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(54) **GPA-GRADE BAINITE STEEL HAVING ULTRA-HIGH YIELD RATIO AND MANUFACTURING METHOD FOR GPA-GRADE BAINITE STEEL**

(57) GPa-grade bainite steel having an ultra-high yield ratio, containing, in addition to Fe, the following chemical elements in mass percentages: 0.12-0.24% of C; 0.2-0.5% of Si; 1.3-2.0% of Mn; 0.001-0.004% of B;

0.01-0.05% of Al; and at least one of Cr, Nb, Ti, and Mo, wherein Cr<0.4%, Nb≤0.06%, Ti<0.1%, and Mo≤0.4%. Also disclosed are a manufacturing method and annealing process for the steel.

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Description**Technical Field**

5 **[0001]** The present disclosure relates to a steel and a method for manufacturing the same, in particular to a GPa-grade bainite steel and a method for manufacturing the same.

Background Art

10 **[0002]** Under the new-era concept of "green-safety", GPa-grade high-strength steel has become one of the automotive structural materials that attracts the most interest of the major automobile manufacturers as higher and higher strength is required for structural parts and safety parts of automobiles.

15 **[0003]** In recent years, more and more automotive structural parts (e.g. components of the cockpit and chassis system) are required to ensure "zero deformation" during service to guarantee proper use of the automobile and safety of the driver and passengers. This imposes very high requirements on the material. Particularly, it is required to have yield strength or yield ratio as high as possible. At present, high-yield-strength or high-yield-ratio materials have attracted more and more attention from automobile manufacturers. The market demand for high-yield-strength or high-yield-ratio GPa-grade steel has also increased day by day.

20 **[0004]** The yield ratio of the GPa-grade high-strength steel mentioned in the existing patents for invention is generally not high. The yield ratio of the dual-phase steel accounting for 90% of the market share of the GPa-grade automotive high-strength steel is only 0.6-0.75. For the rest products accounting for a small proportion, such as martensite steel, quenching-partitioning steel (Q&P steel), and complex phase steel, although the yield ratio has been increased slightly, it is only about 0.75-0.85.

25 **[0005]** For example, the Chinese patent document CN103361577A (published on October 23, 2013 and titled "HIGH-YIELD-RATIO AND HIGH-STRENGTH STEEL SHEET HAVING EXCELLENT PROCESSABILITY") discloses a high-yield-ratio and high-strength steel sheet having a microstructure dominated by ferrite, martensite, tempered martensite and bainite. Its tensile strength can reach 980 MPa or higher, but its yield ratio is only ≥ 0.68 , which still fails to meet the latest requirement of the automotive parts market for high-yield-ratio GPa-grade steel sheets.

30 **[0006]** For another example, the Chinese patent document CN106170574A (published on November 30, 2016 and titled "HIGH-YIELD-RATIO AND HIGH-STRENGTH COLD-ROLLED STEEL SHEET AND MANUFACTURING METHOD THEREFOR") discloses a high-yield-ratio and high-strength cold-rolled steel sheet and a manufacturing method therefor. The structure of the steel sheet mainly contains ferrite, retained austenite, martensite and trace amounts of bainite and tempered ferrite. Its tensile strength can reach 980 MPa or higher, but its yield ratio is only ≥ 0.75 , no more than 0.8 at most. The market demand for GPa-grade high-strength steel having a yield ratio ≥ 0.9 still cannot be satisfied.

35 **[0007]** On the other hand, although some patent documents disclose high-yield-ratio steel sheets having a yield ratio ≥ 0.9 and manufacturing methods therefor, the tensile strength of the steel sheets disclosed by these patent documents cannot reach the level of 980 MPa.

40 **[0008]** For example, the Chinese patent document CN102719736A (published on October 10, 2012 and titled "ULTRA-FINE GRAIN SLIDEWAY STEEL HAVING YIELD RATIO ≥ 0.9 AND PRODUCTION METHOD THEREFOR") discloses a steel sheet having a yield ratio ≥ 0.9 obtained by forming an ultrafine grain structure, but its tensile strength is only at the level of 700 MPa.

45 **[0009]** As it can be seen, for a steel sheet at the present stage, the tensile strength reaching the GPa grade and the yield ratio ≥ 0.9 are two contradictory technical indicators. The technical problem behind this contradiction is that it is technically very difficult to achieve an ultra-high yield ratio of ≥ 0.9 by regulating the structure.

50 **[0010]** First of all, to achieve a high yield ratio, the structure of the matrix in the steel sheet needs to be relatively uniform. For example, the matrix consists of pure bainite or pure martensite. If the steel sheet has a multi-phase or complex-phase matrix structure, such as a matrix structure containing ferrite, retained austenite, tempered martensite and martensite at the same time, it is not easy to obtain a high yield ratio. However, if it's desired that the strength of the steel sheet reaches the GPa level, the mutual cooperation of multiple phases in the structure is often required, such as in the typical ferrite/martensite dual-phase steel and the advanced high-strength steel that contains retained austenite and incorporates the TRIP effect. This is the first aspect of the technical contradiction.

55 **[0011]** However, even with a pure bainite or martensite structure, due to dislocation slip and work hardening caused by processing strain, it's difficult for the yield ratio of the steel sheet to reach ≥ 0.9 . Generally speaking, the yield ratio of a steel sheet having a pure martensite or bainite matrix is about 0.8-0.9.

60 **[0012]** Therefore, in order to further obtain a steel sheet having an ultra-high yield ratio, it is necessary to further design a complex composition and a complex process to prevent dislocation slip and increase the yield strength of the material. For example, the Chinese patent document CN101910436A (published on December 8, 2010 and titled "HIGH-STRENGTH COLD-ROLLED STEEL SHEET HAVING EXCELLENT WEATHER RESISTANCE AND PREPARATION

METHOD THEREFOR") discloses a method for increasing the yield strength of a material by introducing a large amount of expensive solid solution alloy elements Cr, Zr, Co, W, etc. However, considering that the process for preparing the existing GPa-grade ultra-high-strength steel is complicated and the amount of alloy elements added to it is already very high, it is still considerably doubtful whether the above complicated process technology or the addition of expensive alloy elements for further increasing the yield ratio is suitable for combining with the existing GPa-grade ultra-high-strength steel whose structure is already extremely complex. This is the second aspect of the technical contradiction.

[0013] Therefore, a series of technical difficulties such as the first and second technical contradictions mentioned above have to be overcome in order to obtain GPa-grade ultra-high-strength steel having a yield ratio of ≥ 0.9 . This cannot be realized by the existing patent technology.

[0014] As such, in order to solve the above problem, it is desirable to obtain a GPa-grade bainite steel having an ultra-high yield ratio. This GPa-grade bainite steel has an ultra-high yield ratio, an ultra-high strength, and excellent hole-expanding and bending performances at the same time. It can be used to prepare automotive structural parts, and realize the new design concept of "green-safety" for automobiles.

Summary

[0015] One object of the present disclosure is to provide a GPa-grade bainite steel having an ultra-high yield ratio. According to the present disclosure, a GPa-grade bainite steel having an ultra-high yield ratio can be obtained by an appropriate design of the chemical composition. The GPa-grade bainite steel has a tensile strength of ≥ 980 MPa, a yield strength of ≥ 900 MPa, a yield ratio of ≥ 0.9 , and a hole expansion rate of $\geq 55\%$. It has an ultra-high yield ratio, an ultra-high strength, and excellent hole-expanding and bending performances at the same time. It can be used to prepare automotive structural parts, and has good popularization prospect and application value.

[0016] In order to achieve the above object, the present disclosure proposes a GPa-grade bainite steel having an ultra-high yield ratio, comprising the following chemical elements in mass percentages in addition to Fe and unavoidable impurities:

C: 0.12-0.24%;
Si: 0.2-0.5%;
Mn: 1.3-2.0%;
B: 0.001-0.004%;
Al: 0.01-0.05%;
at least one of Cr, Nb, Ti and Mo, wherein $Cr < 0.4\%$, $Nb \leq 0.06\%$, $Ti \leq 0.1\%$, $Mo \leq 0.4\%$.

[0017] Further, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, the mass percentages of the chemical element are:

C: 0.12-0.24%;
Si: 0.2-0.5%;
Mn: 1.3-2.0%;
B: 0.001-0.004%;
Al: 0.01-0.05%;
at least one of Cr, Nb, Ti and Mo, wherein $Cr \leq 0.4\%$, $Nb \leq 0.06\%$, $Ti \leq 0.1\%$, $Mo \leq 0.4\%$;
a balance of Fe and other unavoidable impurities.

[0018] The principles for designing the various chemical elements in the technical solution of the present disclosure will be described in detail as follows:

C: In the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, element C is one of the key elements that control the phase transformation of the structure in the carbon steel. Meanwhile, element C has a great influence on the strength of the steel sheet. Element C can form alloy carbides with other alloy elements, thereby increasing the strength of the steel sheet. If the content of element C in the steel is lower than 0.12%, the strength of the steel will not meet the target requirement; and if the content of element C in the steel is higher than 0.24%, it is easy to form martensite structure and coarse cementite which will deteriorate the performances of the steel sheet. As such, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, the mass percentage of C is controlled at 0.12-0.24%.

[0019] Of course, in some preferred embodiments, in order to obtain better implementation effects, the mass percentage of element C may be controlled at 0.15-0.20%.

[0020] Si: In the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, element Si is an essential element for deoxygenation in steelmaking. It has a certain solid solution strengthening effect, and at

the same time, it also has a certain influence on the formation of bainite (the more element B in the steel, the easier it is to form carbon-free bainite). It should be noted that when the content of element Si in the steel is lower than 0.2%, it is difficult to achieve sufficient deoxygenation effect; and when the content of element Si in the steel is higher than 0.5%, it is easy to form iron oxide scale or tiger stripe color difference, which is not conducive to the surface quality of steel sheets for automobiles. As such, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, the mass percentage of Si is controlled at 0.2-0.5%.

[0021] Mn: In the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, element Mn is the main additive element, and it is one of the key elements that control the phase transformation of the structure in the steel. It should be noted that element Mn is low in cost. It is not only an element for effectively improving the strength of the steel, but also an important element for solid solution strengthening. However, it should be noticed that the content of element Mn in the steel should not be too high. When the content of element Mn in the steel is too high, it will deteriorate the corrosion resistance and welding performance, aggravate the tendency of grain coarsening, and reduce the plasticity and toughness of the steel. As such, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, the mass percentage of Mn is controlled at 1.3-2.0%.

[0022] Of course, in some preferred embodiments, in order to obtain better implementation effects, the mass percentage of element Mn may be controlled at 1.6-2.0%.

[0023] B: In the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, element B is not only beneficial to the formation of bainite in the steel, but also has a significant influence on the strength and hardness of the steel sheet. It should be noted that if the content of element B in the steel is lower than 0.001%, the strength of the steel will not meet the target requirement; and if the content of element B in the steel is higher than 0.004%, it is easy to form brittle borides which will affect the hole-expanding and bending performances of the steel sheet. As such, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, the mass percentage of B is controlled at 0.001-0.004%.

[0024] Al: In the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, element Al is only added to the steel as a deoxygenating element. It can remove element O from the steel to ensure the performances and quality of the steel. As such, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, the mass percentage of Al is controlled at 0.01-0.05%. In some existing technologies, element Al is added to steel in a large amount ($\geq 0.1\%$) as an element for forming ferrite and inhibiting carbide precipitation in an attempt to effectuate solid solution strengthening, or to change the phase transformation temperature, bainite formation kinetics and carbide precipitation kinetics by adding Al, so as to change the phase transformation of the steel to form retained austenite or carbon-free bainite, thereby improving the strength of the steel ultimately. However, the composition control and process adjustment proposed according to the present disclosure can already provide a GPa-grade bainite steel having an ultra-high yield ratio, so there is no need to add a large amount of element Al, thereby avoiding cost increase and greatly increased difficulty in steelmaking and manufacturing.

[0025] Ti, Cr, Nb and Mo: In the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, Ti, Cr, Nb and Mo are optional alloy elements that can be added to the steel to form a second phase of dispersed fine carbide which precipitates to further improve the strength and yield ratio of the steel sheet. In addition, it should be noted that elements Cr and Mo can prolong the incubation period of pearlite and ferrite in the CCT curve, inhibit the formation of pearlite and ferrite, and make it easier to obtain the bainite structure during cooling, which is beneficial to improve the hole expansion rate of the steel.

[0026] As it can be seen, the above four alloy elements have an influence on both the regulation of the structure of the steel sheet and the corresponding annealing process. The factors that influence the formation of carbides have a direct influence on the proportion and morphology of the carbides that are formed. As such, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, the mass percentage of Cr, Nb, Ti and Mo are respectively controlled as follows: $\text{Cr} \leq 0.4\%$, $\text{Nb} \leq 0.06\%$, $\text{Ti} \leq 0.1\%$, $\text{Mo} \leq 0.4\%$.

[0027] On the other hand, the addition of the above alloy elements will increase the material cost. To balance the performances and the cost control, in the technical solution according to the present disclosure, it is preferable to add at least one of Cr, Nb, Ti and Mo to the steel. In some preferred embodiments, the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure comprises at least 0.1-0.4% Cr. In some preferred embodiments, the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure comprises at least 0.1-0.4% Mo. In some preferred embodiments, the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure comprises at least one or both of Cr and Mo. In some preferred embodiments, the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure comprises at least 0.1-0.4% Cr and 0.1-0.4% Mo.

[0028] Further, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, the mass percentages of the chemical elements satisfy at least one of the following:

C: 0.15-0.20%,

Mn: 1.6-2.0%.

[0029] Further, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, among the other unavoidable impurities: $P \leq 0.015\%$; and/or $S \leq 0.004\%$.

[0030] In the above technical solution, both P and S are impurity elements in the steel. If the technical conditions permit, in order to obtain a quenched and tempered steel having better performances and better quality, the amount of impurity elements in the steel should be minimized.

[0031] Further, the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure further comprises at least one of the following chemical elements:

$0 < Cu \leq 0.2\%$, $0 < Ni \leq 0.2\%$, $0 < V \leq 0.2\%$, $0 < Ce \leq 0.2\%$.

[0032] In the technical solution according to the present disclosure, each of the above Cu, Ni, V and Ce elements can further improve the performances of the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure.

[0033] Further, the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure satisfies $0.18 \leq M \leq 0.27$, wherein $M = Cr/2.5 + Ti + V/5 + Nb/1.7 + Mo/1.7$, wherein Cr, V, Nb, Ti and Mo each represent the value in front of the percent sign in the mass percentage of each chemical element.

[0034] In the above technical solution, it should be noted that in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, while the mass percentages of the chemical elements are controlled respectively, in order to impart better performances and quality to the GPa-grade bainite steel, it's preferred to further control M to be $0.18 \leq M \leq 0.27$, wherein $M = Cr/2.5 + Ti + V/5 + Nb/1.7 + Mo/1.7$, wherein Cr, V, Nb, Ti and Mo each represent the value in front of the percent sign in the mass percentage of each chemical element.

[0035] It should be noted that in the present disclosure, if M is too high, it will be easy to form coarse carbides which will deteriorate the hole expansion rate and bending performance of the steel; and if M is too low, the carbide precipitate phase cannot be formed sufficiently, so that the strength and yield ratio of the steel will be insufficient. Therefore, in the present disclosure, M may be controlled to be $0.18 \leq M \leq 0.27$, so as to ensure dispersive precipitation of nano-, submicron- or micron-scale granular carbides in the steel, and ensure a maximum diameter of the granular carbide precipitate.

[0036] Further, the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure satisfies $0.20 \leq C_b \leq 0.27$, wherein the equivalent bainite carbon content $C_b = C - (Mo + Nb)/8 - (Ti + V)/4 - Cr/12 + Ni/10 + Mn/20 + B \times 10$, wherein each element in the formula represents the value in front of the percent sign in the mass percentage of the element.

[0037] In the above technical solution, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, since the alloy elements and the M value have an influence on the precipitation of carbides, they will indirectly influence the equivalent bainite carbon content C_b in the steel. It should be noted that in the present disclosure, if C_b is too low, a single bainite matrix structure cannot be formed in a sufficient amount; and if C_b is too high, the hardness of bainite will be too large, thereby deteriorating the bending and hole-expanding performances of the steel. Therefore, in the present disclosure, while the mass percentages of the chemical elements are controlled respectively, it's preferred to further control C_b to be $0.20 \leq C_b \leq 0.27$, so as to effectively ensure that the phase proportion of acicular lower bainite in the steel is $\geq 90\%$.

[0038] Furthermore, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, its microstructure is mainly acicular lower bainite, and the phase proportion of the acicular lower bainite is $\geq 90\%$.

[0039] Further, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, its microstructure further comprises a nano-, submicron- or micron-scale granular carbide precipitate phase that is precipitated dispersively, and a total phase proportion of the granular carbide precipitate phase + acicular lower bainite is $\geq 99\%$.

[0040] Furthermore, in the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure, the granular carbide precipitate has a maximum diameter of $\leq 2 \mu m$.

[0041] Further, the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure has a tensile strength of ≥ 980 MPa, preferably ≥ 1000 MPa, a yield strength of ≥ 900 MPa, preferably ≥ 950 MPa, a yield ratio of ≥ 0.9 , preferably ≥ 0.95 , and a hole expansion rate of $\geq 55\%$, preferably $\geq 60\%$. In a preferred embodiment, the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure has a tensile strength of ≥ 1000 MPa, a yield strength of ≥ 910 MPa, a yield ratio of ≥ 0.9 , and a hole expansion rate of $\geq 55\%$.

[0042] Further, the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure has a yield strength of ≥ 950 MPa, a yield ratio of ≥ 0.95 , and further preferably a tensile strength of ≥ 1000 MPa, and a hole expansion rate of $\geq 60\%$.

[0043] Further, the GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure has an elongation of $\geq 9.0\%$. Correspondingly, another object of the present disclosure is to provide an annealing process for the above GPa-grade bainite steel having an ultra-high yield ratio. This annealing process plays a key role for the performances of the steel. By designing the process appropriately and controlling relevant process parameters, the GPa-grade bainite steel having an ultra-high yield ratio can be obtained.

[0044] In order to achieve the above object, the present disclosure proposes an annealing process for the above GPa-

grade bainite steel having an ultra-high yield ratio, comprising steps of:

- (a) Heating to a soaking temperature T_s at a heating rate of $\leq 50^\circ\text{C/s}$ at a heating stage, wherein T_s is $840-900^\circ\text{C}$;
- (b) Holding the temperature T_s for 5 minutes or less at a soaking stage;
- (c) Cooling to (T_s-80) to $(T_s-140)^\circ\text{C}$ at a first cooling rate of $\leq 15^\circ\text{C/s}$ at a slow cooling stage;
- (d) Cooling to (T_s-490) to $(T_s-440)^\circ\text{C}$ at a second cooling rate of $\geq (130-Q)^\circ\text{C/s}$ at a fast cooling stage, wherein $Q=C\times 180+Si\times 10+Mn\times 30+Ni\times 50+Cr\times 15+Mo\times 15+B\times 2000$, wherein each element in the formula represents the value in front of the percent sign in the mass percentage of the element;
- (e) Cooling at a third cooling rate for 10-40 s at a controlled cooling stage for self-temperature rise, wherein $[(Q-80)/12]\leq \text{third cooling rate}\leq [(Q-80)/8]$;
- (f) Finally, cooling the strip steel in air to room temperature at an air cooling stage.

[0045] In the technical solution according to the present disclosure, it should be noted that the above annealing process comprises a heating stage, a soaking stage, a slow cooling stage, a fast cooling stage, a controlled cooling stage for self-temperature rise, and an air cooling stage. It plays a key role for the performances of the GPa-grade bainite steel according to the present disclosure.

[0046] In step (a), at the heating stage, it is necessary to ensure heating at a heating rate of $\leq 50^\circ\text{C/s}$ to a soaking temperature T_s : $840-900^\circ\text{C}$, preferably heating to a soaking temperature of $840-870^\circ\text{C}$. The heating rate at the heating stage should not be too high; otherwise, the uniformity of the structure of the strip steel will be reduced. In addition, it should be noted that if the soaking temperature T_s is lower than the soaking temperature range designed above, the strip steel cannot acquire $\geq 90\%$ acicular lower bainite structure; and if the soaking temperature T_s is higher than the soaking temperature range designed above, the grains in the strip steel will be coarse, which will deteriorate the formability of the steel. In some embodiments, the heating rate in step (a) is $5-45^\circ\text{C/s}$.

[0047] In step (b), the soaking time is preferably not less than 1 minute. For example, the soaking time is 1 minute to 4.5 minutes.

[0048] In step (c), it's necessary to cool the strip steel to (T_s-80) to $(T_s-140)^\circ\text{C}$ at a first cooling rate of $\leq 15^\circ\text{C/s}$ at the slow cooling stage. The first cooling rate at the slow cooling stage should not be too high; otherwise, not only energy waste, but also nonuniform structure of the strip steel will be resulted. In addition, it should be noted that if the slow cooling temperature is lower than the slow cooling temperature range designed above, the strip steel cannot acquire $\geq 90\%$ bainite structure; and if the slow cooling temperature is higher than the slow cooling temperature range designed above, a higher cooling capacity and a higher temperature precision control capability will be required at the subsequent fast cooling stage, because the structure uniformity of the strip steel will be deteriorated, and in turn, the performances of the product will be deteriorated if the cooling capacity or temperature precision control capability is insufficient. Preferably, the first cooling rate in step (c) is $5-15^\circ\text{C/s}$, preferably $5-12^\circ\text{C/s}$.

[0049] In step (d), at the fast cooling stage, it's necessary to cool the strip steel to (T_s-490) to $(T_s-440)^\circ\text{C}$ at a second cooling rate of $\geq (130-Q)^\circ\text{C/s}$; wherein $Q=C\times 180+Si\times 10+Mn\times 30+Ni\times 50+Cr\times 15+Mo\times 15+B\times 2000$. If the second cooling rate at the fast cooling stage is insufficient, or the cooling temperature is higher than $(T_s-440)^\circ\text{C}$, bainite transformation will occur prematurely, and a high-temperature bainite structure (such as upper bainite or equiaxed bainite) will be formed. As a result, not only a phase proportion of $\geq 90\%$ of acicular lower bainite in the steel cannot be guaranteed, but the latent heat of phase transformation will also be reduced greatly, so that subsequent controlled cooling for self-temperature rise cannot be implemented. Thus, the material structure will be abnormal, and the steel sheet and steel strip cannot acquire an ultra-high yield ratio. Nevertheless, if the cooling temperature at the fast cooling stage is lower than $(T_s-490)^\circ\text{C}$, a martensite structure will be formed, and thus the hole expansion rate and bending performance of the steel will be reduced.

[0050] In step (e), at the controlled cooling stage for self-temperature rise, if the strip steel can be treated according to the designed parameters at the fast cooling stage, the self-temperature rise phenomenon will occur to the strip steel due to the release of a large quantity of the latent heat of phase transformation. The self-temperature rise can increase the temperature of the strip steel by $50-120^\circ\text{C}$ rapidly, uniformly and efficiently, thereby promoting uniform and dispersive precipitation of carbides. In order to ensure full carbide precipitation and small precipitate size, it is necessary to control the temperature of the strip steel and cool it at a third cooling rate for 10-40s, wherein $[(Q-80)/12]\leq \text{third cooling rate}\leq [(Q-80)/8]$.

[0051] It should be noted that if the third cooling rate is too low or the cooling time is too long at the controlled cooling stage for self-temperature rise, failing to meet the above design requirements according to the present disclosure, carbide precipitate tends to be coarsened, thereby deteriorating the hole expansion rate and bending performance; and if the third cooling rate is too high or the cooling time is too short, it's likely that carbides cannot precipitate fully, so that the steel cannot acquire an ultra-high yield ratio, i.e. a yield ratio of ≥ 0.9 .

[0052] In addition, still another object of the present disclosure is to provide a manufacturing method for the above GPa-grade bainite steel having an ultra-high yield ratio. With the use of this manufacturing method, the GPa-grade

bainite steel having an ultra-high yield ratio according to the present disclosure can be made effectively.

[0053] In order to achieve the above object, the present disclosure proposes a manufacturing method for the above GPa-grade bainite steel having an ultra-high yield ratio, comprising steps of:

- (1) Smelting and casting;
- (2) Hot rolling;
- (3) Post-rolling cooling and coiling;
- (4) Pickling and cold rolling;
- (5) The above annealing process.

[0054] In the technical solution according to the present disclosure, in the above manufacturing method, the main purpose of steps (1)-(4) before the annealing process is to obtain a steel sheet or steel strip having a uniform composition and a uniform initial structure, so as to ensure that the uniformity and stability of the structure and performances can be satisfied in the subsequent annealing process. The annealing process in step (5) plays a key role for the performances of the steel sheet.

[0055] Further, in the manufacturing method according to the present disclosure, in step (2), a heating temperature is controlled at 1150-1260 °C; an initial rolling temperature of finishing rolling is controlled at 1100-1220 °C; and a final rolling temperature of finishing rolling is controlled at 900-950 °C.

[0056] Further, in the manufacturing method according to the present disclosure, in step (3), a cooling rate is controlled at 30-150 °C/s, and a coiling temperature is controlled at 450-580 °C.

[0057] Further, in the manufacturing method according to the present disclosure, in step (4), a cold rolling reduction rate is controlled at $\geq 50\%$.

[0058] Further, in the manufacturing method according to the present disclosure, the GPa-grade bainite steel having an ultra-high yield ratio is the GPa-grade bainite steel having an ultra-high yield ratio described in any embodiment herein.

[0059] Compared with the prior art, the GPa-grade bainite steel having an ultra-high yield ratio and the method of manufacturing the same according to the present disclosure have the following advantages and beneficial effects:

On the premise of ensuring that the composition of chemical elements and the process are relatively simple and controllable, the present disclosure optimizes the combination of alloy elements, and adjusts the annealing process in an innovative way. On the basis of ensuring that the matrix structure of the steel sheet is a simple and single bainite structure, the release of the latent heat of phase transformation is introduced to realize self-temperature rise of the steel strip. This not only reduces energy consumption, but also realizes fast, uniform and efficient control of the temperature rise of the steel strip, thereby inducing dispersive precipitation of the fine second phase. Thus, a GPa-grade bainite steel having an ultra-high yield ratio and good formability is obtained.

[0060] By designing the chemical composition appropriately according to the present disclosure, a GPa-grade bainite steel having an ultra-high yield ratio that has a tensile strength of ≥ 980 MPa, a yield strength of ≥ 900 MPa, a yield ratio of ≥ 0.9 , and a hole expansion rate of $\geq 55\%$ can be obtained. The GPa-grade bainite steel has an ultra-high yield ratio, an ultra-high strength, and excellent hole-expanding and bending performances at the same time. It can be used to prepare automotive structural parts, and realize the new design concept of "green-safety" for automobiles. It has good popularization prospect and application value.

[0061] The annealing process according to the present disclosure plays a key role for the performances of the steel. The annealing process comprises a heating stage, a soaking stage, a slow cooling stage, a fast cooling stage, a controlled cooling stage for self-temperature rise, and an air cooling stage. By designing the process appropriately and controlling relevant process parameters, the GPa-grade bainite steel having an ultra-high yield ratio can be obtained.

[0062] Correspondingly, the manufacturing method according to the present disclosure employs a unique production process. Particularly, the above annealing process is utilized to guarantee the performances of the resulting GPa-grade bainite steel. The resulting GPa-grade bainite steel not only has ultra-high strength and yield ratio, but also has excellent hole-expanding and bending performances.

Description of the Drawings

[0063]

Fig. 1 is a photograph at 3000 $\times$ magnification showing the microstructure of the GPa-grade bainite steel of Example 1.

Fig. 2 is a photograph at 3000 $\times$ magnification showing the microstructure of the comparative steel in Comparative Example 7.

Fig. 3 is a photograph at 1000 $\times$ magnification showing the microstructure of the comparative steel in Comparative Example 8.

Detailed Description

[0064] The GPa-grade bainite steel having an ultra-high yield ratio according to the present disclosure and the manufacturing method for the same will be further explained and illustrated with reference to the accompanying drawings of the specification and the specific Examples. Nonetheless, the explanation and illustration are not intended to unduly limit the technical solution of the present disclosure.

Examples 1-14 and Comparative Examples 1-10

[0065] The GPa-grade bainite steel having an ultra-high yield ratio in each of Examples 1-14 was prepared using the following steps:

- (1) Subjecting the chemical composition shown in Table 1 to smelting and casting.
- (2) Hot rolling: the heating temperature was controlled at 1150-1260°C; the initial temperature of the finishing rolling was controlled at 1100-1220°C; and the final rolling temperature of the finishing rolling was controlled at 900-950°C.
- (3) Post-rolling cooling and coiling: the cooling rate was controlled at 30-150 °C/s; and the coiling temperature was controlled at 450-580 °C.
- (4) Pickling and cold rolling: the cold rolling reduction rate was controlled at $\geq 50\%$.
- (5) Annealing.

[0066] It should be noted that in step (5), the annealing process comprises the following steps:

- (a) Heating to a soaking temperature T_s at a heating rate of $\leq 50^\circ\text{C/s}$ at a heating stage, wherein T_s was 840-900 °C;
- (b) Holding the temperature T_s for 5 minutes or less at a soaking stage;
- (c) Cooling to (T_s-80) to (T_s-140) °C at a first cooling rate of $\leq 15^\circ\text{C/s}$ at a slow cooling stage;
- (d) Cooling to (T_s-490) to (T_s-440) °C at a second cooling rate of $\geq (130-Q)^\circ\text{C/s}$ at a fast cooling stage, wherein $Q = C \times 180 + Si \times 10 + Mn \times 30 + Ni \times 50 + Cr \times 15 + Mo \times 15 + B \times 2000$;
- (e) Cooling at a third cooling rate for 10-40 s at a controlled cooling stage for self-temperature rise, wherein $[(Q-80)/12] \leq \text{third cooling rate} \leq [(Q-80)/8]$;
- (f) Finally, cooling the strip steel in air to room temperature at an air-cooling stage.

[0067] In addition, it should be noted that the GPa-grade bainite steel having an ultra-high yield ratio in each of Examples 1-14 according to the present disclosure was prepared using the above steps. The chemical compositions and related process parameters in these Examples all met the control requirements of the design specification according to the present disclosure.

[0068] The comparative steel in each of Comparative Examples 1-10 was also made by the process comprising smelting and casting, hot rolling, post-rolling cooling and coiling, pickling and cold rolling, and annealing. However, the chemical composition and the relevant process parameters in each of Comparative Examples 1-6 included parameters that failed to meet the requirements of the design according to the present disclosure. Although the chemical composition in each of Comparative Examples 7-10 met the requirements of the design according to the present disclosure, these Comparative Examples all included parameters that failed to meet the requirements of the design according to the present disclosure.

[0069] Among the Examples according to the present disclosure and the Comparative Examples, Comparative Example 7 and Example 1 had the same composition of chemical elements; Comparative Example 8 and Example 2 had the same composition of chemical elements; Comparative Example 9 and Example 6 had the same composition of chemical elements; and Comparative Example 10 and Example 11 had the same composition of chemical elements.

[0070] Table 1 lists the mass percentages (%) of the chemical elements in the GPa-grade bainite steel having an ultra-high yield ratio in each of Examples 1-14 and the mass percentages (%) of the chemical elements in the comparative steel in each of Comparative Examples 1-10.

Table 1. (the balance is Fe and other unavoidable impurities except for P and S)

No.	Steel Grade	Chemical elements																
		C	Si	Mn	Cr	B	Mo	Nb	Ti	P	S	Al	Cu	Ni	V	Ce	C _b	M
Ex. 1 and Comp. Ex. 7	A	0.16	0.45	1.75	0.3	0.002	0.19	0	0	0.010	0.002	0.02	0	0	0	0	0.22	0.23
Ex. 2 and Comp. Ex. 8	B	0.17	0.35	1.82	0.2	0.004	0.23	0	0	0.012	0.003	0.03	0	0	0	0	0.26	0.22
Ex. 3	C	0.13	0.5	1.68	0.25	0.004	0.16	0.03	0.03	0.013	0.001	0.01	0	0	0	0	0.20	0.24
Ex. 4	D	0.19	0.23	2	0.23	0.003	0.13	0.04	0.02	0.011	0.002	0.03	0	0	0	0	0.27	0.21
Ex. 5	E	0.14	0.27	1.88	0.22	0.004	0.15	0	0	0.010	0.002	0.02	0.2	0	0	0	0.24	0.18
Ex. 6 and Comp. Ex. 9	F	0.17	0.22	1.71	0.3	0.004	0.25	0	0	0.008	0.001	0.03	0	0	0	0	0.24	0.27
Ex. 7	G	0.16	0.43	1.56	0.21	0.002	0.15	0.02	0.08	0.009	0.001	0.04	0	0	0	0	0.20	0.26
Ex. 8	H	0.19	0.41	1.53	0.35	0.002	0.12	0.06	0.01	0.010	0.001	0.05	0	0	0	0	0.23	0.26
Ex. 9	I	0.18	0.31	1.61	0.38	0.002	0	0	0.1	0.015	0.003	0.04	0	0	0	0	0.22	0.25
Ex. 10	J	0.2	0.37	1.94	0.25	0.001	0.20	0	0.01	0.010	0.002	0.02	0	0	0.2	0	0.21	0.27
Ex. 11 and Comp. Ex. 10	K	0.15	0.48	1.58	0	0.003	0.37	0	0	0.008	0.002	0.02	0	0	0	0	0.21	0.22
Ex. 12	L	0.22	0.46	1.35	0.16	0.004	0.31	0.04	0	0.009	0.001	0.03	0	0	0	0.2	0.27	0.27
Ex. 13	M	0.12	0.4	1.93	0.11	0.003	0.20	0	0.05	0.008	0.004	0.03	0	0.2	0	0	0.22	0.21
Ex. 14	N	0.24	0.25	1.3	0.17	0.001	0.27	0.01	0.03	0.010	0.001	0.02	0	0	0	0	0.26	0.26
Comp. Ex. 1	O	0.25	0.35	2.1	0.35	0.001	0.2	0	0	0.012	0.001	0.02	0	0	0	0	<u>0.31</u>	0.26
Comp. Ex. 2	P	0.10	0.4	1.7	0.3	0.002	0.25	0	0	0.013	0.003	0.02	0	0	0	0	0.15	0.27
Comp. Ex. 3	Q	0.18	0.3	1.68	0.28	0.004	0.2	0.02	0.05	0.011	0.004	0.02	0	0	0	0	0.24	0.29
Comp. Ex. 4	R	0.17	0.22	1.96	0.2	0.001	0.13	0	0	0.014	0.002	0.02	0	0	0	0	0.25	0.16
Comp. Ex. 5	S	0.15	0.22	1.51	0.22	0.001	0.3	0	0	0.015	0.002	0.02	0.2	0	0	0	0.18	0.26
Comp. Ex. 6	T	0.19	0.22	1.86	0.3	0.004	0.16	0	0.01	0.012	0.003	0.02	0	0	0	0	0.28	0.22
Note: in the above table, C _b =C-(Mo+Nb)/8-(Ti+V)/4-Cr/12+Ni/10+Mn/20+B×10, wherein each element in the formula represents the value in front of the percent sign in the mass percentage of the element; M=Cr/2.5+Ti+V/5+Nb/1.7+Mo/1.7, wherein Cr, V, Nb, Ti and Mo each represent the value in front of the percent sign in the mass percentage of the chemical element.																		

[0071] Table 2-1 and Table 2-2 list the specific process parameters for the GPa-grade bainite steel having an ultra-high yield ratio in each of Examples 1-14 and the comparative steel in each of Comparative Examples 1-10.

Table 2-1

No.	Steel grade	Step (2)			Step (3)		Step (4)
		Heating temperature (°C)	Initial rolling temperature of finishing rolling (°C)	Final rolling temperature of finishing rolling (°C)	Cooling rate (°C/s)	Coiling temperature (°C)	Cold rolling reduction rate (%)
Ex. 1	A	1180	1140	920	70	500	50
Ex. 2	B	1205	1165	945	100	525	55
Ex. 3	C	1210	1170	950	50	570	80
Ex. 4	D	1190	1150	930	90	480	65
Ex. 5	E	1155	1115	900	100	450	70
Ex. 6	F	1190	1150	930	110	510	60
Ex. 7	G	1240	1200	905	40	535	75
Ex. 8	H	1230	1190	910	30	580	55
Ex. 9	I	1255	1215	915	150	470	60
Ex. 10	J	1195	1155	935	120	515	65
Ex. 11	K	1205	1165	900	100	525	55
Ex. 12	L	1175	1135	915	140	495	50
Ex. 13	M	1230	1190	905	130	550	60
Ex. 14	N	1240	1200	950	150	460	65
Comp. Ex. 1	O	1170	1130	910	50	490	50
Comp. Ex. 2	P	1225	1185	915	100	545	70
Comp. Ex. 3	Q	1235	1195	925	120	495	65
Comp. Ex. 4	R	1215	1175	920	100	535	60
Comp. Ex. 5	S	1235	1195	900	80	505	55
Comp. Ex. 6	T	1230	1190	910	90	550	50
Comp. Ex. 7	A	1180	1140	920	70	500	70
Comp. Ex. 8	B	1205	1165	945	110	525	55
Comp. Ex. 9	F	1190	1150	930	90	510	60
Comp. Ex. 10	K	1205	1165	900	100	525	60

Table 2-2

No.	Step (5)										
	Step (a)		Step (b)	Step (c)		Step (d)			Step (e)		
	Heating rate at heating stage (°C/s)	Soaking temperature (°C)	Soaking time at soaking stage (min)	First cooling rate (°C/s)	Cooling temperature at slow cooling stage (°C)	Second cooling rate (°C/s)	Q	Cooling temperature at fast cooling stage (°C)	Third cooling rate (°C/s)	Self-temperature rise (°C)	Cooling time at controlled cooling stage for self-temperature rise (s)
Ex. 1	5	850	2.0	5	740	55	97	365	2	108	10
Ex. 2	15	860	3.0	8	730	50	103	382	2	119	34
Ex. 3	45	900	4.5	10	775	45	93	410	1	65	40
Ex. 4	10	840	1.5	7	755	55	108	390	2.5	120	22
Ex. 5	20	865	1.5	12	737	50	98	385	2	100	23
Ex. 6	5	855	3.5	11	741	50	100	382	2	112	22
Ex. 7	20	875	2.5	4	762	60	89	397	1	58	30
Ex. 8	35	893	4.0	15	755	35	95	405	1.5	65	28
Ex. 9	30	862	1.5	13	725	45	94	400	1.5	51	14
Ex. 10	10	846	2.0	10	735	45	107	405	2.5	115	30
Ex. 11	15	868	1.0	8	746	50	91	380	1	80	20
Ex. 12	40	887	2.5	7	750	40	100	400	2	98	25
Ex. 13	25	858	3.0	7	725	45	104	379	2.5	98	12
Ex. 14	20	880	2.5	5	745	55	93	393	1.5	92	36
Comp. Ex. 1	30	860	2.5	5	740	25	122	391	4.5	123	12
Comp. Ex. 2	25	863	3.0	8	745	45	85	386	<u>1</u>	64	20
Comp. Ex. 3	10	858	2.0	7	735	40	101	396	2.5	111	18
Comp. Ex. 4	15	866	1.5	10	733	42	99	382	<u>3.5</u>	83	10

(continued)

No.	Step (5)										
	Step (a)		Step (b)	Step (c)		Step (d)			Step (e)		
	Heating rate at heating stage (°C/s)	Soaking temperature (°C)	Soaking time at soaking stage (min)	First cooling rate (°C/s)	Cooling temperature at slow cooling stage (°C)	Second cooling rate (°C/s)	Q	Cooling temperature at fast cooling stage (°C)	Third cooling rate (°C/s)	Self-temperature rise (°C)	Cooling time at controlled cooling stage for self-temperature rise (s)
Comp. Ex. 5	5	854	2.0	15	720	50	84	378	<u>1</u>	71	30
Comp. Ex. 6	20	857	2.5	10	725	30	107	393	3	111	25
Comp. Ex. 7	5	852	4.0	7	740	<u>20</u>	97	405	2	48	10
Comp. Ex. 8	35	860	3.5	8	730	30	103	<u>450</u>	2.5	45	10
Comp. Ex. 9	40	855	3.0	5	741	35	100	382	<u>1</u>	112	10
Comp. Ex. 10	30	868	1.5	10	746	45	91	380	<u>3</u>	80	20
Note: in the above table, $Q=C\times 180+Si\times 10+Mn\times 30+Ni\times 50+Cr\times 15+Mo\times 15+B\times 2000$, wherein each element in the formula represents the value in front of the percent sign in the mass percentage of the element.											

[0072] Relevant mechanical performance tests were performed on the GPa-grade bainite steel having an ultra-high yield ratio in each of Examples 1-14 and the comparative steel in each of Comparative Example 1-10. The mechanical performance test results of the Examples and Comparative Examples are listed in Table 3. The relevant performance test methods are described as follows.

[0073] The resulting GPa-grade bainite steel having an ultra-high yield ratio in each of Examples 1-14 and the comparative steel in each of Comparative Example 1-10 were sampled respectively. A transverse JIS 5# tensile sample was used to determine the yield strength and tensile strength of the steel, and the middle area of the sheet was used to determine the hole expansion rate and bending performance of the steel.

[0074] The hole expansion rate of the steel was determined in a hole expanding test, wherein a test piece with a hole in the center was pressed into a die with a punch to expand the central hole of the test piece until the edge of the hole in the plate necked or through-plate cracks appeared. Since the manner for preparing the original hole in the center of the test piece and the quality of the corresponding edge of the original hole have a great influence on the test result of the hole expansion rate, the test and test method were implemented according to the test method of hole expansion rate specified in the ISO/DIS 16630 standard. The original hole in the center was in the form of a punched hole (corresponding to the processing method for an original hole having the worst edge quality). The 180° bending test was implemented using the method for determining bending performance in the GB/T232-2010 standard (bending diameter $d=1a$).

[0075] Table 3 lists the test results of the mechanical performances of the GPa-grade bainite steel having an ultra-high yield ratio in each of Examples 1-14 and the comparative steel in each of Comparative Examples 1-10.

Table 3

No.	Mechanical performances					
	Yield strength (MPa)	Tensile strength (MPa)	Yield ratio	Elongation (%)	Hole expansion rate (%)	180° bending
Ex. 1	959	1003	0.96	9.3	68.2	$d=1a$ qualified
Ex. 2	933	1022	0.91	9.7	62.2	$d=1a$ qualified
Ex. 3	927	1010	0.92	9.8	62	$d=1a$ qualified
Ex. 4	936	1038	0.90	9.6	56.7	$d=1a$ qualified
Ex. 5	918	1019	0.90	10.5	58.4	$d=1a$ qualified
Ex. 6	966	1031	0.94	9.5	65.4	$d=1a$ qualified
Ex. 7	924	1016	0.91	9.6	61.3	$d=1a$ qualified
Ex. 8	922	1026	0.90	10.5	61.8	$d=1a$ qualified
Ex. 9	915	1015	0.90	11	55.5	$d=1a$ qualified
Ex. 10	948	1020	0.93	9.7	61	$d=1a$ qualified
Ex. 11	911	1008	0.90	10.7	55.9	$d=1a$ qualified
Ex. 12	942	1037	0.91	10.3	59.3	$d=1a$ qualified
Ex. 13	915	1008	0.91	10.8	57	$d=1a$ qualified

(continued)

No.	Mechanical performances					
	Yield strength (MPa)	Tensile strength (MPa)	Yield ratio	Elongation (%)	Hole expansion rate (%)	180° bending
Ex. 14	941	1005	0.94	9.4	66.2	d=1a qualified
Comp. Ex. 1	1075	1158	0.93	7.8	44.2	d=1a cracked
Comp. Ex. 2	849	942	0.90	11.2	68.8	d=1a qualified
Comp. Ex. 3	1008	1098	0.92	8.2	51.9	d=1a cracked
Comp. Ex. 4	1031	1129	0.91	8	47.7	d=1a cracked
Comp. Ex. 5	875	977	0.90	108	66.9	d=1a qualified
Comp. Ex. 6	1020	1147	0.89	8.9	50.3	d=1a cracked
Comp. Ex. 7	802	999	0.80	11.9	43.9	d=1a cracked
Comp. Ex. 8	781	996	0.78	12.4	40.1	d=1a cracked
Comp. Ex. 9	974	1035	0.94	8.8	52.2	d=1a cracked
Comp. Ex. 10	887	1002	0.89	11.6	53.4	d=1a cracked

[0076] As it can be seen from Table 3, as compared with the comparative steels in Comparative Examples 1-10, the mechanical performances of the GPa-grade bainite steels having an ultra-high yield ratio in Examples 1-14 according to the present disclosure are obviously better.

[0077] The GPa-grade bainite steels having an ultra-high yield ratio in Examples 1-14 according to the present disclosure have an ultra-high yield ratio, an ultra-high strength and excellent hole-expanding and bending performances at the same time, with a tensile strength of ≥ 980 MPa, a yield strength of ≥ 900 MPa, a yield ratio of ≥ 0.9 , and a hole expansion rate of $\geq 55\%$.

[0078] In some individual preferred embodiments, as in Example 1, the GPa-grade bainite steel having an ultra-high yield ratio in Example 1 has a yield strength of ≥ 950 MPa, and a yield ratio of ≥ 0.95 . That is, it has an ultra-high yield ratio and an ultra-high yield strength.

[0079] Fig. 1 is a photograph at $3000\times$ magnification showing the microstructure of the GPa-grade bainite steel of Example 1.

[0080] As shown by Fig. 1, the microstructure of the matrix of the GPa-grade bainite steel in Example 1 is acicular lower bainite because it was cooled to the lower bainite phase region (the cooling temperature of the fast cooling met the requirement of the present disclosure) at a sufficiently fast cooling rate (the second cooling rate met the requirement of the present disclosure) at the fast cooling stage. In addition, because the cooling rate at the controlled cooling stage for self-temperature rise was suitable (the third cooling rate met the requirement of the present disclosure), the structure also contains a fine nano-, submicron- or micron-scale granular carbide precipitate phase that has been dispersively precipitated. The phase proportion of the acicular lower bainite is $\geq 90\%$; the total phase proportion of the granular carbide precipitate phase + the acicular lower bainite is $\geq 99\%$; and the maximum diameter of the granular carbide precipitate is $\leq 2\ \mu\text{m}$.

[0081] Fig. 2 is a photograph at $3000\times$ magnification showing the microstructure of the comparative steel in Comparative Example 7.

[0082] As shown by Fig. 2, because the cooling rate was insufficient (the second cooling rate did not meet the require-

ment of the present disclosure) when the comparative steel in Comparative Example 7 was cooled at the fast cooling stage, bainite phase transformation occurred in the comparative steel at high temperature before it was cooled to the lower bainite phase region. Although it was still cooled to an appropriate temperature of the lower bainite phase region eventually, its microstructure is still dominated by massive equiaxed bainite, nearly free of acicular lower bainite, and the carbide precipitate is also not fine and uniform enough.

[0083] Fig. 3 is a photograph at 1000 $\times$ magnification showing the microstructure of the comparative steel in Comparative Example 8.

[0084] As shown by Fig. 3, although the cooling rate was appropriate (the second cooling rate met the requirement of the present disclosure) when the comparative steel in Comparative Example 8 was cooled at the fast cooling stage, the cooling temperature of the fast cooling was too high (the cooling temperature at the fast cooling stage did not meet the requirement of the present disclosure). As a result, its microstructure almost consists of massive equiaxed bainite, nearly free of acicular lower bainite, and the carbide precipitate is also not fine and uniform enough.

[0085] To sum up, as it can be seen, by designing the chemical composition appropriately according to the present disclosure, a GPa-grade bainite steel having an ultra-high yield ratio that has a tensile strength of ≥ 980 MPa, a yield strength of ≥ 900 MPa, a yield ratio of ≥ 0.9 , and a hole expansion rate of $\geq 55\%$ can be obtained. The GPa-grade bainite steel has an ultra-high yield ratio, an ultra-high strength, and excellent hole-expanding and bending performances at the same time. It can be used to prepare automotive structural parts, and realize the new design concept of "green-safety" for automobiles. It has good popularization prospect and application value.

[0086] The annealing process according to the present disclosure plays a key role for the performances of the steel. The annealing process comprises a heating stage, a soaking stage, a slow cooling stage, a fast cooling stage, a controlled cooling stage for self-temperature rise, and an air cooling stage. By designing the process appropriately and controlling relevant process parameters, the GPa-grade bainite steel having an ultra-high yield ratio can be obtained.

[0087] Correspondingly, the manufacturing method according to the present disclosure employs a unique production process. Particularly, the above annealing process is utilized to guarantee the performances of the resulting GPa-grade bainite steel. The resulting GPa-grade bainite steel not only has ultra-high strength and yield ratio, but also has excellent hole-expanding and bending performances.

[0088] In addition, the ways in which the various technical features of the present disclosure are combined are not limited to the ways recited in the claims of the present disclosure or the ways described in the specific examples. All the technical features recited in the present disclosure may be combined or integrated freely in any manner, unless contradictions are resulted.

[0089] It should also be noted that the Examples set forth above are only specific examples according to the present disclosure. Obviously, the present disclosure is not limited to the above Examples. Similar variations or modifications made thereto can be directly derived or easily contemplated from the present disclosure by those skilled in the art. They all fall in the protection scope of the present disclosure.

Claims

1. A GPa-grade bainite steel having an ultra-high yield ratio, comprising the following chemical elements in mass percentages in addition to Fe and unavoidable impurities:

C: 0.12-0.24%;
Si: 0.2-0.5%;
Mn: 1.3-2.0%;
B: 0.001-0.004%;
Al: 0.01-0.05%;
at least one of Cr, Nb, Ti and Mo, wherein $Cr < 0.4\%$, $Nb \leq 0.06\%$, $Ti \leq 0.1\%$, $Mo < 0.4\%$.

2. The GPa-grade bainite steel having an ultra-high yield ratio according to claim 1, wherein the mass percentages of the chemical element are:

C: 0.12-0.24%;
Si: 0.2-0.5%;
Mn: 1.3-2.0%;
B: 0.001-0.004%;
Al: 0.01-0.05%;
at least one of Cr, Nb, Ti and Mo, wherein $Cr < 0.4\%$, $Nb \leq 0.06\%$, $Ti \leq 0.1\%$, $Mo \leq 0.4\%$;
a balance of Fe and other unavoidable impurities.

3. The GPa-grade bainite steel having an ultra-high yield ratio according to claim 1 or 2, wherein the mass percentages of the chemical elements satisfy at least one of:

C: 0.15-0.20%,
Mn: 1.6-2.0%.

4. The GPa-grade bainite steel having an ultra-high yield ratio according to claim 1 or 2, wherein among the other unavoidable impurities: $P \leq 0.015\%$; and/or $S \leq 0.004\%$.

5. The GPa-grade bainite steel having an ultra-high yield ratio according to claim 1 or 2, further comprising at least one of the following chemical elements:
 $0 < Cu \leq 0.2\%$, $0 < Ni \leq 0.2\%$, $0 < V \leq 0.2\%$, $0 < Ce \leq 0.2\%$.

6. The GPa-grade bainite steel having an ultra-high yield ratio according to claim 5, wherein it satisfies $0.18 \leq M \leq 0.27$, wherein $M = Cr/2.5 + Ti + V/5 + Nb/1.7 + Mo/1.7$, wherein Cr, V, Nb, Ti and Mo each represent a value in front of a percent sign in the mass percentage of each chemical element; and/or $0.20 \leq C_b \leq 0.27$, wherein an equivalent bainite carbon content $C_b = C - (Mo + Nb)/8 - (Ti + V)/4 - Cr/12 + Ni/10 + Mn/20 + B \times 10$, wherein each element in the above formula represents a value in front of a percent sign in the mass percentage of the element.

7. The GPa-grade bainite steel having an ultra-high yield ratio according to claim 1 or 2, wherein its microstructure is mainly acicular lower bainite, and a phase proportion of the acicular lower bainite is $\geq 90\%$.

8. The GPa-grade bainite steel having an ultra-high yield ratio according to claim 7, wherein its microstructure further comprises a nano-, submicron- or micron-scale granular carbide precipitate phase that is precipitated dispersively, and a total phase proportion of the granular carbide precipitate phase + acicular lower bainite is $\geq 99\%$; preferably, the granular carbide precipitate has a maximum diameter of $\leq 2 \mu m$.

9. The GPa-grade bainite steel having an ultra-high yield ratio according to claim 1, wherein it has a tensile strength of ≥ 980 MPa, a yield strength of ≥ 900 MPa, a yield ratio of ≥ 0.9 , and a hole expansion rate of $\geq 55\%$; preferably a yield strength of ≥ 950 MPa, and a yield ratio of ≥ 0.95 .

10. An annealing process for the GPa-grade bainite steel having an ultra-high yield ratio according to any one of claims 1-9, comprising steps of:

- (a) Heating a strip steel to a soaking temperature T_s at a heating rate of $\leq 50^\circ C/s$ at a heating stage, wherein T_s is $840-900^\circ C$;
(b) Holding the temperature T_s for 5 minutes or less at a soaking stage;
(c) Cooling to $(T_s - 80)$ to $(T_s - 140)^\circ C$ at a first cooling rate of $\leq 15^\circ C/s$ at a slow cooling stage;
(d) Cooling to $(T_s - 490)$ to $(T_s - 440)^\circ C$ at a second cooling rate of $\geq (130 - Q)^\circ C/s$ at a fast cooling stage;
(e) Cooling at a third cooling rate for 10-40 s at a controlled cooling stage for self-temperature rise, wherein $[(Q - 80)/12] \leq \text{third cooling rate} \leq [(Q - 80)/8]$;
(f) Finally, cooling the strip steel in air to room temperature at an air-cooling stage; wherein $Q = C \times 180 + Si \times 10 + Mn \times 30 + Ni \times 50 + Cr \times 15 + Mo \times 15 + B \times 2000$.

11. A manufacturing method for a GPa-grade bainite steel having an ultra-high yield ratio, comprising steps of:

- (1) Smelting and casting;
(2) Hot rolling;
(3) Post-rolling cooling and coiling;
(4) Pickling and cold rolling.
(5) The annealing process according to claim 10.

12. The manufacturing method according to claim 11, wherein in the step (2), a heating temperature is controlled at $1150-1260^\circ C$; an initial rolling temperature of finishing rolling is controlled at $1100-1220^\circ C$; and a final rolling temperature of finishing rolling is controlled at $900-950^\circ C$.

13. The manufacturing method according to claim 11, wherein in step (3), a cooling rate is controlled at $30-150^\circ C/s$, and a coiling temperature is controlled at $450-580^\circ C$.

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14. The manufacturing method according to claim 11, wherein in step (4), a cold rolling reduction rate is controlled at $\geq 50\%$.
- 5 15. The manufacturing method according to claim 11, wherein the GPa-grade bainite steel having an ultra-high yield ratio is the GPa-grade bainite steel having an ultra-high yield ratio according to any one of claims 1-9.

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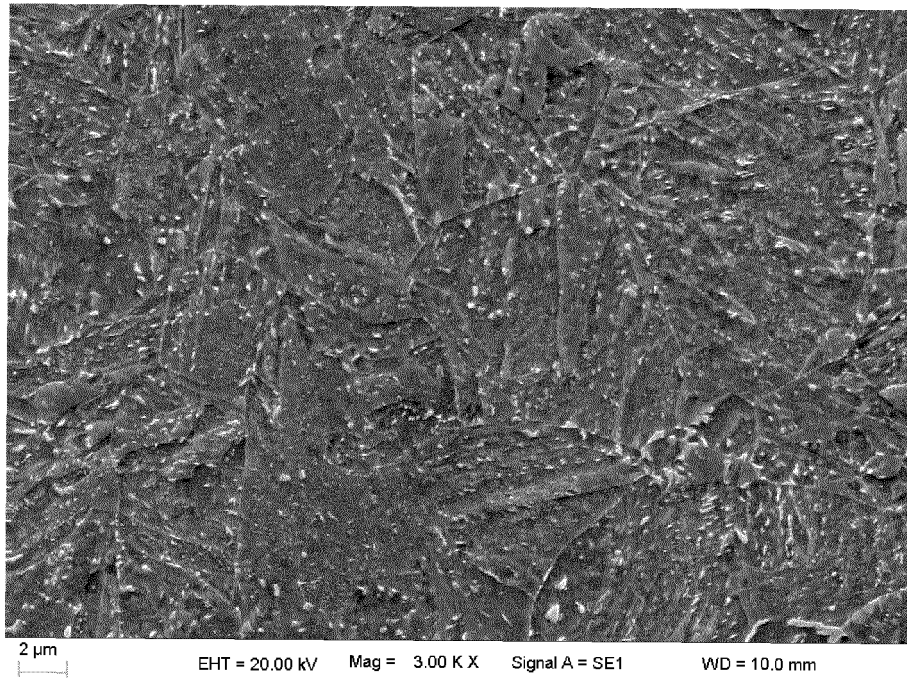


Fig. 1

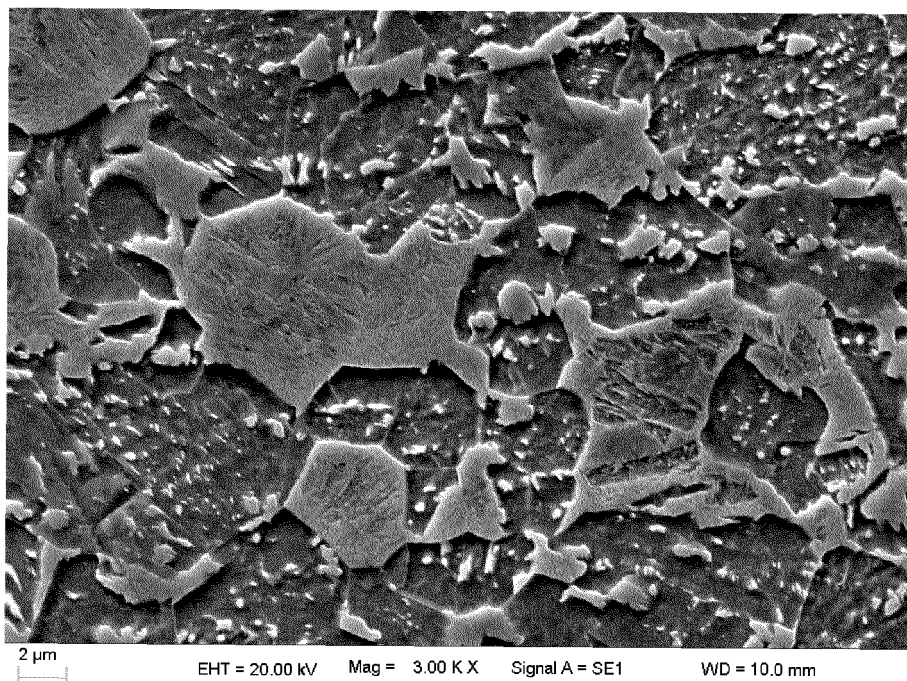


Fig. 2

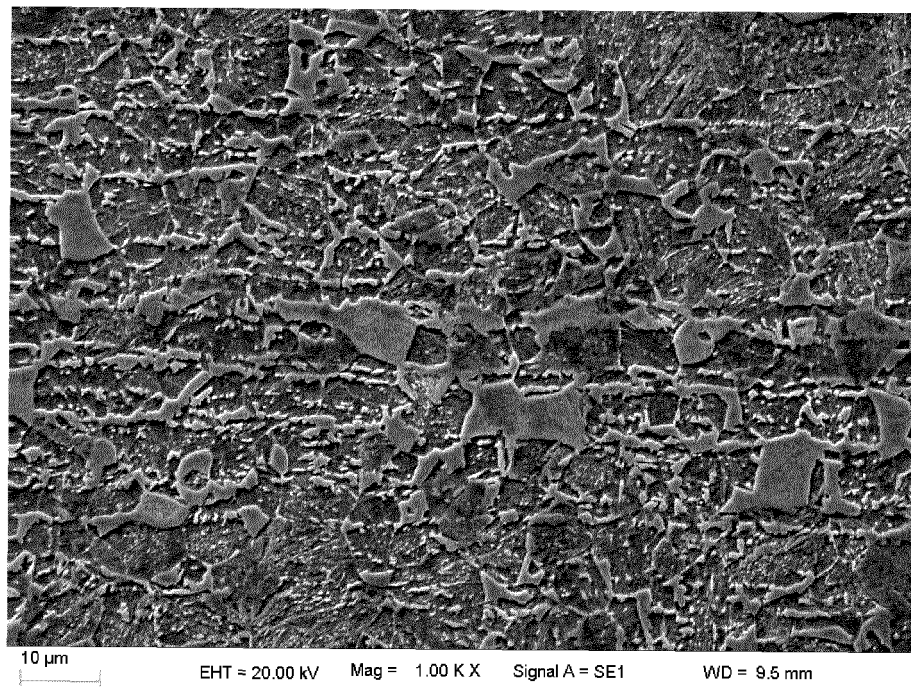


Fig. 3

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2021/114658

A. CLASSIFICATION OF SUBJECT MATTER

C22C 38/02(2006.01)i; C22C 38/04(2006.01)i; C22C 38/06(2006.01)i; C22C 38/12(2006.01)i; C22C 38/20(2006.01)i;
C22C 38/22(2006.01)i; C22C 38/24(2006.01)i; C22C 38/26(2006.01)i; C22C 38/28(2006.01)i; C22C 38/32(2006.01)i;
C22C 38/38(2006.01)i; C22C 38/44(2006.01)i; C22C 38/50(2006.01)i; C22C 38/54(2006.01)i; C22C 38/58(2006.01)i;
C21D 1/26(2006.01)i; C21D 6/00(2006.01)i; C21D 8/02(2006.01)i; C21D 9/00(2006.01)i; C21D 9/52(2006.01)i

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)

C22C; C21D

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

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

CNABS; CNTXT; DWPI; SIPOABS; CNKI; USTXT; EPTXT; WOTXT; ISI Web of Knowledge: 宝山钢铁, 贝氏体, 屈强比, 吉帕级, GPa, 退火, 碳, 硅, 锰, 硼, 铝, 铬, 铌, 钛, 钼, 铜, 镍, 钒, 钨, C, Si, Mn, B, Al, Cr, Nb, Ti, Mo, Cu, Ni, V, Ce, carbon, silicon, manganese, boron, aluminium, aluminum, chrome, chromium, columbium, niobium, titanium, molybdenum, copper, cuprum, nickel, vanadium, cerium, anneal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP H05287439 A (NIPPON STEEL CORP.) 02 November 1993 (1993-11-02) claim 2, description paragraphs 0006-0027	1-9
X	CN 103233183 A (NANJING IRON & STEEL CO., LTD.) 07 August 2013 (2013-08-07) description, paragraphs 0003-0027	1-9
A	CN 1786246 A (ANSHAN IRON AND STEEL GROUP CORPORATION et al.) 14 June 2006 (2006-06-14) entire document	1-15

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

* Special categories of cited documents:

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“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

“&” document member of the same patent family

Date of the actual completion of the international search

04 November 2021

Date of mailing of the international search report

17 November 2021

Name and mailing address of the ISA/CN

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CN2021/114658

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JP	H05287439	A	02 November 1993	None	
CN	103233183	A	07 August 2013	CN	103233183 B 30 March 2016
CN	1786246	A	14 June 2006	CN	100343408 C 17 October 2007

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Form PCT/ISA/210 (patent family annex) (January 2015)

REFERENCES CITED IN THE DESCRIPTION

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- CN 101910436 A [0012]