardly affects the fatigue crack propagation resistance characteristics when the total area ratio thereof is not more than 5% and is thus allowed to be present. Such a structure includes, for example, ferrite, pro-eutectoid cementite, bainite, and martensite.

30 **[0042]** Next, the method for producing the aforementioned rail according to the invention will be described below.

**[0043]** The rail according to the invention can be produced by sequentially subjecting the raw steel material having the above component composition to the following treatments (1) to (3):

- 35 (1) hot rolling  
(2) primary cooling  
(3) secondary cooling

40 **[0044]** Although the raw steel material used as a rail material can be produced by an arbitrary method, it is preferable that the raw steel material be usually produced by casting, particularly continuous casting.

(1) Hot rolling

45 **[0045]** Firstly, the raw steel material is hot-rolled into a rail form. In the invention, the hot-rolling method is not particularly limited and can use an arbitrary method because the prior austenite grain size of the finally obtained rail can be controlled by controlling a finish rolling temperature in the hot rolling.

Heating temperature: not higher than 1350°C

50 **[0046]** The temperature for heating the raw steel material conducted prior to the hot rolling is necessary to be not higher than 1350°C. When the heating temperature exceeds the upper limit, the raw steel material is partly melted by excessive heating and may cause defects in the interior of the rail. Although the lower limit of the heating temperature is not particularly limited, it is preferably not lower than 1150°C to reduce deformation resistance in the rolling.

55 Finish rolling temperature: not lower than 900°C

**[0047]** When the finish-rolling temperature in the hot rolling is lower than 900°C, the rolling is conducted at a low temperature zone of austenite, resulting in introduced processing strain into austenite crystal grains as well as remarkable

elongation of austenite crystal grains. An increase in the austenite grain boundary area causes an increase in the nucleation site of pro-eutectoid cementite, resulting in the deterioration of the fatigue crack propagation resistance characteristics. Therefore, the finish rolling temperature should be not lower than 900°C. Although the upper limit of the finish rolling temperature is not particularly limited, it is preferable to be not higher than 1050°C because an extremely coarse prior austenite grain size deteriorates the ductility and toughness. Note that the finish rolling temperature means a temperature of a side face of a rail head portion at an entry side of the final rolling mill and can be measured by a radiation thermometer.

## (2) Primary cooling

Average cooling rate from 900°C to 750°C: 0.4 to 3°C/s

**[0048]** Secondly, accelerated cooling is conducted. When the average cooling rate of the primary cooling from 900°C to 750°C, which is a formation temperature region of pro-eutectoid cementite, is less than 0.4°C/s, the amount of pro-eutectoid cementite increases. As a result, the pro-eutectoid cementite tends to cause cracks, which may deteriorate the fatigue damage resistance of the rail. Therefore, the lower limit of the average cooling rate in the primary cooling is preferably 0.4°C/s, more preferably 0.7°C/s. When the average cooling rate in the primary cooling exceeds 3°C/s, a martensite structure may be formed to deteriorate the ductility and fatigue damage resistance. Therefore, the upper limit of the average cooling rate in the primary cooling is preferably 3°C/s, more preferably 2°C/s.

## (3) Secondary cooling

Average cooling rate from 750°C to a temperature zone of 400 to 600°C: 1 to 10°C/s

**[0049]** Secondary cooling is performed after the primary cooling is finished. When the average cooling rate from 750°C as a start temperature of the secondary cooling to a cooling stop temperature of the secondary cooling in a temperature zone of 400 to 600°C is less than 1°C/s, the lamellar spacing of the pearlite microstructure is coarsened. This may lower the hardness of the pearlite microstructure to deteriorate the fatigue damage resistance of the rail. In addition, the increase in the cooling time at the low-temperature zone may lower productivity, resulting in an increase in the production cost of the rail. On the other hand, when the average cooling rate in the secondary cooling exceeds 10°C/s, a martensite structure may be produced to deteriorate the ductility and fatigue damage resistance. Therefore, the average cooling rate in the secondary cooling is preferably in the range of 1 to 10°C/s. The upper limit of the average cooling rate in the secondary cooling is more preferably 5°C/s.

**[0050]** Each average cooling rate of the primary and secondary cooling is determined using a surface temperature of a side face on the rail head portion and can be measured by a radiation thermometer. The cooling stop temperature in the secondary cooling is a temperature measured on the side face of the rail head portion using the radiation thermometer after the stop of the accelerated cooling (before recuperation).

## Examples

**[0051]** The configuration and effects of the present invention will be described more specifically in accordance with the following examples. However, the present invention is not limited by the following examples, and may be modified as appropriate within the scope of conformity with the purpose of the present invention, all of which are included in the technical scope of the present invention.

**[0052]** A rail material was produced by subjecting a raw steel material having a component composition shown in Table 1 to a hot rolling and subsequently to accelerated cooling under conditions shown in Table 2. The accelerated cooling was applied to only a head portion of the rail, which is allowed to cool after the cooling is stopped. The finish rolling temperature in Table 2 is a temperature value of a side surface of the rail head portion measured at an entry side of a final rolling mill by a radiation thermometer. The cooling stop temperature in Table 2 is the temperature value of the side surface layer of the rail head portion measured by the radiation thermometer at a time of cooling stop in the secondary cooling. The cooling rate (°C/s) in each case of the primary cooling and the secondary cooling is a value obtained by converting the temperature change from the start of cooling to the stoppage thereof per unit time (second).



# EP 4 174 191 A1

Table 1-1

| Steel No.                                                               | Component composition (mass%) |      |      |       |       |      |                | X      | Remarks         |
|-------------------------------------------------------------------------|-------------------------------|------|------|-------|-------|------|----------------|--------|-----------------|
|                                                                         | C                             | Si   | Mn   | P     | S     | Cr   | Other elements |        |                 |
| S01                                                                     | 0.83                          | 0.59 | 0.48 | 0.011 | 0.007 | 0.91 |                | 42133  | Inventive Steel |
| S02                                                                     | 0.90                          | 0.35 | 0.23 | 0.014 | 0.011 | 1.56 |                | 62851  | Inventive Steel |
| S03                                                                     | 0.85                          | 0.89 | 0.60 | 0.009 | 0.006 | 0.72 |                | 47965  | Inventive Steel |
| S04                                                                     | 0.81                          | 0.37 | 1.79 | 0.016 | 0.003 | 0.25 |                | 37467  | Inventive Steel |
| S05                                                                     | 0.92                          | 1.19 | 0.34 | 0.013 | 0.005 | 1.03 |                | 71934  | Inventive Steel |
| S06                                                                     | 0.84                          | 1.00 | 0.45 | 0.016 | 0.006 | 0.81 |                | 45442  | Inventive Steel |
| S07                                                                     | 1.29                          | 0.13 | 0.76 | 0.015 | 0.005 | 0.22 |                | 364626 | Inventive Steel |
| S08                                                                     | 0.86                          | 0.58 | 0.27 | 0.009 | 0.004 | 0.97 |                | 50008  | Inventive Steel |
| S09                                                                     | 1.00                          | 0.24 | 0.58 | 0.034 | 0.005 | 0.80 |                | 104181 | Inventive Steel |
| S10                                                                     | 0.95                          | 0.41 | 0.34 | 0.012 | 0.007 | 2.01 |                | 83425  | Inventive Steel |
| S11                                                                     | 1.06                          | 0.70 | 0.62 | 0.026 | 0.003 | 1.23 |                | 143079 | Inventive Steel |
| S12                                                                     | 0.89                          | 0.33 | 0.48 | 0.011 | 0.010 | 0.98 |                | 58858  | Inventive Steel |
| S13                                                                     | 0.86                          | 0.52 | 0.73 | 0.016 | 0.009 | 0.67 |                | 50004  | Inventive Steel |
| S14                                                                     | 0.83                          | 0.11 | 0.21 | 0.011 | 0.010 | 2.48 |                | 42725  | Inventive Steel |
| $X = \{(10 \times [\%C]) + ([\%Si]/12) + ([\%Mn]/24) + ([\%Cr]/21)\}^5$ |                               |      |      |       |       |      |                |        |                 |

Table 1-2

| Steel No.                                                               | Component composition (mass%) |      |      |       |       |      |                  | X      | Remarks           |
|-------------------------------------------------------------------------|-------------------------------|------|------|-------|-------|------|------------------|--------|-------------------|
|                                                                         | C                             | Si   | Mn   | P     | S     | Cr   | Other elements   |        |                   |
| S15                                                                     | 0.85                          | 0.84 | 0.30 | 0.010 | 0.008 | 1.05 | V:0.05, Nb:0.018 | 47938  | Inventive Steel   |
| S16                                                                     | 0.93                          | 0.60 | 0.54 | 0.008 | 0.004 | 1.12 | Cu:0.42, Ni:0.19 | 74404  | Inventive Steel   |
| S17                                                                     | 0.87                          | 0.29 | 0.89 | 0.014 | 0.006 | 0.73 | Mo:0.53          | 52654  | Inventive Steel   |
| S18                                                                     | 0.82                          | 0.25 | 1.35 | 0.016 | 0.010 | 0.58 | Al:0.034, W:0.26 | 39502  | Inventive Steel   |
| S19                                                                     | 0.85                          | 0.47 | 0.72 | 0.015 | 0.009 | 0.69 | B:0.004, Ti:0.02 | 47098  | Inventive Steel   |
| S20                                                                     | 0.90                          | 1.02 | 0.36 | 0.009 | 0.005 | 0.45 | Sb: 0.04         | 63141  | Inventive Steel   |
| S21                                                                     | 0.79                          | 0.36 | 0.34 | 0.015 | 0.005 | 0.28 |                  | 31907  | Comparative Steel |
| S22                                                                     | 1.31                          | 0.55 | 0.89 | 0.018 | 0.010 | 0.91 |                  | 404747 | Comparative Steel |
| S23                                                                     | 0.85                          | 0.09 | 0.25 | 0.013 | 0.011 | 0.72 |                  | 45750  | Comparative Steel |
| S24                                                                     | 1.24                          | 1.23 | 0.71 | 0.009 | 0.009 | 0.59 |                  | 312593 | Comparative Steel |
| S25                                                                     | 0.85                          | 0.15 | 0.18 | 0.020 | 0.008 | 0.45 |                  | 45462  | Comparative Steel |
| S26                                                                     | 1.13                          | 0.90 | 1.81 | 0.010 | 0.004 | 0.50 |                  | 198892 | Comparative Steel |
| S27                                                                     | 0.84                          | 0.28 | 0.70 | 0.014 | 0.005 | 0.18 |                  | 43364  | Comparative Steel |
| S28                                                                     | 1.08                          | 0.51 | 1.27 | 0.012 | 0.006 | 2.51 |                  | 162148 | Comparative Steel |
| $X = \{(10 \times [\%C]) + ([\%Si]/12) + ([\%Mn]/24) + ([\%Cr]/21)\}^5$ |                               |      |      |       |       |      |                  |        |                   |

Table 2-1

| Test No. | Steel No. | Pro duction condi tions |                           |                                                  |                                                    |                         | Te st results                                   |                      |                                                              |                                                      | Remarks           |
|----------|-----------|-------------------------|---------------------------|--------------------------------------------------|----------------------------------------------------|-------------------------|-------------------------------------------------|----------------------|--------------------------------------------------------------|------------------------------------------------------|-------------------|
|          |           | Heating temp. [°C]      | Finish rolling temp. [°C] | Average cooling rate in primary cooling [°C/sec] | Average cooling rate in secondary cooling [°C/sec] | Cooling stop temp. [°C] | Prior austenite grain size: R <sub>A</sub> [μm] | CP =X/R <sub>A</sub> | Fatigue crack propagation rate * [×10 <sup>-8</sup> m/cycle] | Number of cycles to failure [×10 <sup>5</sup> times] |                   |
| 1        | S01       | 1250                    | 930                       | 1.2                                              | 3.4                                                | 525                     | 40                                              | 1053                 | 4.7                                                          | 8.25                                                 | Inventive Example |
| 2        | S02       | 1300                    | 950                       | 1.4                                              | 2.6                                                | 550                     | 46                                              | 1366                 | 5.1                                                          | 10.25                                                | Inventive Example |
| 3        | S03       | 1250                    | 930                       | 1.0                                              | 3.1                                                | 550                     | 37                                              | 1296                 | 5.5                                                          | 8.50                                                 | Inventive Example |
| 4        | S04       | 1200                    | 900                       | 0.4                                              | 1.2                                                | 550                     | 26                                              | 1441                 | 7.3                                                          | 8.75                                                 | Inventive Example |
| 5        | S05       | 1150                    | 910                       | 0.9                                              | 2.5                                                | 550                     | 30                                              | 2398                 | 7.1                                                          | 9.50                                                 | Inventive Example |
| 6        | S06       | 1275                    | 950                       | 1.8                                              | 3.6                                                | 500                     | 52                                              | 874                  | 3.9                                                          | 8.50                                                 | Inventive Example |
| 7        | S07       | 1225                    | 1040                      | 3.0                                              | 9.8                                                | 525                     | 149                                             | 2447                 | 7.9                                                          | 8.25                                                 | Inventive Example |
| 8        | S08       | 1250                    | 920                       | 2.0                                              | 4.0                                                | 550                     | 46                                              | 1087                 | 4.2                                                          | 8.50                                                 | Inventive Example |
| 9        | S09       | 1200                    | 930                       | 0.8                                              | 2.9                                                | 550                     | 43                                              | 2423                 | 6.2                                                          | 9.25                                                 | Inventive Example |
| 10       | S10       | 1300                    | 900                       | 1.1                                              | 1.8                                                | 500                     | 36                                              | 2317                 | 5.9                                                          | 10.75                                                | Inventive Example |
| 11       | S11       | 1250                    | 960                       | 0.9                                              | 2.6                                                | 550                     | 66                                              | 2168                 | 5.5                                                          | 9.50                                                 | Inventive Example |
| 12       | S12       | 1225                    | 940                       | 1.4                                              | 3.7                                                | 550                     | 54                                              | 1090                 | 4.6                                                          | 8.50                                                 | Inventive Example |
| 13       | S13       | 1200                    | 970                       | 0.7                                              | 4.1                                                | 525                     | 70                                              | 714                  | 4.0                                                          | 8.25                                                 | Inventive Example |

(continued)

| Test No. | Steel No. | Pro duction condi tions |                           |                                                  |                                                    |                         | Te st results                                       |                      |                                                                     |                                                    | Remarks           |
|----------|-----------|-------------------------|---------------------------|--------------------------------------------------|----------------------------------------------------|-------------------------|-----------------------------------------------------|----------------------|---------------------------------------------------------------------|----------------------------------------------------|-------------------|
|          |           | Heating temp. [°C]      | Finish rolling temp. [°C] | Average cooling rate in primary cooling [°C/sec] | Average cooling rate in secondary cooling [°C/sec] | Cooling stop temp. [°C] | Prior austenite grain size: $R_A$ [ $\mu\text{m}$ ] | CP =X/R <sub>A</sub> | Fatigue crack propagation rate * [ $\times 10^{-8}\text{m/cycle}$ ] | Number of cycles to failure [ $\times 10^5$ times] |                   |
| 14       | S14       | 1250                    | 950                       | 1.0                                              | 4.5                                                | 500                     | 61                                                  | 700                  | 4.2                                                                 | 11.25                                              | Inventive Example |
| 15       | S15       | 1300                    | 930                       | 1.5                                              | 3.0                                                | 550                     | 49                                                  | 978                  | 4.9                                                                 | 9.25                                               | Inventive Example |
| 16       | S16       | 1275                    | 960                       | 2.3                                              | 2.8                                                | 550                     | 53                                                  | 1404                 | 5.8                                                                 | 10.50                                              | Inventive Example |
| 17       | S17       | 1175                    | 920                       | 0.9                                              | 3.6                                                | 550                     | 37                                                  | 1423                 | 4.1                                                                 | 9.00                                               | Inventive Example |
| 18       | S18       | 1200                    | 925                       | 1.2                                              | 2.3                                                | 525                     | 42                                                  | 941                  | 4.5                                                                 | 8.50                                               | Inventive Example |

\*Fatigue crack propagation rate da/dN is a value at a stress intensity factor range  $\Delta K = 20\text{MPa} \cdot \text{m}^{1/2}$ .

Table 2-2

| Test No.                                                                                                                                                                                                                                 | Steel No. | Production conditions |                           |                                                  |                                                    |                         | Test results                           |             |                                                              |                                                    | Remarks             |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|-----------------------|---------------------------|--------------------------------------------------|----------------------------------------------------|-------------------------|----------------------------------------|-------------|--------------------------------------------------------------|----------------------------------------------------|---------------------|
|                                                                                                                                                                                                                                          |           | Heating temp. [°C]    | Finish rolling temp. [°C] | Average cooling rate in primary cooling [°C/sec] | Average cooling rate in secondary cooling [°C/sec] | Cooling stop temp. [°C] | Prior austenite grain size: $R_A$ [μm] | CP $=X/R_A$ | Fatigue crack propagation rate * [ $\times 10^{-8}$ m/cycle] | Number of cycles to failure [ $\times 10^5$ times] |                     |
| 19                                                                                                                                                                                                                                       | S19       | 1250                  | 940                       | 1.0                                              | 4.6                                                | 500                     | 49                                     | 961         | 4.3                                                          | 8.00                                               | Inventive Example   |
| 20                                                                                                                                                                                                                                       | S20       | 1300                  | 990                       | 1.6                                              | 3.9                                                | 550                     | 75                                     | 842         | 5.0                                                          | 8.25                                               | Inventive Example   |
| 21                                                                                                                                                                                                                                       | S21       | 1250                  | 930                       | 1.5                                              | 1.1                                                | 550                     | 41                                     | 778         | 8.1                                                          | 6.75                                               | Comparative Example |
| 22                                                                                                                                                                                                                                       | S22       | 1200                  | 950                       | 0.7                                              | 4.8                                                | 550                     | 56                                     | 7228        | 9.8                                                          | 8.50                                               | Comparative Example |
| 23                                                                                                                                                                                                                                       | S23       | 1200                  | 900                       | 1.0                                              | 2.0                                                | 500                     | 32                                     | 1430        | 8.5                                                          | 7.25                                               | Comparative Example |
| 24                                                                                                                                                                                                                                       | S24       | 1250                  | 920                       | 2.8                                              | 4.5                                                | 525                     | 35                                     | 8931        | 14.7                                                         | 8.25                                               | Comparative Example |
| 25                                                                                                                                                                                                                                       | S25       | 1300                  | 930                       | 0.6                                              | 1.8                                                | 525                     | 43                                     | 1057        | 8.2                                                          | 7.75                                               | Comparative Example |
| 26                                                                                                                                                                                                                                       | S26       | 1225                  | 950                       | 1.9                                              | 3.9                                                | 550                     | 50                                     | 3978        | 9.2                                                          | 8.25                                               | Comparative Example |
| 27                                                                                                                                                                                                                                       | S27       | 1200                  | 970                       | 0.8                                              | 1.5                                                | 500                     | 69                                     | 628         | 8.3                                                          | 7.50                                               | Comparative Example |
| 28                                                                                                                                                                                                                                       | S28       | 1250                  | 940                       | 2.8                                              | 4.6                                                | 525                     | 53                                     | 3059        | 8.7                                                          | 8.50                                               | Comparative Example |
| 29                                                                                                                                                                                                                                       | S01       | 1360                  | 900                       | 1.2                                              | 2.9                                                | 550                     | -                                      | -           | -                                                            | -                                                  | Comparative Example |
| 30                                                                                                                                                                                                                                       | S10       | 1250                  | 890                       | 0.7                                              | 3.0                                                | 500                     | 33                                     | 2528        | 8.2                                                          | 8.75                                               | Comparative Example |
| *Fatigue crack propagation rate $da/dN$ is a value at a stress intensity factor range $\Delta K = 20 \text{ MPa} \cdot \text{m}^{1/2}$ .<br>Test No. 29 cannot be evaluated due to partial melting of raw steel material during heating. |           |                       |                           |                                                  |                                                    |                         |                                        |             |                                                              |                                                    |                     |

**[0053]** An evaluation was conducted on the prior austenite grain size  $R_A$ , fatigue crack propagation resistance characteristics, and fatigue damage resistance of the resulting rail. Each of the evaluations will be described in detail below.

<Prior austenite grain size  $R_A$ >

**[0054]** After the finish rolling in hot rolling, a leading portion of the rail was cut and the cut material was immediately subjected to a water-cooling treatment. From the thus-obtained water-cooled material, a test specimen for a structure observation was taken out in a longitudinal rolling direction at 5-mm depth from a surface of a rail head portion 1 shown in FIG. 2. The thus-obtained test specimen was subjected to mirror polishing and then etching with  $\gamma$ -grains, and a section thereof was observed with an optical microscope of 200 magnification. The prior austenite grain size  $R_A$  was evaluated by measuring grain sizes of 400 or more grains by a trace operation using image analysis software and calculating an average value thereof.

<Fatigue crack propagation resistance characteristics>

**[0055]** Test specimens for fatigue crack propagation were taken out from two positions of the rail head portion and gauge corner (GC) portion shown in FIG. 3 to conduct a fatigue crack propagation test. FIG. 4 is a schematic view showing one example of the test specimen, where FIG. 4(a) is a front view, FIG. 4(b) is a side view, and FIG. 4(c) is an enlarged front view of a notch portion. In FIG. 4, the test specimen has a plate shape with, for example, a width  $W = 20$  mm, a height  $H = 100$  mm, and a thickness  $B = 5$  mm, where a notch portion is formed in an end part of a central portion  $H/2$  of the height  $H$ . The notch portion has a length  $L = 2$  mm and a width  $C = 0.2$  mm where an end part of the notch portion is formed at a radius of curvature  $R = 0.1$  mm. The stress ratio ( $R$  ratio = minimum stress/maximum stress) was 0.1, and the fatigue crack propagation resistance was evaluated by measuring a fatigue crack propagation rate  $da/dN$  (m/cycle) at a stress intensity factor range  $\Delta K = 20$  MPa  $\cdot$  m $^{1/2}$ . When the value of  $da/dN$  is not more than  $8.0 \times 10^{-8}$ , the material was evaluated to have characteristics of suppressing fatigue crack propagation.

<Fatigue damage resistance>

**[0056]** Although it is most desirable to evaluate the fatigue damage resistance by actually laying rails, this requires a long time for testing. Therefore, a Nishihara-type wear specimen, which can evaluate fatigue damage resistance in a short time, was used. In the test, fatigue damage resistance was evaluated by a comparative test simulating actual contact conditions between a rail and a wheel. Concretely, the test was conducted by taking out a Nishihara-type wear specimen 17 having a diameter of 30 mm from the rail head portion 1 provided that a contact face is a curved face having a radius of curvature of  $R = 15$  mm and rotating the specimen 17 in contact with a wheel specimen 18 as shown in FIG. 5. The wheel specimen 18 was prepared by taking out a rod having a diameter of 32 mm from a head portion of a regular rail described in JIS E1101:2012, subjecting the rod to a heat treatment so as to have a Vickers hardness (load: 98N) of Hv 390 and a tempered martensite structure, and working into a cylinder shape having a diameter of 30 mm. The Nishihara-type wear specimen 17 was taken out from a fatigue damage resistance specimen collection area 14 on the surface of the rail head 1 as shown in FIG. 6. Arrows in FIG. 5(a) indicate the rotating directions of the Nishihara-type wear specimen 17 and the wheel specimen 18, respectively. Under such a test environment of oil-lubrication conditions as a contact pressure: 1.8 GPa, a slip ratio: -20%, and a revolution rate: 600 rpm (750 rpm in the wheel specimen), the surface of the specimen was observed every  $2.5 \times 10^4$  times, and the revolution number when a crack of not less than 0.5 mm was caused was defined as the service life for fatigue damage. When the value of the revolution number is not less than  $8 \times 10^5$  times, the specimen is judged to have a fatigue damage resistance.

**[0057]** The test results are also shown in Table 2. In the test results (Test Nos. 1 to 20, ... in Table 2) of the rails that are made of acceptable steels satisfying the component composition according to the invention and CP of not more than 2500 and produced by the production method within ranges of the invention (heating temperature, finish rolling temperature), all the fatigue crack propagation rate  $da/dN$  (m/cycle) at  $\Delta K = 20$  MPa  $\cdot$  m $^{1/2}$  satisfy not more than  $8.0 \times 10^{-8}$ . Also, Test Nos. 1 to 20, in which the primary cooling and secondary cooling conditions are in preferable ranges, satisfy both the fatigue crack propagation rate  $da/dN$  (m/cycle) of not more than  $8.0 \times 10^{-8}$  and the fatigue damage service life of not less than  $8 \times 10^5$  times. In Comparative Examples (Test Nos. 21 to 28, and 30 in Table 2) where the component composition of the rail material does not satisfy the condition of the invention or the production method within the scope of the invention is not adopted, CP exceeds 2500 and the fatigue crack propagation rate  $da/dN$  (m/cycle) exceeds  $8.0 \times 10^{-8}$  or the fatigue damage service life is less than  $8 \times 10^5$  times. In Test No. 29, the heating temperature was too high, so that a part of the raw steel material was melted during the heating. As a result, the steel material could not be subjected to the rolling due to possible breakage during rolling, and hence the characteristics could not be evaluated.

## Industrial Applicability

**[0058]** The rail and the production method thereof according to the invention can stably produce a fatigue damage-resistant rail having an excellent fatigue crack propagation resistance characteristics, which contributes to increasing the service life of the rail for a high-axle load railway and preventing railroad accidents, thereby bringing about industrially beneficial effects.

## Reference Signs List

**[0059]**

- 1 rail head portion
- 11 test specimen taking portion for observing prior austenite grain size
- 12 gauge corner (GC) portion
- 13 head portion
- 14 fatigue damage resistance specimen collection area
- 15 a test specimen for fatigue crack propagation
- 16 notch portion
- 17 Nishihara-type wear specimen
- 18 wheel specimen
- 21 prior austenite grain
- 22 plastic zone
- 23 fatigue crack
- 24 pro-eutectoid cementite
- 25 cleavage fracture
- 26 increase in fatigue crack propagation rate
- 27 decrease in fatigue crack propagation rate
- $R_A$  prior austenite grain size
- $R_P$  plastic zone size

**Claims**

1. A rail having excellent fatigue crack propagation resistance characteristics, **characterized in that**

the rail has a component composition comprising C: 0.80 to 1.30 mass%, Si: 0.10 to 1.20 mass%, Mn: 0.20 to 1.80 mass%, P: not more than 0.035 mass%, S: 0.0005 to 0.012 mass%, Cr: 0.20 to 2.50 mass% and the remainder being Fe and inevitable impurities and satisfying CP represented by the following equation (1) being not more than 2500:

$$CP = X/R_A \quad \dots (1)$$

and

$$X = \{(10 \times [\%C]) + ([\%Si]/12) + ([\%Mn]/24) + ([\%Cr]/21)\}^5 \dots (2),$$

where  $[\%Y]$  is the content of an element Y (mass%), and  $R_A$  is a prior austenite grain size ( $\mu\text{m}$ ).

2. The rail having excellent fatigue crack propagation resistance characteristics according to claim 1, wherein the component composition further contains at least one selected from V: not more than 0.30 mass%, Cu: not more than 1.0 mass%, Ni: not more than 1.0 mass%, Nb: not more than 0.05 mass%, and Mo: not more than 2.0 mass%.
3. The rail having excellent fatigue crack propagation resistance characteristics according to claim 1 or 2, wherein the component composition further contains at least one selected from Al: not more than 0.07 mass%, W: not more

than 1.0 mass%, B: not more than 0.005 mass%, Ti: not more than 0.05 mass%, and Sb: not more than 0.05 mass%.

4. A method for producing a rail having excellent fatigue crack propagation resistance characteristics,  
**characterized in that**

5 a raw steel material having a component composition according to any one of claims 1 to 3 is heated to not higher than 1350°C and hot-rolled such that a finish temperature is not lower than 900°C.

5. The method for producing a rail having excellent fatigue crack propagation resistance characteristics according to claim 4, wherein,

10 after the hot rolling, accelerated cooling is conducted at a cooling rate of 0.4 to 3°C/s from 900°C to 750°C and at a cooling rate of 1 to 10°C/s from 750°C to a cooling stop temperature of 400 to 600°C.

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FIG. 1(a)

Prior austenite grain size  $R_A$   
 $\doteq$   
 Plastic zone size  $R_P$

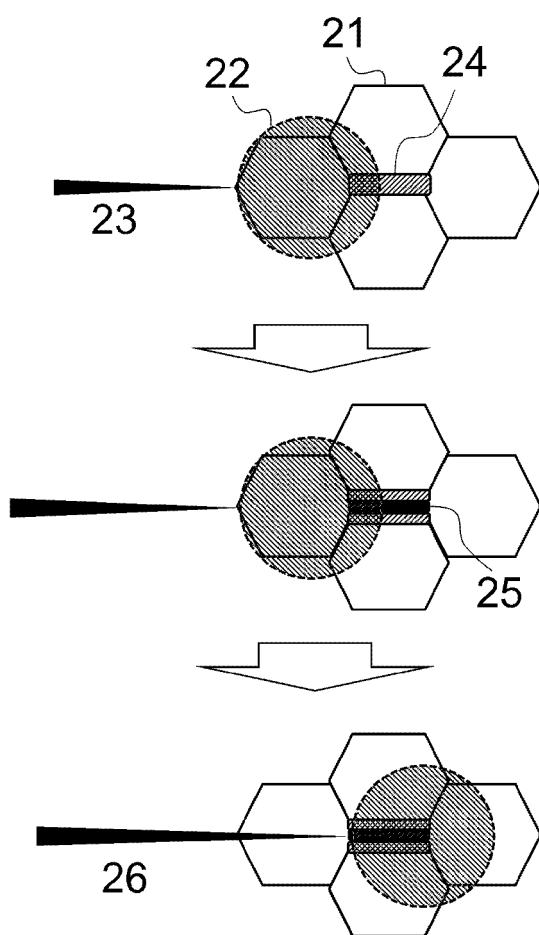


FIG. 1(b)

Prior austenite grain size  $R_A$   
 $>$   
 Plastic zone size  $R_P$

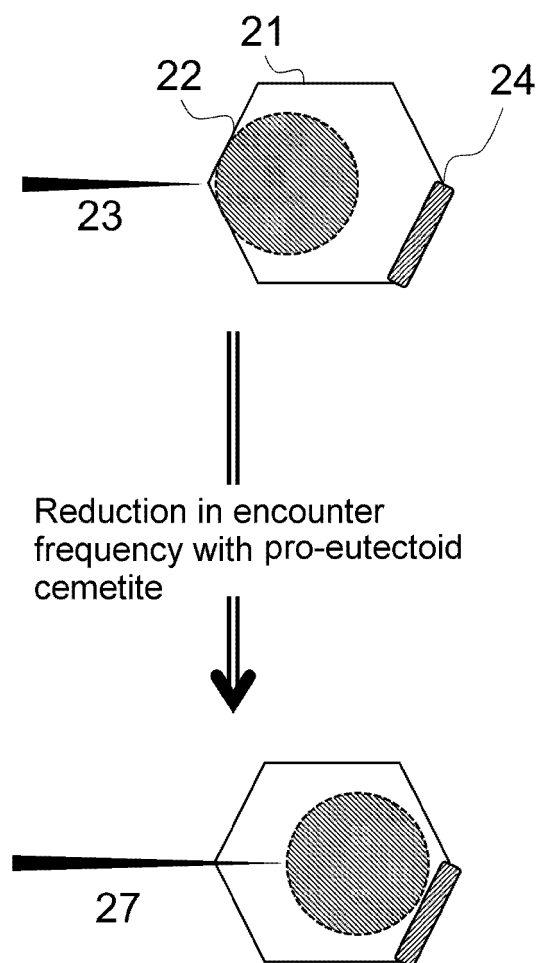




FIG. 2

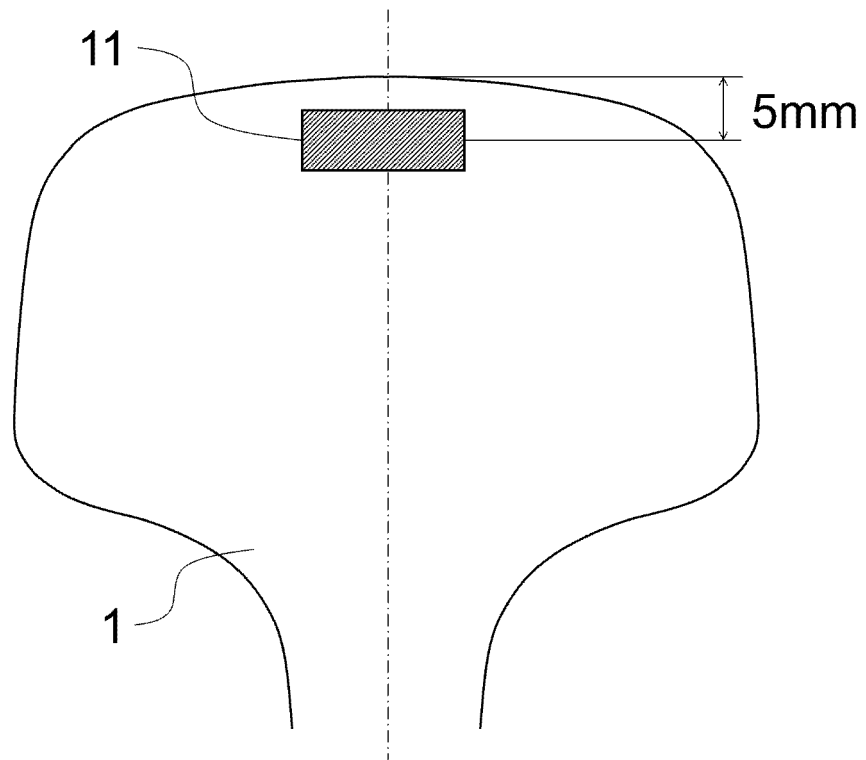
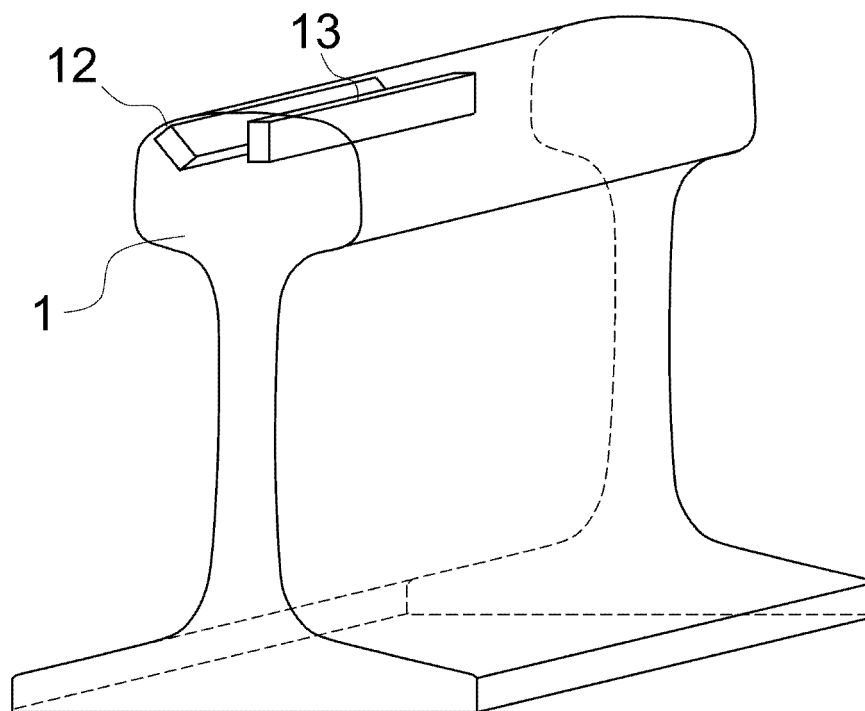


FIG. 3



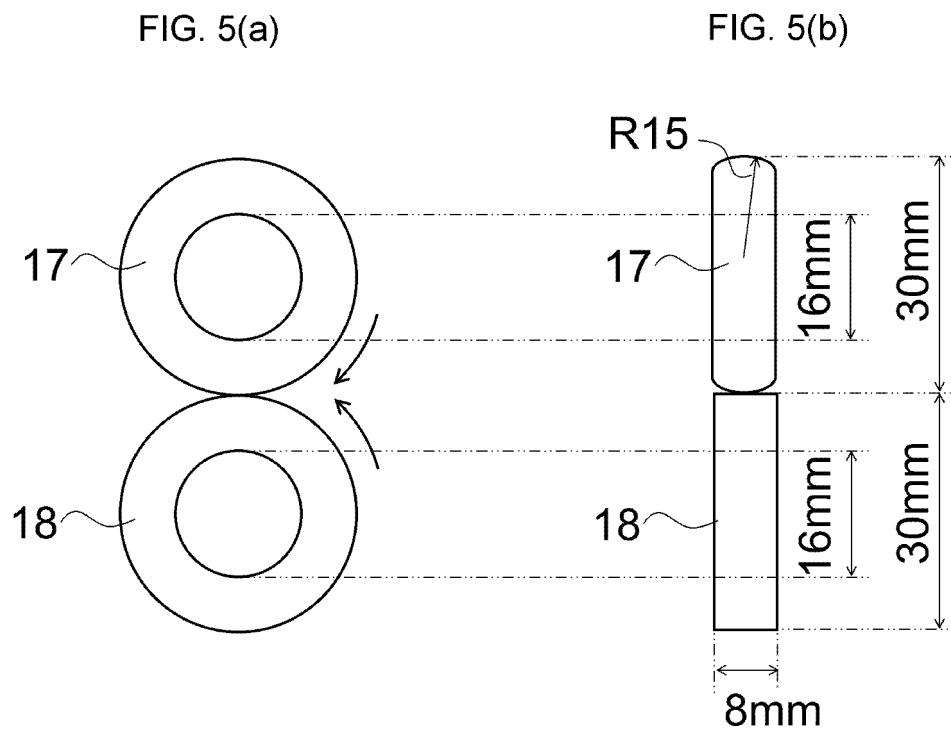
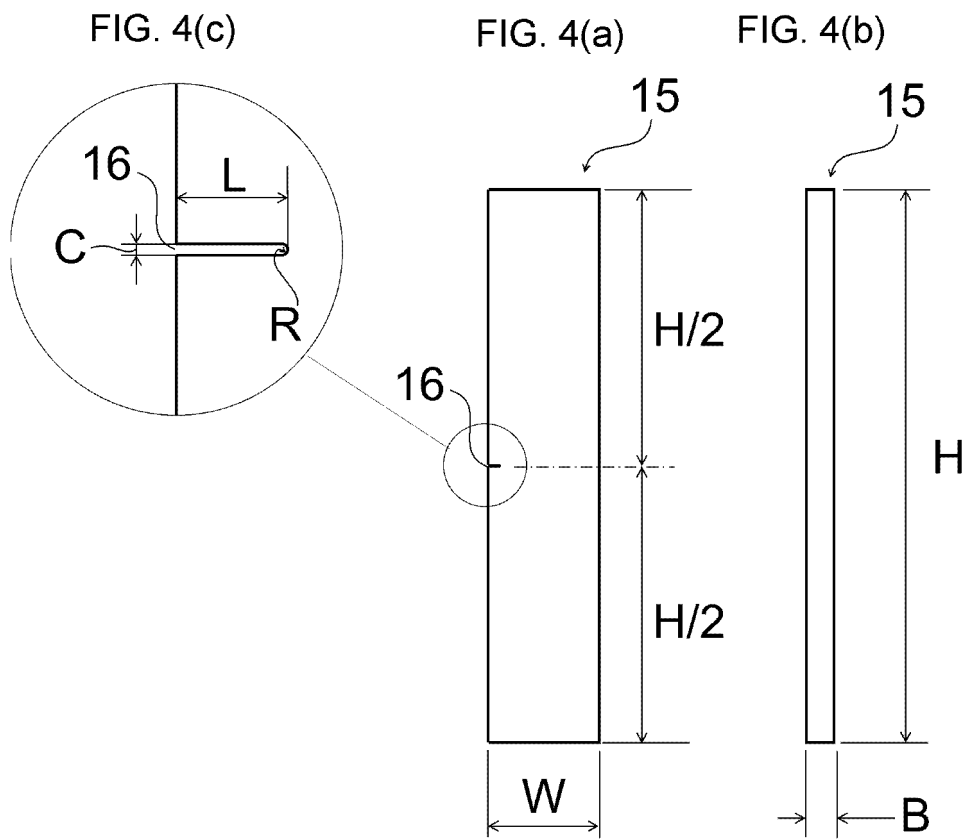
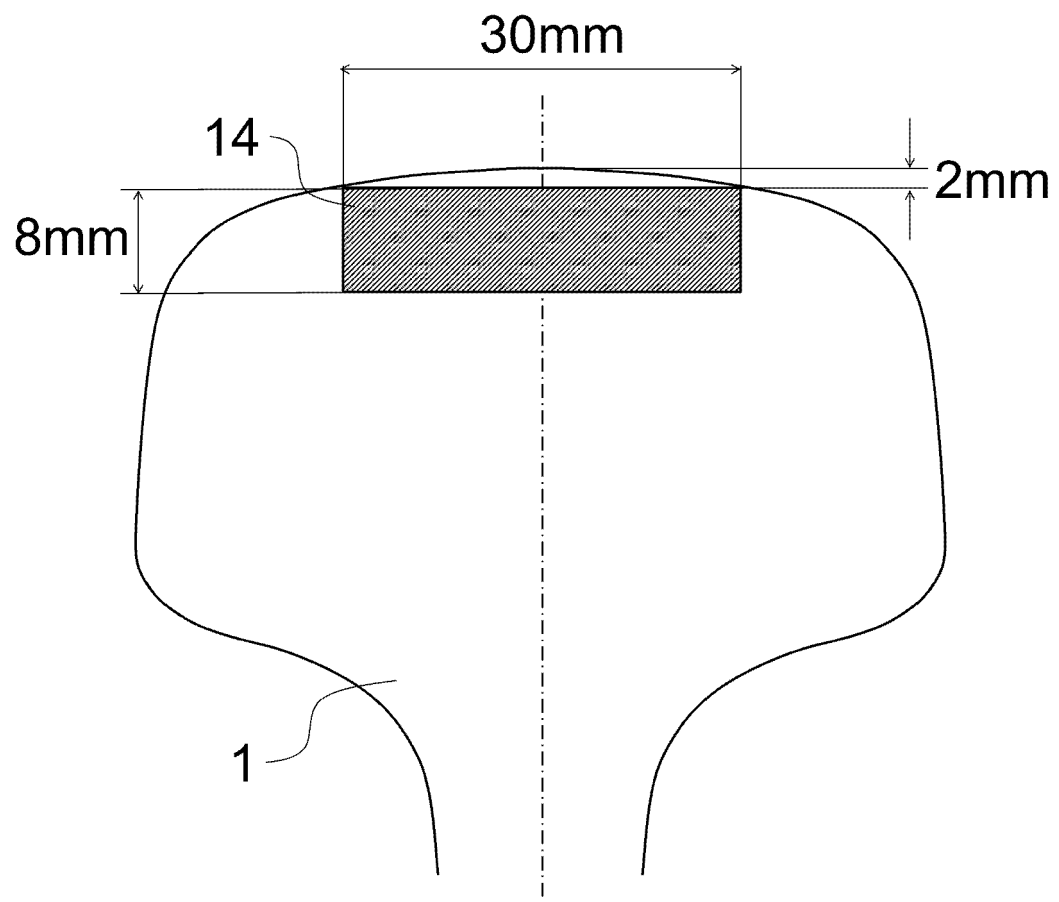


FIG. 6



## INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2021/020871

## A. CLASSIFICATION OF SUBJECT MATTER

Int.Cl. C21D8/00(2006.01)i, C22C38/00(2006.01)i, C22C38/38(2006.01)i, C22C38/60(2006.01)i

FI: C22C38/00301Z, C21D8/00A, C22C38/38, C22C38/60

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Int.Cl. C21D8/00, C21D9/04, C22C38/00-38/60, E01B5/00-5/18

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Published examined utility model applications of Japan 1922-1996

Published unexamined utility model applications of Japan 1971-2021

Registered utility model specifications of Japan 1996-2021

Published registered utility model applications of Japan 1994-2021

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                | Relevant to claim No. |
|-----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| X         | WO 2018/174095 A1 (JFE STEEL CORPORATION) 27                                                                                                                      | 4-5                   |
| A         | September 2018 (2018-09-27), claims, paragraphs [0039], [0044], [0052], table 1, steel samples A1, A2, table 3, steel samples A1, B2, B4-7, B10, B12, B16, B18-26 | 1-3                   |
| X         | WO 2019/189686 A1 (JFE STEEL CORPORATION) 03                                                                                                                      | 4-5                   |
| A         | October 2019 (2019-10-03), claims, paragraphs [0042], [0044], [0045], table 2, test no. 8-10, 13, 14, 16, 17, 23, 31, 32, 39                                      | 1-3                   |
| A         | US 2020/0017943 A1 (VOESTALPINE SCHIENEN GMBH) 16                                                                                                                 | 1-5                   |
|           | January 2020 (2020-01-16)                                                                                                                                         |                       |
| A         | JP 2010-185106 A (JFE STEEL CORPORATION) 26 August                                                                                                                | 1-5                   |
|           | 2010 (2010-08-26)                                                                                                                                                 |                       |
| A         | WO 2020/067520 A1 (NIPPON STEEL CORP.) 02 April                                                                                                                   | 1-5                   |
|           | 2020 (2020-04-02)                                                                                                                                                 |                       |



Further documents are listed in the continuation of Box C.



See patent family annex.

\* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&amp;" document member of the same patent family

Date of the actual completion of the international search

15 July 2021

Date of mailing of the international search report

03 August 2021

Name and mailing address of the ISA/

Japan Patent Office

3-4-3, Kasumigaseki, Chiyoda-ku,

Tokyo 100-8915, Japan

Authorized officer

Telephone No.

**INTERNATIONAL SEARCH REPORT**  
Information on patent family members

International application No.

PCT/JP2021/020871

WO 2018/174095 A1 27 September 2018 US 2020/0002780 A1  
 claims, paragraphs [0116], [0121],  
 [0130], table 1, steel samples A1, A2,  
 table 3, steel samples A1, B2, B4-7,  
 B10, B12, B16, B18-26  
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