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(72) Inventors:

- **TADA, Masafumi**
Tokyo 100-0011 (JP)
- **FUKUOKA, Kazuaki**
Tokyo 100-0011 (JP)

(74) Representative: **Haseltine Lake Kempner LLP**

**One Portwall Square
Portwall Lane
Bristol BS1 6BH (GB)**

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(71) Applicant: **JFE Steel Corporation**
Tokyo 100-0011 (JP)

(54) **STEEL COMPONENT AND PRODUCTION METHOD FOR SAME**

(57) A method to achieve a high yield ratio, specifically a yield ratio of 0.60 or more in a component from non-heat-treated steel, which is steel that is not subjected to thermal refining treatment after hot forging, and in particular non-heat-treated steel having bainitic microstructure. The component includes a predetermined chemical composition containing, in mass%, C: 0.21 % to 0.24 %, Si: 0.11 % to 0.25 %, Mn: 1.81 % to 1.99%, P: 0.014 % to 0.025 %, S: 0.035 % to 0.060 %, Cr: 0.55 % to 0.65 %, Al: 0.010 % to 0.050 %, Ti: 0.005 % to 0.020 %, V: 0.15 % to 0.20 % and N: 0.0090 % to 0.0150 %, in amounts such that a value of F1 obtained by Formula (1) is 0.65 % or more, with the balance as Fe and inevitable impurity. Bainitic microstructure area fraction is 85 % or more and Retained austenite area fraction is 5 % or less. Crystal grains of the bainitic microstructure have an average diameter of 10 μm or more and 25 μm or less, an average aspect ratio of 0.5 or more, and an average ratio of crystal grain boundary length to crystal grain circumference of 60 or less.

$$F1 = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14 \quad \dots (1)$$

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Description

TECHNICAL FIELD

- 5 **[0001]** The present disclosure relates to steel components, for example, steel components used in the undercarriages of automobiles and trucks, more specifically knuckles and front axles, and methods of producing same.

BACKGROUND

- 10 **[0002]** In recent years, concerns about global warming have led to calls in the industrial world for the curbing of CO₂ emissions. In response to this demand, the automobile industry is not only promoting the curbing of CO₂ emissions as exhaust gas from automobiles themselves, but is also considering various ways to curb CO₂ emissions in the component production process. As one technology to curb CO₂ emissions in the production process of such automobile components, development of non-heat-treated components has been active. Non-heat-treated components are those for which heat treatment to build up component strength is omitted, that is, thermal refinement processing of steel is omitted. The omission of heat treatment is made possible, for example, by technology that allows component strength to be built up during cooling of the component after the hot forging process in the component production process.

- 15 **[0003]** Non-heat-treated components are broadly classified into two categories based on their metallic microstructure. That is, the main metallic microstructure consists of two phases, ferrite and pearlite, or the main metallic microstructure consists of bainite. In the former, non-heat-treated steel mainly consisting of ferrite and pearlite, strengthening by precipitation entirely due to vanadium is used. In other words, vanadium carbides precipitate finely during the cooling process after hot forging of the component, strengthening the microstructure by precipitation, and therefore component strength equivalent to when thermal refining treatment is performed in the state after hot forging is obtainable. On the other hand, the strengthening mechanism for non-heat-treated components with bainitic microstructure is transformation strengthening. That is, the bainite transformation in the cooling process after hot forging creates a microstructure that is excellent in both strength and toughness. Which non-heat-treated steel is used depends on the required properties of the component, but typically, non-heat-treated steel with a bainitic microstructure tends to be used for components that require both strength and toughness.

- 20 **[0004]** Non-heat-treated steel that has a bainitic microstructure has a good balance of strength and toughness as above, but yield stress is typically lower, and the ratio of yield stress to tensile strength, the ultimate strength of steel material, or the so-called yield ratio, tends to be low. Further, yield stress varies more than tensile strength. It is arguable that yield stress, the strength at which plastic deformation begins, is more important than the ultimate strength of steel material in the design of steel for mechanical structure. From such a design perspective, steel with low yield stress is difficult to use, no matter how good tensile strength and toughness are. This is a technical problem for steels that have bainitic microstructure.

- 25 **[0005]** As technologies to address such a technical problem, the techniques of Patent Literature (PTL) 1 and PTL 2 have been proposed. In PTL 1, a technique is proposed to improve yield ratio and fatigue ratio (ratio of fatigue strength to tensile strength at 10⁷ rpm in the Ono-type rotary bending fatigue test) by controlling cooling to room temperature after hot forging and then tempering in a temperature range from 400 °C to 700 °C. Further, in PTL 2, a technique is proposed to increase yield stress by controlling a cooling rate to room temperature after hot working and then tempering at 200 °C to 600 °C.

- 30 **[0006]** However, these techniques require tempering after hot forging, which greatly reduces the benefits of non-heat-treated processing. Therefore, there has also been a pursuit of techniques to satisfy the required properties without tempering.

- 35 **[0007]** For example, in PTL 3, a technique is proposed to improve yield stress by slow cooling at a specified cooling rate between 200 °C and 500 °C during cooling after hot forging. However, in order to perform slow cooling in a specified temperature range, investing in equipment to modify existing cooling facilities is essential. In recent years, assembly plants for automobiles and trucks have been built in Southeast Asia and other regions outside of Japan, which has led to more local procurement of hot forging components. In plants being built in Southeast Asian countries and elsewhere, forged products after hot forging are often stacked in steel boxes. In such cases, it may be assumed that there is a significant difference in cooling rates between forged products near the bottom of a box and forged products stacked in an upper portion of the box. Further, most boxes are cuboid, and therefore cooling rates will differ among forged products near the four corners of a box, forged products near the sides of the box, and forged products near the center of the box. The strength building process of non-heat-treated steel is mainly a cooling process after hot forging, and therefore controlling the cooling rate during the cooling process is important. The problem in local procurement is that this cooling rate might not be adequately controlled. To address this problem, the introduction of the technique according to PTL 3 requires that plants in such countries have dedicated facilities for slow cooling after hot forging. However, it is extremely difficult to newly introduce such facilities to the improvement of such countries. Therefore, there is a demand for non-heat-treated steel that can achieve a defined strength without needing to strictly control cooling rate after hot forging. In other words, there is a demand for non-heat-treated steel that has mechanical properties that do not vary too much even when cooling rate varies

a little.

[0008] Further, in PTL 4, a microstructural factor that impairs yield ratio and fatigue ratio is identified as martensite austenite constituent-retained austenite mixed microstructure, and a technique is proposed to reduce the amount of Si added as a method to reduce this factor. However, in order to realize steel with Si reduced to the level specified in PTL 4 in an actual steelmaking process, steel must be produced by a refining method where Si is not used in the steelmaking process, which incurs high production costs and is undesirable from an economic viewpoint.

[0009] In PTL 5, a technique is proposed to simultaneously improve toughness and free-cutting by causing sulfide inclusions having a cross-section area of $3 \mu\text{m}^2$ or more to be contained at 200 per mm^2 or more. However, in order to achieve this sulfide content, sulfide must be precipitated and coarsened prior to hot working, which requires heat treatment or holding at high temperature for a long time when heating for hot working.

CITATION LIST

Patent Literature

[0010]

PTL 1: JP H05-156354 A

PTL 2: JP H05-287373 A

PTL 3: JP H04-285118 A

PTL 4: JP H10-298703 A

PTL 5: JP 2001-200332 A

SUMMARY

(Technical Problem)

[0011] The present disclosure is made in view of the above circumstances. That is, it would be helpful to provide a way to achieve a high yield ratio, specifically a yield ratio of 0.60 or more, in components from non-heat-treated steel, which is steel that is not subjected to thermal refining treatment after hot forging, and in particular non-heat-treated steel having bainitic microstructure. The target value for the yield ratio is 0.60 or more from the viewpoint of suppressing variation in mechanical properties. That is, yield stress is more sensitive than tensile stress in terms of cooling rate dependence of mechanical properties of steel having bainitic microstructure as the main microstructure. In other words, yield stress has a greater effect than tensile strength on variation in mechanical properties due to variation in cooling rate. Here, tensile stress is the ultimate stress value in a nominal stress-nominal strain curve obtained in a tensile test. Further, yield stress is the 0.2 % offset stress from the elastic range in the same curve. That is, when the yield ratio, the ratio of yield stress to tensile stress, is a certain value or more, the steel may be regarded as a steel with controlled yield stress variation, even when the steel is a non-heat-treated steel having a mainly bainitic microstructure. From this perspective, a yield ratio of 0.60 or more for a non-heat-treated steel having a bainitic microstructure may be considered to have a low sensitivity to cooling rate.

(Solution to Problem)

[0012] The inventors have made extensive studies to develop a non-heat-treated steel that has a yield ratio of 0.60 or more without tempering treatment, without using the techniques described in PTL 4 and PTL 5.

[0013] It is understood that the yielding phenomenon of metal under stress is the beginning of large-scale dislocation motion. That is, when stress applied to a dislocation source exceeds a certain threshold, dislocations are generated and propagate from the dislocation source, and dislocations so generated move in response to the stress and accumulate at crystal grain boundaries, causing stress at the crystal grain boundaries. When stress generated this way at a crystal grain boundary exceeds a certain threshold, macroscopic deformation begins, in which dislocations entangle not only crystal grains where dislocations accumulate inside the crystal grain boundary but also crystal grains that are adjacent, causing simultaneous large-scale deformation of many crystal grains. This is the yielding phenomenon.

[0014] Looking at the process of yielding described above, there are several possible ways to increase yield stress: (i) reduce dislocation density, (ii) reduce dislocation sources, (iii) make it harder for dislocations to be generated from dislocation sources, and (iv) increase the threshold for deformation of crystal grains in which dislocations accumulate. However, in bainitic microstructure type non-heat-treated steel, controlling (i), (ii), and (iii) for yield ratio is difficult. This is because in bainitic microstructure type non-heat-treated steel, dislocation density generated by bainite transformation is higher than that of ferrite and pearlite microstructures when steel is cooled to room temperature after hot forging. Further,

bainite has a high amount of fine cementite that is a dislocation source. In the first place, dislocation strengthening obtained during transformation and strengthening by precipitation by fine cementite are the strengthening mechanisms of bainite. When the type, shape, and distribution of precipitates are determined, the threshold and the like for dislocation generation from such dislocation sources will also be determined. Increasing yield stress by controlling dislocation sources would contradict the very concept of developing a bainitic microstructure type non-heat-treated steel in the first place. Given this, it is necessary to allow dislocations to generate, propagate, and accumulate in the early stages of stress loading, and for crystal grains to be hard to deform even when dislocations accumulate. That is, (iv) is important to obtain high yield ratio in steel with mainly bainitic microstructure.

[0015] In terms of (iv), there are two ways to make crystal grains hard to deform even when dislocations accumulate.

[0016] The first is to refine crystal grain size. When crystal grain size is fine, distance from dislocation source to crystal grain boundary is short, which limits the amount of dislocations that accumulate, and stress due to dislocation accumulation is accordingly suppressed. That is, fine crystal grain size is basically better.

[0017] That is, in a bainitic microstructure non-heat-treated steel, average diameter of crystal grains is required to be 25 μm or less, surrounded by crystal grain boundaries that have an angular difference in crystal orientation of 15° or more between adjacent crystal grains. On the other hand, when crystal grains become too fine, crystal grain boundaries themselves will act as dislocation sources, and therefore a lower limit is necessary. The lower limit is 10 μm in average diameter. For crystal grain size, the reason for specifying crystal grains surrounded by crystal grain boundaries having an angular difference in crystal orientation of 15° or more between adjacent crystal grains is that dislocations tend to pass through crystal grain boundaries with angles less than this, that is, sufficient dislocations do not accumulate.

[0018] The second is to control a crystal grain shape. The closer crystal grains are to a true sphere, the less likely the crystal grains are to deform. That is, the closer the aspect ratio (minor axis length/major axis length) of crystal grains is to 1, the better. Further, the closer crystal grain boundary lengths are to that of true circles, the better. For bainitic microstructure non-heat-treated steel, the aspect ratio (minor axis length/major axis length) of crystal grains needs to be 0.5 or more, and an average ratio of crystal grain boundary length to crystal grain circumference needs to be 60 or less.

[0019] Crystal grain circumference means circumference of a cross-section through the center of a true sphere (that is, a true circle), assuming that the crystal grain is a true sphere. However, to determine such a circumference, the true volume of the crystal grain needs to be known. However, calculating such a volume from microstructure observation of a cross-section, as is currently done in observation of metallic microstructure, requires mathematical processing, and for microstructures such as that of non-heat-treated steel, where the presence of texture is expected, accurate calculation is extremely difficult. As a compromise, as crystal grain circumference, we used the circumference obtained from the area of an arbitrary cross-section of a crystal grain, under the assumption that the crystal grain under consideration is a true sphere. That is, the circumference of a true circle based on the area of a crystal grain, assuming that the area of the crystal grains is a perfect circle, as observed in metallic microstructure observation.

[0020] Finally, the amount of retained austenite present in bainitic microstructure is 5 % or less by area fraction. The crystal structure of retained austenite is a face-centered cubic lattice. In contrast, ferrite, the underlying microstructure of bainite, is a body-centered cubic lattice, which is more easily deformed than a face-centered cubic lattice. That is, retained austenite phase in ferrite is not only finer but also more difficult to deform than ferrite, and acts as a dislocation source. Accordingly, the smaller the amount of retained austenite, the better.

[0021] Based on the above findings regarding the effect of microstructure on yield stress, the inventors narrowed down the scope to examining various combinations of steel alloy component balance and cooling rate after hot forging that are able to obtain the bainitic microstructure described above, and arrived at the present disclosure.

[0022] Primary features of the present disclosure are as follows.

1. A steel component comprising: a chemical composition containing (consisting of), in mass%,

C: 0.21 % to 0.24 %,

Si: 0.11 % to 0.25 %,

Mn: 1.81 % to 1.99 %,

P: 0.014 % to 0.025 %,

S: 0.035 % to 0.060 %,

Cr: 0.55 % to 0.65 %,

Al: 0.010 % to 0.050 %,

Ti: 0.005 % to 0.020 %,

V: 0.15 % to 0.20 %, and

N: 0.0090 % to 0.0150 %,

in amounts such that a value of F1 obtained by Formula (1) is 0.65 % or more, with the balance as Fe and inevitable impurity; and a bainitic microstructure area fraction of 85 % or more and a retained austenite area fraction of 5 % or less, wherein

crystal grains of the bainitic microstructure have an average diameter of 10 μm or more and 25 μm or less, an average aspect ratio of 0.5 or more, and an average ratio of crystal grain boundary length to crystal grain circumference of 60 or less,

$$F1 = C + \text{Si}/24 + \text{Mn}/6 + \text{Ni}/40 + \text{Cr}/5 + \text{Mo}/4 + \text{V}/14 \quad \dots (1)$$

where each element symbol in Formula (1) is content in mass% of the element, and elements not included are considered as 0 for F1 calculation.

2. The steel component according to 1, above, wherein a ratio of a difference between the maximum value Hv_1 and the minimum value Hv_2 of Vickers hardness at 1 mm below the surface of the steel component to the maximum value Hv_1 , $((Hv_1 - Hv_2)/Hv_1) \times 100$, is 10 % or less.

3. The steel component according to 1 or 2, above, wherein the chemical composition further contains, in mass%, at least one selected from the group consisting of:

Cu: 0.25 % or less,
Ni: 0.25 % or less,
Mo: 0.15 % or less, and
Nb: 0.030 % or less.

4. A method of producing a steel component, comprising: applying hot forging after heating and holding at 1150 °C or more to a steel material comprising the chemical composition according to 1 or 3, above, to obtain a hot forging material, and then cooling the hot forging material from 1000 °C to 800 °C at an average cooling rate of 0.7 °C/s or more and 3.5 °C/s or less, and from 800 °C to 550 °C at an average cooling rate of 0.5 °C/s or more and 2.0 °C/s or less.

5. The method of producing a steel component according to 4, above, wherein the cooling from 800 °C to 550 °C is performed where a ratio of a difference between the maximum value V_1 and the minimum value V_2 of cooling rate distribution in the hot forging material to the maximum value V_1 , $((V_1 - V_2)/V_1) \times 100$, is 25 % or less.

(Advantageous Effect)

[0023] According to the steel component of the present disclosure, the ratio of yield stress to tensile strength (yield ratio) can be 0.60 or more without tempering because a bainitic microstructure satisfying desired conditions is obtainable in an area fraction of 85 % or more during cooling after hot forging.

DETAILED DESCRIPTION

[0024] A detailed description is provided below. First, the reasons for limiting the amount of each element in the chemical composition are explained. Note that the unit "%" of each chemical component indicates "mass%" unless otherwise specified.

C: 0.21 % to 0.24 %

C (carbon) is a beneficial element that forms a solute or carbide in steel, and improves steel strength. Bainitic microstructure is a microstructure of precipitated fine cementite, and therefore when a certain amount of C is not present in steel, there is not enough cementite to obtain sufficient strengthening by precipitation, resulting in low yield stress and unsatisfactory yield ratio. C addition of 0.21 % or more is therefore required. However, when added in excess, the amount of cementite, a dislocation source, becomes too high, and this too means that a satisfactory yield stress is not maintained. Accordingly, an upper limit to the amount added is 0.24 %.

Si: 0.11 % to 0.25 %

Si (silicon) is a beneficial element that is a solute in steel, increases steel strength, improves quench hardenability, and increases bainite area fraction. To obtain these effects, addition of 0.11 % or more is required. However, Si also has a detrimental effect, forming a thick coating during preheating for hot forging and degrading scale separability before hot forging. To avoid this, addition exceeding 0.25 % needs to be avoided. Content is preferably 0.13 % to 0.23 %.

Mn: 1.81 % to 1.99 %

Mn (manganese) is an important element that is a solute in steel and has a variety of beneficial effects such as increasing steel strength, increasing quench hardenability of steel, and combining with S to form sulfides to improve machinability by cutting of steel. To obtain these effects, addition of 1.81 % or more is required. However, when Mn is added in excess, the amount of retained austenite becomes too high and satisfactory yield stress is not maintained.

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Accordingly, an upper limit to the amount added is 1.99 %. Content is preferably 1.83 % to 1.97 %.

P: 0.014 % to 0.025 %

P (phosphorus) is a beneficial element that is a solute in steel and increases steel yield stress. To obtain this effect, addition of 0.014 % or more is required. However, P segregates at crystal grain boundaries of austenite after hot forging and has an aspect of deteriorating toughness at room temperature. To avoid this, P content is 0.025 % or less. Content is preferably 0.014 % to 0.022 %.

S: 0.035 % to 0.060 %

S (sulfur) is a beneficial element that combines with Mn to form sulfides in steel, and has an effect of increasing machinability by cutting of steel. To obtain this effect, addition of 0.035 % or more is required. However, excessive addition of S not only reduces the beneficial effects of Mn, such as increased strength and improved quench hardenability, by forming a large amount of MnS and reducing the amount of Mn forming a solute in Fe, but MnS also acts as a dislocation source, resulting in lower steel yield stress. To avoid this, an upper limit of S to be added is 0.060 %. Content is more preferably less than 0.050 %.

Cr: 0.55 % to 0.65 %

Cr (chromium) is an important element that is a solute in steel and has a variety of beneficial effects, such as increasing steel strength and increasing steel quench hardenability. To obtain these effects, addition of 0.55 % or more is required. However, when Cr is added in excess, the amount of retained austenite becomes too high and high yield stress is not maintained. Accordingly, an upper limit to the amount added is 0.65 %.

Al: 0.010 % to 0.050 %

Al (aluminum) is a beneficial element that combines with oxygen, which inevitably enters molten steel from the air during steel refining and casting, to render the oxygen harmless. When deoxidation by Al is not sufficient, excess oxygen in steel combines with Ti, and an effect of Ti described below is not fully realized. Addition of 0.010 % or more is required to render oxygen harmless. However, when more than 0.050 % is added, instead aluminum oxide itself becomes included in large amounts in steel, deteriorating steel toughness, and therefore addition exceeding 0.050 % is to be avoided. Content is preferably 0.020 % to 0.045 %.

Ti: 0.005 % to 0.020 %

Ti (titanium) is a beneficial element that forms very fine precipitates in steel and acts to prevent deterioration of toughness by inhibiting coarsening of austenite grains before and after hot forging. To obtain this effect, addition of 0.005 % or more is required. However, when more than 0.020 % is added, precipitates coarsen during heating before hot forging and no beneficial effect is obtained. Addition exceeding 0.020 % therefore needs to be avoided. Content is preferably 0.006 % to 0.017 %.

V: 0.15 % to 0.20 %

V (vanadium) is a beneficial element that is a solute in steel, and causes solid solution strengthening of steel as well as increasing steel quench hardenability. To obtain such effects, addition of 0.15 % or more is required. However, V also acts to deteriorate steel toughness by combining with C to form precipitates. To avoid this, an amount of V added is 0.20 % or less. Content is preferably 0.16 % to 0.19 %.

N: 0.0090 % to 0.0150 %

N (nitrogen) is a beneficial element that acts to prevent deterioration of toughness mainly by combining with Ti and V to inhibit austenite grain coarsening before and after hot forging. To obtain this effect, addition of 0.0090 % or more is required. However, when more than 0.0150 % is added, strain aging (an effect in which N segregates around dislocations and forms a Cottrell atmosphere that significantly hinders dislocation mobility) occurs at room temperature, and impact value at -50 °C, described below, is significantly reduced. To avoid this, an upper limit of N to be added is 0.0150 %. Content is preferably 0.0095 % to 0.0130 %.

F1: 0.65 % or more

$$F1 = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14$$

[0025] Here, each element symbol in Formula (1) is content in mass% of the element, and elements not included are considered as 0 for F1 calculation.

[0026] A minimum of composition regulation to obtain a bainitic microstructure is as described above, according to a range of addition for each type of chemical component. Further, in order to enhance the robustness of mechanical properties obtained when there may be a range of cooling rates in actual cooling after hot forging, additive alloying element balance needs to be specified according to Formula (1), indicated as F1. When the formula that defines this balance is F1, the value of F1 needs to be 0.65 % or more. That is, when the above value is less than 0.65 %, then even when a mainly bainite microstructure is obtained, obtaining steel with a yield ratio of 0.60 or more is difficult.

[0027] Including the above elements, the balance is Fe and inevitable impurity.

[0028] Here, elements considered as inevitable impurity include O (oxygen), B (boron), Mg (magnesium), Ca (calcium), and REM (rare earth metals). The content of any of these elements is less than 0.0015 %.

[0029] Further, one or more of Cu, Ni, Mo, or Nb may be added to the chemical composition described above as required.

Cu: 0.25 % or less

Cu (copper) is an element that is a solute in steel, causes solid solution strengthening of steel, and may be added to secure strength. When Cu is added, addition of 0.03 % or more is preferred. However, excessive addition of Cu increases retained austenite and lowers yield stress, resulting in failure to obtain the defined yield ratio. To avoid this, an upper limit of addition is 0.25 %. The upper limit of addition is more preferably 0.20 %.

Ni: 0.25 % or less

Ni (nickel) is an element that is a solute in steel, causes solid solution strengthening of steel, and may be added to secure strength. When Ni is added, addition of 0.03 % or more is preferred. However, excessive addition of Ni increases retained austenite and lowers yield stress, resulting in failure to obtain the defined yield ratio. To avoid this, an upper limit of addition is 0.25 %. The upper limit of addition is more preferably 0.20 %.

Mo: 0.15 % or less

Mo (molybdenum) is an element that is a solute in steel and has a variety of beneficial effects, such as increasing steel strength and increasing steel quench hardenability, and is preferably added at 0.10 % or more. However, when Mo is added in excess, the amount of retained austenite becomes too high and satisfactory yield stress is not maintained. Accordingly, when added, an upper limit is 0.15 %.

Nb: 0.030 % or less

Nb (niobium) is a beneficial element that forms very fine precipitates in steel and acts to prevent deterioration of toughness by inhibiting coarsening of austenite grains before and after hot forging, and is preferably added at 0.013 % or more. However, excessive addition of Nb causes frequent surface defects in hot rolling. Accordingly, when added, an upper limit is 0.030 %.

[0030] Specific microstructure requirements are described below.

[Bainitic microstructure area fraction: 85 % or more]

[0031] Bainitic microstructure has a good balance of strength and toughness, and is therefore appropriate for non-heat-treated steel. Specifically, when steel has a bainitic microstructure, impact value at -50 °C is 35 J/cm² or more, as determined by the Charpy impact test specified in Japanese Industrial Standard JIS Z2242. That is, an impact value of 35 J/cm² or more at -50 °C secures sufficient toughness at the operating temperatures expected in terrestrial environments where humans use automobiles or heavy-duty vehicles such as trucks and trailers. To obtain such a property, a bainitic microstructure with an area fraction of 85 % or more is required. The area fraction is more preferably 90 % or more.

[0032] Microstructure other than bainitic microstructure is not particularly limited, and may be pearlite, ferrite, or the like, but retained austenite needs to have an area fraction of 5 % or less.

[Retained austenite area fraction: 5 % or less]

[0033] Retained austenite acts as a dislocation source and lowers yield stress, and therefore the lower the area fraction, the better, with an upper limit of 5 %. An area fraction of 0 % is of course possible.

[Average diameter of crystal grains in bainitic microstructure: 10 μm or more and 25 μm or less]

[0034] Bainitic microstructure crystal grain size is a very important factor in making crystal grains hard to deform. A crystal grain here is a crystal grain surrounded by a crystal grain boundary having an angular difference in crystal orientation of 15° or more between the grain boundary and adjacent crystal grains. Further, average diameter here means a weighted average of diameters of all crystal grains in a field of view in a range including 20 or more crystal grains as described above in any given observation plane of a test piece. Further, diameter of a crystal grain is the diameter obtained from an area of the crystal grain when shape of the crystal grain observed in a microstructure observation cross-section is assumed to be a true circle.

[0035] That is, in order for a crystal grain to be hard to deform, the average diameter of the crystal grain needs to be 25 μm or less. Distance from dislocation source to crystal grain boundary is short, and therefore an amount of dislocations that can accumulate is limited and stress due to dislocation accumulation is correspondingly suppressed, resulting in suppression of crystal grain deformation. The average diameter is more preferably 23 μm or less. However, when too fine, crystal grain boundaries themselves act as dislocation sources, and therefore a lower limit is 10 μm. The average diameter is preferably 12 μm or more.

[Average aspect ratio of crystal grains: 0.5 or more]

[0036] In order for a crystal grain to be hard to deform, the closer the shape of the crystal grain to a true sphere, the better. Accordingly, the aspect ratio of crystal grains needs to be 0.5 or more. The aspect ratio is preferably 0.55 or more.

[0037] Here, the aspect ratio of a crystal grain is obtained as follows. First, the center of gravity of a crystal grain obtained by observation is determined. Two arbitrary straight lines are drawn on the crystal grain orthogonal to each other intersecting at the center of gravity. When the center of gravity is not located in the crystal grain, as in a C-shape crystal grain, a point on the crystal grain boundary closest to the obtained center of gravity is used as the center of gravity. In any line of two straight lines drawn in this way, a distance between the two points on the line that intersect the circumference of the crystal grain is an "intersection distance". When a difference between the intersection distance of one line and the intersection distance of another line is the maximum difference for the two arbitrary straight lines, the longer intersection distance is the longest major axis length and the shorter intersection distance is the shortest minor axis length. The aspect ratio of the crystal grain is the value obtained by dividing the shortest minor axis length by the longest major axis length. Further, the average of the aspect ratio is the calculated average of the aspect ratios of all crystal grains in the same field of view in a range including 20 or more crystal grains in any observation plane of the test piece.

[Average ratio of crystal grain boundary length to crystal grain circumference: 60 or less]

[0038] The ratio of crystal grain boundary length to crystal grain circumference, determined from the crystal grain diameter described above, needs to be 60 or less on average. Here, crystal grain boundary length is the length of a crystal grain boundary determined by converting the total number of pixels judged to be a crystal grain boundary in a crystal grain measured by electron backscatter diffraction (EBSD), as described below, into a length by the observation magnification factor. Hereinafter, the ratio of the crystal grain boundary length to the crystal grain circumference is also referred to as the crystal grain boundary length ratio. Averaging of the crystal grain boundary length ratio is also a weighted average of crystal grain boundary length ratios of all crystal grains in a field of view in a range including 20 or more crystal grains in any given observation plane of a test piece. The average ratio of crystal grain boundary length to crystal grain circumference (hereinafter also referred to as crystal grain boundary length average ratio) may also be determined by EBSD as mentioned above. When the crystal grain boundary length average ratio exceeds 60, the area of the crystal grain boundary which is a source of dislocation emission becomes too large, making obtaining a sufficient yield ratio difficult. The crystal grain boundary length average ratio is more preferably 55 or less.

[0039] Further, a ratio of a difference between the maximum value Hv_1 and the minimum value Hv_2 of Vickers hardness at 1 mm below the surface of the steel component to the maximum value Hv_1 , that is $((Hv_1 - Hv_2)/Hv_1) \times 100$, is preferably 10 % or less.

$$[((Hv_1 - Hv_2)/Hv_1) \times 100: 10 \% \text{ or less}]$$

[0040] A steel component that satisfies the above conditions has a desired mechanical property. The mechanical property thus obtained is preferably uniform in each steel component. Accordingly, the difference in hardness below the surface of the component $((Hv_1 - Hv_2)/Hv_1) \times 100$ (hereinafter also referred to as the sub-surface hardness difference) is preferably 10 % or less. That is, deformation of a component is restricted by surface hardness, a sub-surface hardness difference of 10 % or less results in a more uniform performance as a component.

[0041] The sub-surface hardness difference may be determined according to a measurement method described in the Examples below.

[0042] Next, the conditions for producing the steel component described above are explained.

[0043] That is, steel according to the chemical composition described above is melted and cast into steel material, for example, a steel ingot, which is then heated and held at a temperature of 1150 °C or more before hot forging into a desired component shape. Further, it is essential that the hot forging material after hot forging be cooled at an average cooling rate of 0.7 °C/s or more and 3.5 °C/s or less from 1000 °C to 800 °C and 0.5 °C/s or more and 2.0 °C/s or less from 800 °C to 550 °C.

[Steel material heating temperature: 1150 °C or more]

[0044] First, the steel material is heated to 1150 °C or more. In order to secure forgeability during hot forging, precipitates that deteriorate forgeability, carbides and nitrides, need to be heated to 1150 °C or more to be dissolved. Although there is no particular need to restrict an upper limit, 1300 °C or less is preferable from the viewpoint of yield rate deterioration due to surface oxide coating.

[0045] The steel material is heated and held at a temperature of 1150 °C or more and then hot forged into a desired

component shape, but the conditions of hot forging are not particularly limited, and a typical practice of hot forging to form and work each component may be followed. After the hot forging, the following two-stage cooling needs to be performed. Incidentally, two-stage cooling is particularly advantageously adapted to box stacking after hot forging, as practiced in plants of other countries as mentioned above. That is, the cooling rate from the end of hot forging to 800 °C, which is the first stage of cooling, is consistent with specifications for a stage before the forged products are placed in a box. The cooling rate below 800 °C, which is the second stage of cooling, is then consistent with regulations for a stage from the time the forged products are placed in the box until the start of transformation. The cooling method may be air cooling, but the cooling method needs to be designed so that the entire component is within the specified cooling rate.

[Average cooling rate from 1000 °C to 800 °C: 0.7 °C/s or more and 3.5 °C/s or less]

[0046] In the process of imparting desired strength to a non-heat-treated steel component, the cooling rate during the cooling process of the component after hot forging is very important. Here, the geometry of hot forging components is not uniform but varies, and therefore some portions during cooling have a slower cooling rate while others have a faster cooling rate. In order to obtain somewhat uniform properties throughout a component during the cooling process when cooling rates vary within a component, the non-heat-treated steel used as the material needs to be robust with respect to cooling rate. From this perspective, when the average cooling rate from 1000 °C to 800 °C is less than 0.7 °C/s for a steel having the chemical composition ranges specified in the present disclosure, prior austenite grains before bainite transformation become coarse, resulting in an average grain size of bainite exceeding 25 μm. The average cooling rate from 1000 °C to 800 °C is therefore 0.7 °C/s or more. The average cooling rate is preferably 0.9 °C/s or more. The average cooling rate is more preferably 1.0 °C/s or more.

[0047] However, when the average cooling rate in the temperature interval described above exceeds 3.5 °C/s, prior austenite grains before bainite transformation become too fine, resulting in an average grain size of bainite of less than 10 μm. The cooling rate from 1000 °C to 800 °C is therefore 3.5 °C/s or less. The cooling rate is preferably 3.2 °C/s or less. The cooling rate is more preferably 3.0 °C/s or less.

[Average cooling rate from 800 °C to 550 °C: 0.5 °C/s or more and 2.0 °C/s or less]

[0048] As described above, from the viewpoint of imparting robustness with respect to cooling rate for non-heat-treated steel, the average cooling rate from 1000 °C to 800 °C is controlled to the range of 0.7 °C/s or more and 3.5 °C/s or less. However, even when this condition is satisfied, average cooling rate in the subsequent temperature range from 800 °C to 550 °C also needs to be specified. That is, when the average cooling rate from 800 °C to 550 °C is less than 0.5 °C/s, the crystal grain boundary length average ratio described above exceeds 60. The average cooling rate from 800 °C to 550 °C is therefore 0.5 °C/s or more. The average cooling rate is preferably 0.7 °C/s or more. The average cooling rate is more preferably 0.8 °C/s or more.

[0049] On the other hand, even when the average cooling rate from 1000 °C to 800 °C is within the above specified range, when the average cooling rate from 800 °C to 550 °C exceeds 2.0 °C/s, the average aspect ratio of crystal grains as described above becomes less than 0.5. The average cooling rate from 800 °C to 550 °C is therefore 2.0 °C/s or less. The average cooling rate is preferably 1.7 °C/s or less. The average cooling rate is more preferably 1.5 °C/s or less.

[0050] Further, the cooling from 800 °C to 550 °C is preferably performed where a ratio of a difference between the maximum value V_1 and the minimum value V_2 of cooling rate distribution in the hot forging material to the maximum value V_1 , that is $((V_1 - V_2)/V_1) \times 100$, is 25 % or less for the hot forging material provided with a component shape by hot forging.

$$[((V_1 - V_2)/V_1) \times 100 \text{ is } 25 \% \text{ or less}]$$

[0051] As mentioned above, mechanical properties are preferably uniform in each steel component, and for component performance in particular, uniform microstructure and hardness is preferred. Accordingly, keeping the cooling rate in a certain range even when component geometry is complex is beneficial. For this purpose, the cooling rate difference in hot forging material $(V_1 - V_2)/V_1$ (hereinafter also referred to as cooling rate difference) is preferably 25 % or less. When the cooling rate difference is 25 % or less, differences in microstructure and hardness are small and mechanical performance of the component is more uniform.

[0052] The cooling rate difference may be determined according to a measurement method described in the Examples below.

[Examples 1]

[0053] The following examples are illustrative of the present disclosure. However, each example in the following

examples is only illustrative, and the present disclosure is not limited to the following examples.

[0054] Steel having the compositions listed in Table 1 was melted in a vacuum melting furnace and 50 kg steel ingots (steel material) were cast. Resulting steel ingots were hot-worked at a temperature of 1150 °C or more into cylinders having a diameter of 37 mm. The resulting cylinders, 37 mm in diameter, were then hot swaged (hot forged) immediately after being held at 1250 °C for 1 h to make 25 mm diameter round bars. Three round bars were prepared for each Steel No., produced under the same production conditions.

[0055] The starting temperature for the hot swaging process was 1100 °C or more. When the starting temperature of the hot swaging process was controlled in this way, the end temperature of the swaging process was roughly 1000 °C or more. After the swaging process was completed, the 25 mm diameter round bars were cooled to obtain steel components from 1000 °C to 800 °C at an average cooling rate range of 0.7 °C/s or more and 3.5 °C/s or less and from 800 °C to 550 °C at an average cooling rate of 0.5 °C/s or more to 2.0 °C/s or less. Table 2 lists each production condition.

[0056] During the cooling process after the swaging process, a thermo viewer was used to measure the change in temperature over time at five locations at a pitch of 50 mm from the tip of the round bar in the axial direction, and the average cooling rate at each measurement location was determined. The cooling rates from 1000 °C to 800 °C and from 800 °C to 550 °C listed in Table 2 are the average values of the average cooling rates calculated at the five locations. Further, the cooling rate difference $((V_1 - V_2)/V_1) \times 100$ in the temperature range from 800 °C to 550 °C in the cooling process was obtained from the maximum value V_1 and the minimum value V_2 of the average cooling rates from 800 °C to 550 °C at the five locations.

[Table 1]

[Table 1]

Steel No.	(mass%)													Remarks
	C	Si	Mn	P	S	Cr	Al	Ti	V	N	Cu	Ni	Mo	
1	0.21	0.12	1.83	0.014	0.039	0.62	0.017	0.011	0.18	0.0096	0.06			F1 0.66
2	0.23	0.15	1.90	0.018	0.051	0.57	0.029	0.019	0.16	0.0104	0.05	0.05		0.68
3	0.24	0.24	1.95	0.020	0.044	0.64	0.024	0.012	0.15	0.0109				0.71
4	0.21	0.11	1.85	0.024	0.056	0.57	0.018	0.008	0.20	0.0113		0.09		0.65
5	0.21	0.17	1.84	0.022	0.038	0.59	0.033	0.005	0.16	0.0097	0.22	0.25		0.66
6	0.22	0.25	1.91	0.014	0.055	0.58	0.034	0.013	0.16	0.0138				0.68
7	0.21	0.18	1.82	0.017	0.052	0.60	0.028	0.015	0.20	0.0105	0.18	0.10		0.66
8	0.23	0.13	1.98	0.015	0.040	0.63	0.046	0.020	0.19	0.0103			0.12	0.73
9	0.21	0.16	1.92	0.020	0.057	0.61	0.010	0.016	0.17	0.0114	0.20			0.67
10	0.22	0.17	1.89	0.024	0.053	0.65	0.045	0.013	0.20	0.0090				0.69
11	0.24	0.23	1.94	0.016	0.037	0.55	0.023	0.005	0.16	0.0140	0.08	0.05		0.70
12	0.24	0.21	1.83	0.025	0.055	0.62	0.016	0.018	0.18	0.0110				0.69
13	0.23	0.25	1.93	0.023	0.059	0.61	0.044	0.017	0.15	0.0095		0.19		0.70
14	0.23	0.13	1.84	0.021	0.043	0.59	0.043	0.018	0.19	0.0115	0.24	0.10		0.68
15	0.21	0.16	1.94	0.017	0.045	0.65	0.019	0.008	0.17	0.0106	0.20	0.10		0.68
16	0.22	0.22	1.87	0.016	0.041	0.63	0.047	0.005	0.15	0.0145	0.22	0.23		0.68
17	0.21	0.18	1.95	0.018	0.058	0.60	0.031	0.014	0.19	0.0098	0.20	0.18		0.68
18	0.24	0.13	1.92	0.019	0.045	0.56	0.011	0.007	0.18	0.0116				0.69
19	0.22	0.24	1.96	0.019	0.046	0.64	0.042	0.011	0.16	0.0102	0.14			0.70
20	0.21	0.11	1.81	0.021	0.035	0.55	0.049	0.019	0.20	0.0149	0.24	0.12	0.14	0.68
21	0.24	0.14	1.97	0.015	0.048	0.60	0.025	0.010	0.18	0.0091			0.10	0.73
22	0.22	0.15	1.81	0.020	0.042	0.64	0.012	0.006	0.17	0.0150		0.07		0.67
23	0.24	0.20	1.89	0.018	0.042	0.61	0.021	0.015	0.19	0.0107				0.70
24	0.22	0.19	1.99	0.023	0.047	0.56	0.048	0.020	0.20	0.0112	0.13	0.07		0.69
25	0.23	0.14	1.85	0.021	0.054	0.56	0.027	0.006	0.15	0.0093	0.09		0.08	0.69
26	0.22	0.22	1.88	0.024	0.046	0.58	0.014	0.017	0.18	0.0111	0.21			0.67
27	0.23	0.14	1.86	0.022	0.059	0.57	0.032	0.009	0.15	0.0108		0.09		0.67
28	0.23	0.11	1.96	0.016	0.049	0.62	0.020	0.007	0.19	0.0099				0.70
29	0.22	0.22	1.91	0.015	0.049	0.61	0.033	0.012	0.17	0.0112	0.13	0.04		0.68
30	0.24	0.12	1.87	0.023	0.041	0.65	0.050	0.010	0.17	0.0094				0.70
31	0.24	0.12	1.93	0.019	0.043	0.58	0.026	0.016	0.19	0.0101	0.25	0.11		0.70
32	0.22	0.21	1.82	0.020	0.060	0.63	0.015	0.006	0.16	0.0092		0.22		0.68
33	0.21	0.23	1.91	0.025	0.047	0.55	0.022	0.009	0.18	0.0122	0.17		0.05	0.67
34	0.21	0.19	1.97	0.014	0.055	0.59	0.013	0.014	0.20	0.0147	0.20	0.20		0.68

Conforming Examples

[Table 1 (cont'd)]

Steel No.	C	Si	Mn	P	S	Cr	Al	Ti	V	N	Cu	Ni	Mo	Nb	F1	Remarks
35	0.10	0.20	1.90	0.013	0.053	0.90	0.033	0.006	0.18	0.0101					0.62	Comparative Examples
36	0.10	0.20	2.10	0.012	0.055	1.00	0.024	0.009	0.10	0.0092			0.20		0.72	
37	0.23	0.22	1.85	0.013	0.055	0.60	0.023	0.008	0.17	0.0110	0.22	0.13			0.68	
38	0.38	0.75	2.09	0.013	0.011	0.28	0.029	0.010	0.01	0.0120			0.08	0.013	0.84	
39	0.22	0.14	1.88	0.013	0.054	0.64	0.033	0.012	0.18	0.0115	0.14	0.07			0.68	
40	0.25	0.07	2.00	0.015	0.038	0.50	0.029	0.014	0.30	0.0102			0.04		0.72	
41	0.21	0.24	2.00	0.016	0.040	0.55	0.032	0.011	0.19	0.0133	0.20	0.10			0.68	
42	0.14	0.20	1.55	0.011	0.060	0.06	0.025	0.025	0.30	0.0050					0.44	
43	0.24	0.15	1.80	0.022	0.051	0.59	0.029	0.010	0.16	0.0109	0.21	0.14			0.68	
44	0.34	0.10	1.81	0.022	0.045	0.41	0.029	0.009	0.20	0.0234		0.10	0.02		0.75	
45	0.31	0.10	1.81	0.020	0.039	0.42	0.025	0.008	0.20	0.0054		0.25	0.02		0.73	
46	0.24	0.10	1.96	0.015	0.052	0.60	0.032	0.011	0.15	0.0099	0.17	0.11			0.70	
47	0.27	1.02	1.52	0.045	0.021	0.11	0.027	0.010	0.15	0.0091					0.60	
48	0.25	0.19	1.82	0.026	0.042	0.56	0.030	0.011	0.19	0.0095	0.18	0.09			0.69	
49	0.15	0.10	2.50	0.010	0.009	0.20	0.035	0.070	0.05	0.0072			0.20		0.66	
50	0.20	0.14	1.91	0.018	0.039	0.56	0.025	0.011	0.17	0.0141	0.16	0.09			0.65	
51	0.25	0.21	1.90	0.022	0.005	0.60	0.034	0.009	0.09	0.0097			0.03		0.71	
52	0.25	0.22	1.93	0.022	0.050	0.61	0.029	0.009	0.16	0.0111	0.15	0.08			0.72	
53	0.21	0.10	1.89	0.024	0.100	0.82	0.017	0.012		0.0040					0.69	
54	0.21	0.12	1.81	0.020	0.044	0.51	0.022	0.014	0.15	0.0141	0.12	0.05			0.63	
55	0.23	0.14	1.82	0.016	0.039	0.56	0.019	0.019	0.16	0.0099	0.29	0.15			0.67	
56	0.24	0.13	1.98	0.021	0.043	0.60	0.018	0.009	0.15	0.0102	0.19	0.28			0.71	
57	0.21	0.22	1.89	0.020	0.049	0.59	0.008	0.014	0.16	0.0103	0.18	0.06			0.67	
58	0.23	0.19	1.85	0.018	0.053	0.62	0.053	0.018	0.16	0.0091	0.18	0.09			0.68	
59	0.23	0.23	1.99	0.025	0.057	0.61	0.029	0.011	0.19	0.0192	0.18	0.10			0.71	

[0057] Further, the sub-surface hardness and microstructure of the round bars (steel components) that had undergone cooling rate measurements were investigated.

[0058] The sub-surface hardness was measured with a Vickers hardness tester at two arbitrary circumferential locations 1 mm radially from the surface in radial cross-sections (also referred to as C-sections) of each of the five cooling rate measurement locations, at 10 locations throughout the round bar. The maximum value Hv_1 and minimum value Hv_2 of the measurement results were used to calculate $((Hv_1 - Hv_2)/Hv_1) \times 100$ as the sub-surface hardness difference. The obtained sub-surface hardness differences are listed in Table 2 as the maximum values at the five cooling rate measurement locations.

[0059] Further, microstructure was investigated using the radial cross-sections of the five cooling rate measurement locations as observation planes.

[0060] That is, the bainite area fraction was determined by a point-counting method from optical micrographs of observation planes that were appropriately etched with a nital solution. The point-counting method is an area fraction measurement method that determines the percentage of points of the microstructure for which the area fraction is to be determined out of the total number of points appropriately located on an optical micrograph. Although there are no particular preferred conditions for size or arrangement of the points, the points are typically arranged at intersections of lines disposed equally and orthogonally on the micrograph, that is, a grid of points. There is no rule for line thickness, but grid points are typically configured with lines that are 0.5 pt to 0.75 pt thick on a slide in Microsoft's PowerPoint application, for example. The grid points thus configured are overlaid on the micrograph, and the total number of grid points on the microstructure for which the area fraction determined as above is to be measured, as a percentage of the total number of grid points, may be regarded as the area fraction or volume fraction. When a grid point overlapped with a microstructure border, it was counted as 0.5 points. The bainite area fraction of the steel component was then determined by subtracting the retained austenite area fraction determined by EBSD, described below, from the bainite area fraction thus determined. The obtained bainite area fractions are listed in Table 2 as average values from five cooling rate measurement locations.

[0061] Further, the retained austenite area fraction, average grain size of the bainitic microstructure, average aspect ratio of the crystal grains, and crystal grain boundary length average ratios were measured using electron backscatter diffraction (EBSD). Each of the above items was measured by EBSD in five randomly selected fields of view, the average of each was obtained at five cooling rate measurement locations, and this average value of the five cooling rate measurement locations was used as the value of the steel component. The definition of a crystal grain in this microstructure investigation by EBSD was, as mentioned above, a crystal grain surrounded by a crystal grain boundary where the angular difference in crystal orientation of adjacent crystal grain is 15° or more.

[0062] Further, from a round bar (steel component) that was not the round bar (steel component) whose sub-surface hardness was measured, five locations corresponding to the five cooling rate measurement locations described above were defined (hereinafter also referred to as "locations corresponding to measurement"). Among the five locations corresponding to measurement, taking the third location corresponding to measurement as a boundary, two No. 4 tensile test pieces as specified in JIS Z2241 were collected from D/2 positions (D: round bar diameter) at one end and the other end of the round bar. Accordingly, one test piece included the first and second of the locations corresponding to measurement, and the other test piece included the fourth and fifth of the locations corresponding to measurement.

[0063] Further, from a round bar (steel component) that was not the round bar whose sub-surface hardness was measured or the round bar from which the tensile test pieces were collected, five U-notch test pieces for the Charpy impact test specified in JIS Z2242 were collected from D/4 positions, one from each of the five locations corresponding to measurement. The notch depth of the Charpy impact test piece was 5 mm.

[0064] From the test pieces thus obtained, mechanical properties were investigated as follows.

[0065] First, tensile tests were conducted at a tensile speed of 0.167 mm/s, in accordance with JIS Z2241. Through the tensile tests, yield stress (strength obtained by offsetting the straight line obtained from the slope of elastic deformation by 0.2 % from the elastic limit, also referred to as 0.2 % proof stress) and ultimate strength (ultimate strength in the nominal stress-nominal strain curve obtained by the tensile test, also referred to as tensile strength) were determined. The yield stress and tensile strength obtained were averaged over the two test pieces. When yield ratio, which is the ratio of yield stress to tensile strength, was 0.60 or more, it may be said that variation in mechanical properties of the steel component had been suppressed.

[0066] In the Charpy impact test, the impact value at -50 °C was determined in accordance with JIS Z2242. The impact values obtained were the minimum values for the five test pieces. When the impact value was 35 J/cm² or more, it may be said that the steel component had excellent toughness.

[0067] The measurement results are listed in Table 2.

[Table 2]

[Table 2]

Steel component No.	Steel No.	Cooling rate 1000 °C to 800 °C (°C/s)	Cooling rate 800 °C to 550 °C (°C/s)	Cooling rate difference at 800 °C to 550 °C (°C/s)	Bainite fraction (%)	Retained austenite fraction (%)	Average grain size (μm)	Average aspect ratio of crystal grains	Average ratio of actual crystal grain boundary length to crystal grain circumference	Sub-surface hardness difference (%)	Yield stress (MPa)	Tensile strength (MPa)	Yield ratio	Impact value -50 °C (J/cm ²)	Remarks
1	1	1.0	1.9	8	92	3	18	0.56	43	3	590	952	0.62	61	Examples
2	2	2.2	1.5	10	91	2	13	0.59	41	5	577	962	0.60	45	
3	3	2.9	0.7	11	96	3	19	0.56	57	9	609	967	0.63	54	
4	4	0.7	0.8	12	90	4	14	0.60	41	9	624	945	0.66	59	
5	5	1.4	1.0	4	86	2	17	0.57	60	7	632	972	0.65	47	
6	6	0.9	1.4	7	86	5	20	0.55	46	9	636	963	0.66	46	
7	7	1.5	1.5	26	93	4	12	0.61	46	12	577	946	0.61	53	
8	8	1.7	0.8	4	87	2	15	0.55	27	12	619	953	0.65	51	
9	9	3.5	1.1	3	92	1	17	0.60	41	4	620	968	0.64	59	
10	10	0.8	1.3	10	85	1	16	0.55	38	5	652	973	0.67	52	
11	11	3.0	0.7	11	88	5	21	0.57	43	4	606	947	0.64	53	
12	12	1.3	1.4	8	89	1	17	0.59	43	6	598	964	0.62	62	
13	13	2.8	0.9	3	97	3	18	0.58	41	7	601	954	0.63	58	
14	14	0.7	1.2	6	89	2	23	0.58	38	6	623	974	0.64	54	
15	15	1.6	0.7	5	87	1	16	0.60	38	7	626	948	0.66	51	
16	16	2.1	0.8	3	88	2	22	0.56	54	9	586	960	0.61	48	
17	17	3.2	1.6	6	93	2	19	0.57	49	8	610	969	0.63	53	
18	18	2.6	0.6	4	90	5	18	0.58	43	8	663	975	0.68	56	
19	19	1.0	1.1	6	94	3	16	0.56	29	8	598	949	0.63	59	
20	20	1.8	2.0	8	90	4	15	0.59	36	9	641	956	0.67	50	
21	21	3.5	0.9	9	91	3	23	0.55	27	6	579	965	0.60	51	
22	22	1.9	1.5	27	87	4	19	0.57	36	13	601	970	0.62	54	
23	23	3.1	1.3	3	95	3	13	0.56	38	4	608	950	0.64	56	
24	24	0.9	1.8	9	92	4	14	0.58	34	6	595	976	0.61	65	
25	25	3.4	0.8	10	88	5	22	0.60	41	3	641	957	0.67	54	
26	26	1.2	1.0	8	93	2	20	0.57	32	7	589	966	0.61	50	
27	27	3.0	1.5	7	86	2	14	0.58	34	8	618	951	0.65	49	
28	28	2.5	0.7	7	95	5	12	0.60	46	5	652	959	0.68	46	
29	29	1.5	1.3	11	94	4	21	0.59	32	7	609	967	0.63	45	
30	30	2.7	0.8	10	91	2	21	0.57	36	8	583	971	0.60	43	
31	31	1.1	1.7	9	85	1	20	0.58	51	5	655	977	0.67	44	
32	32	3.2	1.1	10	94	1	22	0.55	29	6	596	961	0.62	61	
33	33	2.8	0.5	4	96	3	13	0.59	38	7	623	958	0.65	57	
34	34	3.3	1.2	7	89	2	15	0.61	43	5	628	952	0.66	59	

[Table 2 (cont'd)]

Steel component No.	Steel No.	Cooling rate 1000 °C to 800 °C (°C/s)	Cooling rate 800 °C to 550 °C (°C/s)	Cooling rate difference at 800 °C to 550 °C (%)	Bainite area fraction (%)	Retained austenite area fraction (%)	Average grain size (μm)	Average aspect ratio of crystal grains	Average ratio of actual crystal grain boundary length to crystal grain circumference	Sub-surface hardness difference (%)	Yield stress (MPa)	Tensile strength (MPa)	Yield ratio	Impact value -50 °C (J/cm ²)	Remarks
35	35	2.2	1.0	9	92	3	13	0.59	43	6	497	887	0.56	51	Comparative Examples
36	36	1.4	0.7	5	86	1	14	0.60	41	7	469	901	0.52	55	
37	37	3.5	0.7	11	85	2	15	0.54	49	8	562	953	0.59	56	
38	38	1.6	1.5	6	89	3	21	0.55	41	9	575	974	0.59	48	
39	39	1.8	1.0	11	94	4	23	0.58	36	7	566	975	0.58	51	
40	40	3.0	1.7	8	92	7	10	0.56	36	6	523	950	0.55	55	
41	41	2.7	1.9	5	86	6	18	0.55	32	5	551	966	0.57	61	
42	42	0.7	1.5	7	91	3	11	0.60	36	5	427	890	0.48	59	
43	43	1.7	0.8	7	82	4	20	0.53	51	7	655	961	0.68	29	
44	44	2.8	1.4	6	82	2	21	0.57	41	9	486	972	0.50	19	
45	45	3.2	1.6	10	81	1	11	0.61	25	6	520	946	0.55	21	
46	46	1.9	2.0	3	83	2	15	0.57	46	5	632	964	0.66	23	
47	47	3.4	0.7	6	93	4	18	0.59	43	4	543	969	0.56	43	
48	48	3.0	0.5	4	88	1	24	0.52	29	7	488	976	0.50	39	
49	49	1.1	0.8	10	94	2	18	0.58	54	5	495	951	0.52	46	
50	50	3.3	1.3	7	94	2	10	0.61	46	6	567	977	0.58	47	
51	51	1.0	0.8	6	86	5	19	0.57	43	4	533	952	0.56	51	
52	52	0.9	1.5	10	90	4	24	0.56	27	2	575	974	0.59	50	
53	53	0.8	1.1	8	90	8	21	0.55	34	6	532	967	0.55	46	
54	54	1.6	0.7	12	90	4	13	0.51	38	7	655	962	0.68	30	
55	55	1.0	1.4	8	86	10	21	0.56	57	5	506	973	0.52	59	
56	56	3.1	1.4	9	86	9	18	0.55	25	6	541	949	0.57	57	
57	57	1.5	2.0	3	92	2	22	0.58	29	5	598	966	0.62	23	
58	58	2.3	0.7	6	89	2	15	0.59	36	6	623	966	0.65	22	
59	59	1.4	1.9	7	91	1	25	0.50	60	4	598	952	0.63	14	

[0068] In Table 1 and Table 2, Steel No. 1 to Steel No. 34 are examples that satisfy the chemical composition of the present disclosure. Steel Nos. 1 to 34 were steel material that was cooled after hot forging within the cooling rate range according to the present disclosure, and the resulting Steel component Nos. 1 to 34 had the microstructure and excellent mechanical properties specified in the present disclosure.

[0069] In the comparative example of Steel component No. 35, Cr was high enough, but C and P deviated from the specifications of the present disclosure, and therefore sufficient yield stress was not obtained, resulting in the steel component having a low yield ratio.

[0070] In the comparative example of Steel component No. 36, C and P, as well as Mn and Cr, deviated from the specifications of the present disclosure, and therefore sufficient yield stress was not obtained, resulting in the steel component having a low yield ratio.

[0071] In the comparative example of Steel component No. 37, P deviated from the specifications of the present disclosure, and therefore sufficient yield stress was not obtained, resulting in the steel component having a low yield ratio.

[0072] In the comparative example of Steel component No. 38, C, Si, Mn, and P were low and deviated from the specifications of the present disclosure, and therefore sufficient yield stress was not obtained, resulting in the steel component having a low yield ratio.

[0073] In the comparative example of Steel component No. 39, the specifications of the present disclosure were satisfied except for P, but the amount of P added was less than specified, resulting in the steel component having a low yield ratio.

[0074] In the comparative example of Steel component No. 40, C, Mn, and V were added in excess of the amounts specified, and therefore the retained austenite area fraction was in excess of that specified, resulting in the steel component having a low yield ratio.

[0075] In the comparative example of Steel component No. 41, Mn was added in excess of the amount specified, and therefore the retained austenite area fraction was in excess of that specified, resulting in the steel component having a low yield ratio.

[0076] In the comparative example of Steel component No. 42, C, Mn, P, and Cr were below the specifications of the present disclosure, and therefore sufficient yield stress was not obtained, resulting in the steel component having a low yield ratio.

[0077] In the comparative example of Steel component No. 43, Mn was below the specification of the present disclosure, and therefore although the F1 value itself satisfied the specification by addition of other elements, sufficient bainite area fraction was not obtained, resulting in the impact value at -50 °C being below 35 J/cm².

[0078] In the comparative examples of Steel component Nos. 44 and 45, C was higher than specified and Si was lower than specified, and therefore sufficient yield stress was not obtained and sufficient bainite area fraction was also not obtained, resulting in the impact value at -50 °C being below 35 J/cm².

[0079] In the comparative example of Steel component No. 46, Si was below the specification of the present disclosure, and therefore although the F1 value itself satisfied the specification by addition of other alloying elements, sufficient bainite area fraction was not obtained, resulting in the impact value at -50 °C being below 35 J/cm².

[0080] In the comparative example of Steel component No. 47, C and Si exceeded the specifications of the present disclosure, and therefore the amount of cementite was too high and sufficient yield stress was not obtained, resulting in the steel component having a low yield ratio.

[0081] In the comparative example of Steel component No. 48, C exceeded the specification of the present disclosure, and therefore the amount of cementite was too high and sufficient yield stress was not obtained, resulting in the steel component having a low yield ratio.

[0082] In the comparative examples of Steel component Nos. 49 and 50, C was below the specification of the present disclosure, and therefore sufficient strengthening by precipitation was not obtained and yield stress was not increased, resulting in the steel component having a low yield ratio.

[0083] In the comparative examples of Steel component Nos. 51 and 52, C exceeded the specification of the present disclosure, and therefore the amount of cementite was too high and sufficient yield stress was not obtained, resulting in the steel components having a low yield ratio.

[0084] In the comparative example of Steel component No. 53, S and Cr exceeded the specification of the present disclosure, and therefore the excess S caused the amount of dislocation source MnS to become excessive, and the excess Cr caused the amount of retained austenite to exceed the specification of the present disclosure, resulting in the steel component having a low yield ratio.

[0085] In the comparative example of Steel component No. 54, the value of F1 was below 0.65, and therefore a sufficient amount of bainite was not obtained, resulting in an impact value at -50 °C less than 35 J/cm².

[0086] In the comparative example of Steel component No. 55, the added amount of Cu exceeded the specification of the present disclosure, and therefore the amount of retained austenite exceeded the specification of the present disclosure, resulting in the steel component having insufficient yield stress and a low yield ratio.

[0087] In the comparative example of Steel component No. 56, the added amount of Ni exceeded the specification of the

present disclosure, and therefore the amount of retained austenite exceeded the specification of the present disclosure, resulting in the steel component having insufficient yield stress and a low yield ratio.

[0088] In the comparative example of Steel component No. 57, the added amount of Al was below the lower limit specified in the present disclosure, resulting in the effect of microstructure refinement by Ti being insufficient, and the impact value at -50 °C was below 35 J/cm².

[0089] In the comparative example of Steel component No. 58, the added amount of Al was above the upper limit specified in the present disclosure, resulting in an excess of aluminum oxides excessively dispersed in the steel, and therefore the impact value at -50 °C was below 35 J/cm².

[0090] In the comparative example of Steel component No. 59, the added amount of N was above the upper limit specified in the present disclosure, resulting in the impact value at -50 °C being below 35 J/cm².

[Examples 2]

[0091] Next, steel having the chemical composition of Steel No. 11 indicated in Table 1 was melted in a vacuum melting furnace, 50 kg steel ingots (steel material) were cast, 25 mm diameter round bars were obtained by swaging processing under the same conditions as in Examples 1, and steel components were obtained by cooling under the various cooling rate conditions listed in Table 3. Some round bars (Steel component Nos. A13, A14, A15, and A16) were 30 mm in diameter for a 150 mm long end portion. That is, a cooling rate difference was intentionally added to simulate the case where the component has a complex shape and to investigate the effect of the cooling rate difference on properties.

[0092] The results of the investigation of the microstructure, sub-surface hardness, and mechanical properties of the steel components thus obtained, as in Examples 1, are listed in Table 3. Here, the cooling rate difference was determined as in Examples 1.

[Table 3]

[0093]

[Table 3]

Steel component No.	Steel No.	Cooling rate 1000 °C to 800 °C (°C/s)	Cooling rate 800 °C to 550 °C (°C/s)	Cooling rate difference at 800 °C to 550 °C (%)	Bainite area fraction (%)	Retained austenite area fraction (%)	Average grain size (μm)	Average aspect ratio of crystal grains	Average ratio of actual crystal grain boundary length to crystal grain circumference	Hardness difference (%)	Yield stress (MPa)	Tensile strength (MPa)	Yield ratio	Impact value -50 °C (J/cm ²)	Remarks
A1	11	0.6	1.2	9	92	4	28	0.57	41	3	555	962	0.58	51	Comparative Example
A2	11	0.9	1.4	8	96	4	24	0.60	27	5	636	946	0.67	48	Example
A3	11	1.0	1.4	12	86	1	21	0.55	34	4	601	954	0.63	59	Example
A4	11	3.6	0.9	10	88	2	7	0.60	29	5	565	975	0.58	51	Comparative Example
A5	11	3.2	1.0	13	87	4	11	0.58	55	6	608	950	0.64	47	Example
A6	11	3.0	0.8	7	88	5	13	0.56	41	7	589	959	0.61	46	Example
A7	11	1.1	0.4	5	91	2	23	0.55	77	8	577	977	0.59	53	Comparative Example
A8	11	1.7	0.7	9	92	3	19	0.60	43	6	628	901	0.70	51	Example
A9	11	2.2	0.8	12	86	2	13	0.55	36	5	575	890	0.65	59	Example
A10	11	2.7	2.1	16	96	3	12	0.41	34	6	544	946	0.58	46	Comparative Example
A11	11	1.3	1.7	14	85	2	22	0.55	49	4	620	976	0.64	53	Example
A12	11	2.4	1.5	12	92	4	13	0.60	57	5	623	949	0.66	51	Example
A13	11	2.1	1.8	27	93	3	19	0.58	51	14	561	967	0.64	39	Example
A14	11	2.4	1.9	28	95	4	20	0.59	53	16	552	958	0.65	41	Example
A15	11	1.6	1.0	22	90	2	22	0.61	55	8	543	954	0.67	51	Example
A16	11	1.4	0.9	19	88	3	21	0.54	52	9	532	941	0.69	49	Example

[0094] Steel component Nos. A2, A3, A5, A6, A8, A9, A11, and A12 listed in Table 3 are examples that satisfy the conditions of the present disclosure for chemical composition and cooling rate condition after hot forging.

[0095] In contrast, Steel component No. A1 is a comparative example where the cooling rate from 1000 °C to 800 °C was less than the specification of the present disclosure, where the average bainite crystal grain size exceeded the upper limit of 25 μm specified in the present disclosure, and the yield ratio of 0.60 or more was not obtained.

[0096] Further, Steel component No. A4 is a comparative example where the cooling rate from 1000 °C to 800 °C was above the specification of the present disclosure, resulting in the average bainite crystal grain size falling below the lower limit of 10 μm specified in the present disclosure, and the yield ratio of 0.60 or more not being obtained.

[0097] Steel component No. A7 is a comparative example where the cooling rate from 800 °C to 550 °C was less than the specification of the present disclosure, resulting in the average ratio of crystal grain length to circumference length when the crystal grain is assumed to be a true circle exceeded the upper limit of 60 specified in the present disclosure, and a yield ratio of 0.60 or more was not obtained.

[0098] Steel component No. A10 is a comparative example where the cooling rate from 800 °C to 550 °C was less than the specification of the present disclosure, resulting in the average aspect ratio of crystal grains being smaller than the lower limit of 0.5 specified in the present disclosure, and a yield ratio of 0.60 or more was not obtained.

[0099] Steel component Nos. A13, A14, A15, and A16 were partially 30 mm in diameter. Steel component Nos. A13 and A14 are examples where cooling rate differences from 800 °C to 550 °C exceeded 25 %, and therefore sub-surface hardness differences in the components exceeded 10 %. On the other hand, steel component Nos. A15 and A16 are examples where the cooling rate differences were less than 25 %, and therefore sub-surface hardness differences in the components were suppressed to 10 % or less.

Claims

1. A steel component comprising: a chemical composition containing, in mass%,

C: 0.21 % to 0.24 %,

Si: 0.11 % to 0.25 %,

Mn: 1.81 % to 1.99 %,

P: 0.014 % to 0.025 %,

S: 0.035 % to 0.060 %,

Cr: 0.55 % to 0.65 %,

Al: 0.010 % to 0.050 %,

Ti: 0.005 % to 0.020 %,

V: 0.15 % to 0.20 %, and

N: 0.0090 % to 0.0150 %,

in amounts such that a value of F1 obtained by Formula (1) is 0.65 % or more, with the balance as Fe and inevitable impurity; and a bainitic microstructure area fraction of 85 % or more and a retained austenite area fraction of 5 % or less, wherein

crystal grains of the bainitic microstructure have an average diameter of 10 μm or more and 25 μm or less, an average aspect ratio of 0.5 or more, and an average ratio of crystal grain boundary length to crystal grain circumference of 60 or less,

$$F1 = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14 \quad \dots (1)$$

where each element symbol in Formula (1) is content in mass% of the element, and elements not included are considered as 0 for F1 calculation.

2. The steel component according to claim 1, wherein a ratio of a difference between the maximum value Hv_1 and the minimum value Hv_2 of Vickers hardness at 1 mm below the surface of the steel component to the maximum value Hv_1 , $((Hv_1 - Hv_2)/Hv_1) \times 100$, is 10 % or less.

3. The steel component according to claim 1 or 2, wherein the chemical composition further contains, in mass%, at least one selected from the group consisting of:

Cu: 0.25 % or less,

Ni: 0.25 % or less,

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Mo: 0.15 % or less, and

Nb: 0.030 % or less.

4. A method of producing a steel component, comprising: applying hot forging after heating and holding at 1150 °C or more to a steel material comprising the chemical composition according to claim 1 or 3, to obtain a hot forging material, and then cooling the hot forging material from 1000 °C to 800 °C at an average cooling rate of 0.7 °C/s or more and 3.5 °C/s or less, and from 800 °C to 550 °C at an average cooling rate of 0.5 °C/s or more and 2.0 °C/s or less.
5. The method of producing a steel component according to claim 4, wherein the cooling from 800 °C to 550 °C is performed where a ratio of a difference between the maximum value V_1 and the minimum value V_2 of cooling rate distribution in the hot forging material to the maximum value V_1 , $((V_1 - V_2)/V_1) \times 100$, is 25 % or less.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2023/002508

A. CLASSIFICATION OF SUBJECT MATTER

C22C 38/00(2006.01)i; **C21D 8/00**(2006.01)i; **C22C 38/60**(2006.01)i
FI: C22C38/00 301Z; C21D8/00 B; C22C38/60

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C22C38/00-38/60; C21D8/00

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

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2023
Registered utility model specifications of Japan 1996-2023
Published registered utility model applications of Japan 1994-2023

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 9-111412 A (SUMITOMO METAL IND LTD) 28 April 1997 (1997-04-28)	1-5
A	JP 5-279788 A (SUMITOMO METAL IND LTD) 26 October 1993 (1993-10-26)	1-5
A	WO 2018/155610 A1 (NIPPON STEEL & SUMITOMO METAL CORP) 30 August 2018 (2018-08-30)	1-5
A	KR 10-2014-0056767 A (HYUNDAI STEEL COMPANY) 12 May 2014 (2014-05-12)	1-5
A	KR 10-2004-0037738 A (HYUNDAI MOTOR COMPANY) 07 May 2004 (2004-05-07)	1-5

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

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Japan Patent Office (ISA/JP)
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/JP2023/002508

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
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JP 5-279788 A	26 October 1993	(Family: none)	
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REFERENCES CITED IN THE DESCRIPTION

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