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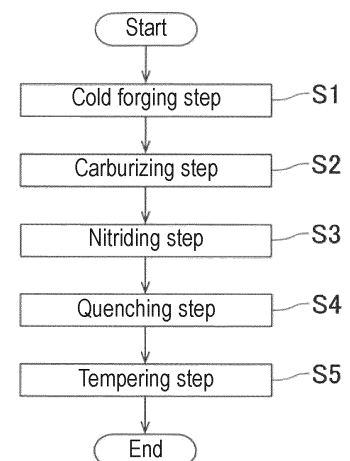
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(54) **METHOD FOR PRODUCING STEEL MEMBER**

(57) This method for producing a steel member includes: a carburizing step of causing carbon to infiltrate into a steel member in an austenitized state by heating the steel member to a temperature equal to or higher than an austenitic transformation completion temperature, at a carbon concentration at which the steel member and the carbon have a hypoeutectoid composition, and removing cold from the steel member in which the carbon has been caused to infiltrate; and a quenching step of, after the carburizing step, heating the steel member again to a temperature equal to or higher than the austenitic transformation completion temperature, and rapidly cooling the steel member that has been heated.

FIG. 1



Description

TECHNICAL FIELD

[0001] The present invention relates to a method for producing a steel member.

BACKGROUND ART

[0002] Conventionally, there is a known method for producing a steel member including a carburizing step of causing carbon to infiltrate into a steel member in an austenitized state. Such a method for producing a steel member is disclosed in, for example, JP 2019-127624 A.

[0003] JP 2019-127624 A discloses a method for producing a steel member, and the method includes a carburizing step of causing carbon to infiltrate into a steel member in an austenitized state. In the method for producing a steel member described in JP 2019-127624 A, in the carburizing step, carbon is caused to infiltrate into the steel member in the austenitized state at a carbon concentration at which the steel member and carbon have a hypereutectoid composition.

CITATION LIST

PATENT LITERATURE

[0004] Patent Literature 1: JP 2019-127624 A

SUMMARY OF INVENTION

TECHNICAL PROBLEMS

[0005] However, in the production of the steel member described in JP 2019-127624 A, carbon is caused to infiltrate into the steel member in the austenitized state at the carbon concentration at which the steel member and carbon have a hypereutectoid composition. Thus, the concentration of carbon entering the steel member tends to be excessively high. Here, the hardness of a steel member is, in general, substantially proportional to a carbon concentration in a surface (carburized layer) of the steel member. In addition, the hardness of a steel member is, in general, substantially inversely proportional to the toughness of the steel member. That is, in the production of the steel member described in JP 2019-127624 A, the hardness of the steel member tends to be excessively high, and the toughness of the steel member tends to be excessively low. When the toughness of the steel member decreases, the steel member becomes weaker against impact. For this reason, a method for producing a steel member, capable of improving the hardness and the toughness of the steel member in a well-balanced manner is desired.

[0006] The present invention has been made to solve the above problems, and the present invention provides a method for producing a steel member, capable of im-

proving hardness and toughness of the steel member in a well-balanced manner.

SOLUTIONS TO PROBLEMS

[0007] In order to achieve the above, a method for producing a steel member according to one aspect of the present invention includes: a carburizing step of causing carbon to infiltrate into a steel member in an austenitized state by heating the steel member to a temperature equal to or higher than an austenitic transformation completion temperature, at a carbon concentration at which the steel member and the carbon have a hypoeutectoid composition, and slowly cooling the steel member in which the carbon has been caused to infiltrate; and a quenching step of, after the carburizing step, heating the steel member again to a temperature equal to or higher than the austenitic transformation completion temperature, and rapidly cooling the steel member that has been heated.

[0008] In the method for producing a steel member according to the one aspect of the present invention, in the carburizing step, the carbon is caused to infiltrate into the steel member in the austenitized state at the carbon concentration at which the steel member and the carbon have the hypoeutectoid composition, as described above. Thus, the concentration of the carbon entering the steel member does not become excessively high, unlike a case in which carburizing is performed by causing carbon to infiltrate into a steel member in an austenitized state at a carbon concentration at which the steel member and carbon have a hypereutectoid composition. Therefore, the hardness of the steel member does not become excessively high, and the toughness of the steel member does not become excessively low. As a result, it is possible to improve the hardness and the toughness of the steel member in a well-balanced manner. Therefore, the improvement in hardness enables improvement in bending fatigue strength and the like, and the improvement in toughness enables improvement in strength against impact.

ADVANTAGEOUS EFFECTS OF INVENTION

[0009] According to the present invention, it is possible to provide a method for producing a steel member, capable of improving hardness and toughness of the steel member in a well-balanced manner, as described above.

BRIEF DESCRIPTION OF DRAWINGS

[0010]

FIG. 1 is a diagram showing a flow of production of a steel member according to an embodiment of the present invention.

FIG. 2 is a diagram showing a change in temperature of a steel member in a method for producing a steel

member according to the embodiment of the present invention.

FIG. 3 is a phase diagram of S20C as an example of a steel member.

FIG. 4 is a diagram showing a change in temperature of a steel member in a method for producing a steel member according to Comparative Example 1.

FIG. 5 is a diagram showing a change in temperature of a steel member in a method for producing a steel member according to Comparative Example 2.

FIG. 6 is a diagram showing bending fatigue strength and toughness of a steel member in the method for producing a steel member according to the embodiment of the present invention, a steel member in a method for producing a steel member according to a first modification, a steel member in a method for producing a steel member according to a second modification, and a steel member in the method for producing a steel member according to Comparative Example 1.

FIG. 7 is a diagram showing bending fatigue strength of the steel member in the method for producing a steel member according to the embodiment of the present invention, the steel member in the method for producing a steel member according to the first modification, and a steel member in the method for producing a steel member according to Comparative Example 2.

FIG. 8 is a diagram showing torsional fatigue strength of a steel member in the method for producing a steel member according to the embodiment of the present invention, a steel member in the method for producing a steel member according to the first modification, and a steel member in a method for producing a steel member according to Comparative Example 3.

FIG. 9 is a diagram showing surface hardness, surface hardened layer depth, carbon concentration in a surface, and the like of each of the steel member in the method for producing a steel member according to the embodiment of the present invention, the steel member in the method for producing a steel member according to the first modification, and the steel member in the method for producing a steel member according to Comparative Example 2.

FIG. 10 is a diagram showing grain boundary oxidation depth and average crystal grain size of each of the steel member in the method for producing a steel member according to the embodiment of the present invention and the steel member in the method for producing a steel member according to Comparative Example 2.

DESCRIPTION OF EMBODIMENT

[0011] Hereinafter, an embodiment of the present invention will be described with reference to the drawings.

[Method for producing steel member]

[0012] A method for producing a steel member according to the embodiment of the present invention will be described with reference to FIGS. 1 to 3. Note that the method for producing a steel member according to the embodiment of the present invention can be applied to, for example, a steel member such as a gear, a bearing, or a shaft.

(Cold forging step)

[0013] First, as shown in FIG. 1, in step S 1, a cold forging step is performed. The cold forging step (S1) is a step of forging a steel member at ordinary temperature to have a desired shape (for example, a shape of a gear, a bearing, a shaft, or the like). For the steel member, case-hardening steel (for example, SCM420) for allowing a hardened layer to be generated by performing heat treatment or the like on a surface is used.

(Carburizing step)

[0014] Next, in step S2, a carburizing step is performed. As shown in FIG. 2, the carburizing step (S2) is a step of causing carbon to infiltrate into the steel member in an austenitized state by heating the steel member to a temperature T1 (for example, about 1000°C) equal to or higher than an austenitic transformation completion temperature A3, and slowly cooling the steel member in which carbon has been caused to infiltrate. As shown in FIG. 3, the steel member in an austenitized state is a steel member including austenite (γ -iron). The austenitic transformation completion temperature A3 is a temperature at which austenitic transformation of the steel member is completed by heating the steel member. Specifically, as shown in FIG. 2, the steel member is placed in a first heat treatment chamber, and then the steel member is heated to the temperature T1 such that the steel member is brought into an austenitized state. Subsequently, in a state where the steel member is held at the temperature T1 (that is, a state where the steel member is austenitized), a carburizing gas (for example, C_2H_2) is introduced into the first heat treatment chamber. Thereafter, the carburizing gas is decomposed on the surface of the steel member in the austenitized state, thereby generating carbon. Then, the generated carbon diffuses from the surface toward the inside of the steel member, whereby a carburized layer is formed in a surface layer portion of the steel member. Next, the steel member is slowly cooled such that the steel member becomes pearlitic. The slow cooling of the steel member is performed at a cooling rate at which the steel member becomes pearlitic. That is, the slow cooling of the steel member is performed at a cooling rate at which the steel member does not become martensitic. In addition, the slow cooling of the steel member is performed in an inert gas (for example, Ar, N_2 , He, or the like)

atmosphere in order to prevent formation of an oxide film on the steel member. Note that the carburizing step (S2) is performed while the inside of the first heat treatment chamber is depressurized by a vacuum pump.

[0015] As shown in FIG. 3, in the case of a carbon concentration at which the steel member and carbon have a hypoeutectoid composition (a concentration of lower than about 0.77%), the steel member is in a state of including ferrite (α -iron) and pearlite at a temperature lower than an austenitic transformation start temperature A1. In addition, in the case of a concentration lower than the carbon concentration at which the steel member and carbon have a hypoeutectoid composition, the steel member is in a state of including austenite (γ -iron) and ferrite (α -iron) at a temperature higher than the austenitic transformation start temperature A1 and lower than the austenitic transformation completion temperature A3. Further, in the case of a carbon concentration lower than the carbon concentration at which the steel member and carbon have a hypoeutectoid composition, the steel member is in a state of including austenite (γ -iron) at a temperature higher than the austenitic transformation completion temperature A3.

[0016] As shown in FIG. 2, in the carburizing step (S2), carbon is caused to infiltrate into the steel member in the austenitized state at the carbon concentration at which the steel member and carbon have a hypoeutectoid composition. Specifically, as the carburizing gas is continuously introduced into the first heat treatment chamber, the carbon concentration in the surface (carburized layer) of the steel member increases. Then, a time during which the carburizing gas is introduced is adjusted such that a carbon concentration in the surface (carburized layer) of the steel member is lower than a carbon concentration at which the steel member and carbon have a eutectoid composition (for example, about 0.77% in a case where the steel member is SCM420, which is a case-hardening steel). Here, the hardness of the steel member is, in general, substantially proportional to a carbon concentration in the surface (carburized layer) of the steel member. In addition, the hardness of the steel member is, in general, substantially inversely proportional to the toughness of the steel member. Thus, with this carburizing, the concentration of carbon entering the steel member does not become excessively high, unlike a case in which carburizing is performed by causing carbon to infiltrate into a steel member in an austenitized state at a carbon concentration at which the steel member and carbon have a hypereutectoid composition (a concentration of about 0.77% or higher). Therefore, the hardness of the steel member does not become excessively high, and the toughness of the steel member does not become excessively low. As a result, it is possible to improve the hardness and the toughness of the steel member in a well-balanced manner. Therefore, the improvement in hardness enables improvement in bending fatigue strength and the like, and the improvement in toughness enables improvement in strength against im-

pact.

(Nitriding step)

[0017] Next, as shown in FIG. 1, in step S3, a nitriding step is performed. As shown in FIG. 2, the nitriding step (S3) is a step of causing nitrogen to infiltrate into the steel member in a state where the steel member is heated to a temperature T2 (for example, about 810°C) lower than the austenitic transformation completion temperature A3. Specifically, the steel member is placed in a second heat treatment chamber. Then, the steel member brought into a state of being pearlitic in the carburizing step (S2) is heated to the temperature T2. At this time, the steel member is in a state where ferrite (α -iron) and austenite (γ -iron) are mixed. Then, in a state where the steel member is held at the temperature T2 (that is, a state where ferrite (α -iron) and austenite (γ -iron) are mixed in the steel member), a predetermined amount (for example, 0.8 m³/h) of a nitriding gas (for example, NH₃) is introduced into the second heat treatment chamber. Then, the nitriding gas is decomposed on the surface of the steel member, thereby generating nitrogen. Then, the generated carbon diffuses from the surface toward the inside of the steel member, whereby nitrogen enters the carburized layer in the surface layer portion of the steel member to form a carbonitrided layer. Note that the nitriding step (S3) is performed while the carbon concentration inside the second heat treatment chamber is adjusted such that the carbon concentration in the carburized layer does not decrease. Here, the amount of nitrogen entering the surface layer portion of the steel member is, in general, substantially inversely proportional to the temperature of the steel member at a temperature equal to or higher than the austenitic transformation start temperature A1 (described later). In addition, when nitrogen is caused to enter the carburized layer in the surface layer portion of the steel member, in general, voids are more likely to be generated in the steel member as the carbon concentration in the carburized layer increases. Moreover, in general, a grain boundary oxidation layer is more likely to be formed on the steel member as the temperature of the steel member increases. Further, the hardness of the steel member is improved as the amount of nitrogen entering the surface layer portion of the steel member increases. Thus, with this nitriding, it is possible to increase the amount of nitrogen entering the steel member and it is possible to reduce generation of voids or formation of a grain boundary oxidation layer in the steel member, as compared with a case in which nitriding is performed by causing nitrogen to infiltrate into the steel member in a state where the steel member is heated to a temperature T3 (for example, about 850°C) equal to or higher than the austenitic transformation completion temperature A3. As a result, it is possible to effectively improve the hardness of the steel member, and thus it is possible to ensure sufficient hardness of the steel member even when the hardness of

the steel member decreases by the amount equivalent to the improvement in the toughness of the steel member made in the carburizing step (S2).

[0018] In the nitriding step (S3), a time during which the nitriding gas is introduced and the amount of the nitriding gas are adjusted such that a nitrogen concentration in the surface (carbonitrided layer) of the steel member becomes a predetermined concentration. That is, the nitriding step (S3) is a step of causing nitrogen to infiltrate into the steel member such that a nitrogen concentration in the surface of the steel member becomes the predetermined concentration. The predetermined concentration is about 0.5% or lower, as a minimum requirement. The predetermined concentration is preferably about 0.05% or higher and 0.35% or lower. Thus, the nitriding can be performed to improve the hardness and the toughness of the steel member in a well-balanced manner.

[0019] The nitriding step (S3) is a step of causing nitrogen to infiltrate into the steel member at the temperature T2 (for example, about 810°C) equal to or higher than the austenitic transformation start temperature A1 and lower than the austenitic transformation completion temperature A3. The austenitic transformation start temperature A1 is a temperature at which austenitic transformation of the steel member starts. Here, in a case where nitriding is performed by causing nitrogen to infiltrate into the steel member at a temperature lower than the austenitic transformation start temperature A1, the amount of nitrogen entering the steel member, in general, significantly decreases, as compared with a case where nitriding is performed by causing nitrogen to infiltrate into the steel member at a temperature equal to or higher than the austenitic transformation start temperature A1. Thus, with the nitriding of the nitriding step (S3), it is possible to increase the amount of nitrogen entering the steel member, as compared with a case in which nitriding is performed by causing nitrogen to infiltrate into the steel member at the temperature lower than the austenitic transformation start temperature A1.

[0020] As described above, in step S1, the cold forging step has been performed. That is, the carburizing step (S2) is performed on the steel member that has been cold forged. Thus, in the carburizing step (S2), the steel member is heated and slowly cooled, whereby residual stress generated in the steel member by the cold forging can be removed from the steel member. As a result, it is possible to reduce coarsening of crystal grains of the steel member caused due to the residual stress, in the subsequent step (quenching step (S4) or the like to be described later). That is, it is possible to reduce a decrease in strength of the steel member caused due to the coarsening of the crystal grains. In addition, it is possible to reduce the coarsening of the crystal grains, to reduce an increase in dimensional change for each portion of the steel member in the subsequent step. Further, it is possible to use a case-hardening steel (for example, SCM420) generally used as a steel member, without using a special steel member to which Nb, Ti, V, or the

like is added in order to reduce occurrence of the coarsening of the crystal grains in the cold-forged steel member.

5 (Quenching step)

[0021] Next, as shown in FIG. 1, in step S4, a quenching step is performed. As shown in FIG. 2, the quenching step (S4) is a step of heating the steel member again to the temperature T3 (for example, about 850°C) equal to or higher than the austenitic transformation completion temperature A3, and rapidly cooling the steel member that has been heated. Specifically, the steel member is placed in the second heat treatment chamber. Then, the steel member is heated again to the temperature T3 such that the steel member is austenitized. Then, after a state in which the steel member is held at the temperature T3 (that is, a state in which the steel member is austenitized) is maintained for a while, the steel member is conveyed from the heat treatment chamber to the inside of a cooling apparatus, and the steel member is rapidly cooled such that the steel member becomes martensitic. The rapid cooling of the steel member is performed at a cooling rate at which the steel member becomes martensitic. That is, the rapid cooling of the steel member is performed at a cooling rate at which the steel member does not become pearlitic. In addition, the rapid cooling of the steel member is performed by using water or oil.

[0022] The quenching step (S4) is a step of, immediately after the nitriding step (S3), heating the steel member from the temperature T2 (for example, about 810°C) lower than the austenitic transformation completion temperature A3 to the temperature T3 (for example, about 850°C) equal to or higher than the austenitic transformation completion temperature A3, and rapidly cooling the steel member that has been heated. That is, the nitriding step (S3) and the quenching step (S4) are continuously performed in this order. Thus, the steel member in a state of being heated to the temperature T2 (for example, about 810°C) lower than the austenitic transformation completion temperature A3 in the nitriding step (S3) only needs to be heated from the temperature T2 (for example, about 810°C) to the temperature T3 (for example, about 850°C) equal to or higher than the austenitic transformation completion temperature A3. Therefore, it is possible to reduce consumption energy in heating of the steel member as compared with a case in which the quenching step (S4) is not performed immediately after the nitriding step (S3).

50 (Tempering step)

[0023] Next, as shown in FIG. 1, in step S5, a tempering step is performed. The tempering step (S5) is a step of reheating and cooling the martensitic steel member. Thus, the steel member in a state where the hardness is temporarily excessively increased and the toughness is temporarily excessively decreased by being martensi-

tic is tempered, whereby the steel member is brought into a state of having appropriate fatigue strength and toughness.

[Examples]

[0024] With reference to FIGS. 4 to 10, examples of the method for producing a steel member according to the above embodiment will be described while comparison is performed with a method for producing a steel member according to Comparative Example 1 and a method for producing a steel member according to Comparative Example 2.

(Production of steel member according to above embodiment)

[0025] On the basis of the method for producing a steel member according to the above embodiment, a steel member was produced such that the steel member was formed as a gear (Example 1). Specifically, first, a cold forging step of performing cold forging on the steel member was performed. For the steel member, SCM420, which is a case-hardening steel, was used. Then, a carburizing step of causing carbon to infiltrate into the steel member in an austenitized state by heating the steel member to the temperature T1 (1000°C) equal to or higher than the austenitic transformation completion temperature A3, and slowly cooling the steel member in which carbon was caused to infiltrate was performed. In the carburizing step, carbon was caused to infiltrate into the steel member in the austenitized state at a carbon concentration at which the steel member and carbon had a hypoeutectoid composition (a concentration of lower than 0.77%). The carburizing step was performed while the inside of the first heat treatment chamber was depressurized by a vacuum pump. Then, a nitriding step of causing nitrogen to infiltrate into the steel member in a state where the steel member was heated to the temperature T2 (810°C) lower than the austenitic transformation completion temperature A3 was performed. Next, immediately after the nitriding step, a quenching step of heating the steel member again to the temperature T3 (850°C) equal to or higher than the austenitic transformation completion temperature A3, and rapidly cooling the heated steel member was performed. Then, a tempering step of reheating and cooling the martensitic steel member was performed.

(Production of steel members according to first modification and second modification)

[0026] As a first modification of the above embodiment, a steel member was produced by omitting the nitriding step from the method for producing a steel member according to the above embodiment (Example 2). In addition, as a second modification of the above embodiment, a steel member was produced by omitting the

nitriding step from the method for producing a steel member according to the above embodiment, and by replacing the case-hardening steel, which is used for the steel member in the method for producing a steel member according to the above embodiment, with a sintered material (Example 3).

(Production of other steel members according to above embodiment and first modification)

[0027] On the basis of the method for producing a steel member according to the above embodiment, a steel member was produced such that the steel member was formed as a shaft (Example 4). In addition, on the basis of the method for producing a steel member according to the first modification, a steel member was produced such that the steel member was formed as a shaft (Example 5).

(Production of steel member according to Comparative Example 1)

[0028] On the basis of a method for producing a steel member according to Comparative Example 1 shown in FIG. 4, a steel member was produced such that the steel member was formed as a gear. Specifically, first, a cold forging step was performed similarly to the method for producing a steel member according to the above embodiment. For the steel member, SCM420, which is a case-hardening steel, was used similarly to the method for producing a steel member according to the above embodiment. Then, similarly to the method for producing a steel member according to the above embodiment, a carburizing step of causing carbon to infiltrate into the steel member in an austenitized state by heating the steel member to the temperature T1 (1000°C) equal to or higher than the austenitic transformation completion temperature A3, and slowly cooling the steel member in which carbon was caused to infiltrate was performed. Unlike the method for producing a steel member according to the above embodiment, in the carburizing step, on the way of the slow cooling of the steel member, the steel member was maintained in a state of being held at a temperature T4 (710°C) lower than the austenitic transformation start temperature A1 for a predetermined time such that only part of austenite was transformed into pearlite. That is, a state in which the steel member is at a higher temperature (a state in which the steel member is not at ordinary temperature) is longer than that in the method for producing a steel member according to the above embodiment by a time during which the steel member is maintained in the state of being held at the temperature T4 (710°C). In addition, unlike the method for producing a steel member according to the above embodiment, in the carburizing step, carbon was caused to infiltrate into the steel member in the austenitized state at a carbon concentration (0.77% or higher) at which the steel member and carbon had a hypereutectoid compo-

sition. Note that the carburizing step was performed while the inside of a heat treatment chamber was depressurized by a vacuum pump, similarly to the method for producing a steel member according to the above embodiment. Then, a quenching step of rapidly cooling the steel member after the steel member was heated to the temperature T3 (850°C) equal to or higher than the austenitic transformation completion temperature A3 and the steel member was maintained for a while at the temperature T3 (850°C) was performed. Note that in the quenching step, when a state in which the steel member was held at the temperature T3 (850°C) (that is, a state in which the steel member was austenitized) was maintained for a while, a nitriding step of causing nitrogen to infiltrate into the steel member was also performed. Then, a tempering step was performed similarly to the method for producing a steel member according to the above embodiment.

(Production of steel member according to Comparative Example 2)

[0029] On the basis of a method for producing a steel member according to Comparative Example 2 shown in FIG. 5, a steel member was produced such that the steel member was formed as a gear. Specifically, first, a cold forging step was performed similarly to the method for producing a steel member according to the above embodiment. For the steel member, SCM420, which is a case-hardening steel, was used similarly to the method for producing a steel member according to the above embodiment. Then, similarly to the method for producing a steel member according to the above embodiment, a carburizing step of causing carbon to infiltrate into the steel member in an austenitized state by heating the steel member to the temperature T1 (1000°C) equal to or higher than the austenitic transformation completion temperature A3, and slowly cooling the steel member in which carbon was caused to infiltrate was performed. Note that slow cooling in the carburizing step was performed until the temperature of the steel member reached the temperature T3 (850°C) for a quenching step. In addition, unlike the method for producing a steel member according to the above embodiment, in the carburizing step, carbon was caused to infiltrate into the steel member in an austenitized state at a carbon concentration (0.77%) at which the steel member and carbon had a eutectoid composition. Note that unlike the method for producing a steel member according to the above embodiment, the inside of a heat treatment chamber was not depressurized in the carburizing step. Then, after the steel member was maintained for a while at the temperature T3 (850°C) equal to or higher than the austenitic transformation completion temperature A3, a quenching step of rapidly cooling the steel member was performed. That is, unlike the method for producing a steel member according to the above embodiment, the quenching step was performed immediately after the

carburizing step without causing the steel member to be pearlitic after the carburizing step. Note that unlike the method for producing a steel member according to the above embodiment, a nitriding step was not performed. Then, a tempering step was performed similarly to the method for producing a steel member according to the above embodiment.

(Production of steel member according to Comparative Example 3)

[0030] As Comparative Example 3, a steel member was produced by replacing the gear, which was formed as the steel member in the method for producing a steel member according to Comparative Example 2, with a shaft.

(Test results on performance of steel members)

[0031] Hereinafter, the test results will be described on performance of the steel members (the steel member of Example 1 and the steel member of Example 4) using the method for producing a steel member according to the above embodiment, the steel members (the steel member of Example 2 and the steel member of Example 5) using the method for producing a steel member according to the first modification, the steel member (the steel member of Example 3) using the method for producing a steel member according to the second modification, the steel member (the steel member of Comparative Example 1) using the method for producing a steel member according to Comparative Example 1, the steel member (the steel member of Comparative Example 2) using the method for producing a steel member according to Comparative Example 2, and the steel member (the steel member of Comparative Example 3) using the method for producing a steel member according to Comparative Example 3.

[0032] As shown in FIG. 6, in each of the steel member of Example 1 (SCM (with nitriding) in the drawing), the steel member of Example 2 (SCM (without nitriding) in the drawing), and the steel member of Example 3 (sintered material (without nitriding) in the drawing), crack generation energy E_i (J/cm²) and bending fatigue strength σ (MPa) at the time of the impact test were higher than those of the steel member of Comparative Example 1 (SCM420 (Comparative Example 1) in the drawing). Specifically, the crack generation energy E_i of the steel member of Example 1 was higher than the crack generation energy E_i of the steel member of Comparative Example 1. The crack generation energy E_i of the steel member of Example 2 was higher than the crack generation energy E_i of the steel member. The crack generation energy E_i of the steel member of Example 3 was higher than the crack generation energy E_i of the steel member of Example 2. The bending fatigue strength σ of the steel member of Example 3 was higher than the bending fatigue strength σ of the steel member of Com-

parative Example 1. The bending fatigue strength σ of the steel member of Example 2 was higher than the bending fatigue strength σ of the steel member of Example 3. The bending fatigue strength σ of the steel member of Example 1 was higher than the bending fatigue strength σ of the steel member of Example 2. Note that the magnitude of the crack generation energy E_i at the time of the impact test is substantially proportional to the magnitude of toughness. In addition, the bending fatigue strength σ means the magnitude of strength against bending. The bending fatigue strength σ is, in general, substantially proportional to the hardness. The crack generation energy E_i at the time of the impact test was measured by the Charpy impact test. In addition, the bending fatigue strength σ was measured by the Ono-type rotary bending fatigue test.

[0033] As shown in FIG. 7, in each of the steel member of Example 1 (SCM (with nitriding) in the drawing) and the steel member of Example 2 (SCM (without nitriding) in the drawing), the bending fatigue strength σ (MPa) was higher than that of the steel member of Comparative Example 2 (SCM420 (Comparative Example 2) in the drawing).

[0034] As shown in FIG. 8, in each of the steel member of Example 4 (SCM (with nitriding) in the drawing) and the steel member of Example 5 (SCM (without nitriding) in the drawing), torque amplitude T_a (N·m) was larger than that of the steel member of Comparative Example 3 (SCM420 (Comparative Example 3) in the drawing). Note that the torque amplitude T_a is an index indicating torsional fatigue strength. The torque amplitude T_a was measured by a torsional fatigue test.

[0035] As shown in FIG. 9, surface hardness of the steel member of Comparative Example 2 (SCM420 (Comparative Example 2) in the drawing) was 760 HV, whereas surface hardness of the steel member of Example 1 (SCM (with nitriding) in the drawing) was 770 and surface hardness of the steel member of Example 2 (SCM (without nitriding) in the drawing) was 771. That is, each of the steel member of Example 1 and the steel member of Example 2 had surface hardness higher than that of the steel member of Comparative Example 2. Note that the surface hardness was measured by the Vickers hardness test based on JIS Z 2244.

[0036] A surface hardened layer depth of the steel member of Comparative Example 2 (SCM420 (Comparative Example 2) in the drawing) was 0.77 mm, whereas a surface hardened layer depth of the steel member of Example 1 (SCM (with nitriding) in the drawing) was 0.82 mm and a surface hardened layer depth of the steel member of Example 2 (SCM (without nitriding) in the drawing) was 0.80 mm. That is, each of the steel member of Example 1 and the steel member of Example 2 had a surface hardened layer depth larger than that of the steel member of Comparative Example 2.

[0037] A carbon concentration in the surface of the steel member of Comparative Example 2 (SCM420 (Comparative Example 2) in the drawing) was 0.70 wt%, whereas a carbon concentration in the surface of

the steel member of Example 1 (SCM (with nitriding) in the drawing) was 0.54 wt% and a carbon concentration in the surface of the steel member of Example 2 (SCM (without nitriding) in the drawing) was 0.57 wt%. That is, each of the steel member of Example 1 and the steel member of Example 2 had a carbon concentration in the surface significantly lower than that of the steel member of Comparative Example 2. This is considered to be because in the steel member of Comparative Example 2, carbon was, in the carburizing step, caused to infiltrate into the steel member in the austenitized state at the carbon concentration (0.77%) at which the steel member and carbon had the eutectoid composition, whereas in each of the steel member of Example 1 and the steel member of Example 2, carbon was, in the carburizing step, caused to infiltrate into the steel member in the austenitized state at the carbon concentration (lower than 0.77%) at which the steel member and carbon had the hypoeutectoid composition.

[0038] A total carburizing depth of the steel member of Example 1 (SCM (with nitriding) in the drawing), a total carburizing depth of the steel member of Example 2 (SCM (without nitriding) in the drawing), and a total carburizing depth of the steel member of Comparative Example 2 (SCM420 (Comparative Example 2) in the drawing) were all 1.4 mm. This is considered to be because in each of the steel member of Example 1, the steel portion of Example 2, and the steel member of Comparative Example 2, carbon was caused to infiltrate into the steel member in the austenitized state by heating the steel member to the temperature T_1 (1000°C).

[0039] A nitrogen concentration in the surface of the steel member of Example 1 (SCM (with nitriding) in the drawing) was 0.34 wt%. That is, in the steel member of Example 1, the nitrogen concentration in the surface was lower than the carbon concentration in the surface. In addition, a total nitriding depth of the steel member of Example 1 (SCM (with nitriding) in the drawing) was 0.3 mm. That is, in the steel member of Example 1, the total nitriding depth was smaller than the total carburizing depth in the surface.

[0040] As shown in FIG. 10, a grain boundary oxidation depth of the steel member of Comparative Example 2 (SCM420 (Comparative Example 2) in the drawing) was 14 μm , whereas a grain boundary oxidation depth of the steel member of Example 1 (SCM (with nitriding) in the drawing) was 5 μm . That is, the steel member of Example 1 had a grain boundary oxidation depth smaller than that of the steel member of Comparative Example 2. Thus, in the steel member of Example 1, the formation of the grain boundary oxidation layer in the production process was greatly reduced.

[0041] The minimum value (MIN in the drawing) of the crystal grain size of the steel member of Example 1 and the minimum value of the crystal grain size of the steel member of Comparative Example 2 were both 10 μm . On the other hand, the maximum value (MAX in the drawing)

of the crystal grain size of the steel member of Comparative Example 2 was 170 μm , whereas the maximum value of the crystal grain size of the steel member of Example 1 was 22 μm . Moreover, the average crystal grain size of the steel member of Comparative Example 2 was 38 μm , whereas the average crystal grain size of the steel member of Example 1 was 14 μm . That is, the steel member of Example 1 had an average crystal grain size smaller than that of the steel member of Comparative Example 2. Thus, in the steel member of Example 1, coarsening of the crystal grain size in the production process was greatly reduced.

[0042] As described above, the steel members of the examples (Examples 1 to 5) were shown to be relatively high in toughness, bending fatigue strength, surface hardness, surface hardened layer depth, and the like. Therefore, the method for producing a steel member according to the above embodiment, the method for producing a steel member according to the first modification of the above embodiment, and the method for producing a steel member according to the second modification of the above embodiment are suitable as a method for producing a steel member (for example, a gear, a bearing, a shaft, or the like) that is required to have both high hardness and high toughness.

[Modifications]

[0043] Note that it should be understood that the embodiment disclosed herein is illustrative in all respects and is not restrictive. The scope of the present invention is defined not by the description of the above embodiment but by the claims, and includes all changes (modifications) within the meaning and the scope equivalent to those of the claims.

[0044] For example, in the above embodiment, an example has been illustrated in which the carburizing step (S2) is performed on the cold-forged steel member. However, the present invention is not limited thereto. In the present invention, the carburizing step may be performed on a hot-forged steel member.

[0045] Further, in the above embodiment, an example has been illustrated in which the nitriding step (S3) is a step of causing nitrogen to infiltrate into the steel member at the temperature T2 that is equal to or higher than the austenitic transformation start temperature A1 and lower than the austenitic transformation completion temperature A3. However, the present invention is not limited thereto. In the present invention, the nitriding step may be a step of causing nitrogen to infiltrate into the steel member at a temperature lower than the austenitic transformation start temperature.

[0046] Further, in the above embodiment, an example has been illustrated in which the nitriding step (S3) is a step of causing nitrogen to infiltrate into the steel member in the state where the steel member is heated to the temperature T2 that is lower than the austenitic transformation completion temperature A3. However, the pre-

sent invention is not limited thereto. In the present invention, as in Comparative Example 1, the nitriding step may be a step of causing nitrogen to infiltrate into the steel member in a state where the steel member is heated to a temperature equal to or higher than the austenitic transformation completion temperature. In that case, as in Comparative Example 1, the nitriding step may be performed simultaneously with the heating in the quenching step.

[0047] Further, in the above embodiment, an example has been illustrated in which the nitriding step (S3) of causing nitrogen to infiltrate into the steel member is performed. However, the present invention is not limited thereto. In the present invention, as in the first modification and the second modification described above, the nitriding step of causing nitrogen to infiltrate into a steel member need not be performed.

[0048] Further, in the above embodiment, an example has been illustrated in which the case-hardening steel is used for the steel member. However, the present invention is not limited thereto. In the present invention, as in the second modification described above, a sintered material may be used for the steel member.

REFERENCE SIGNS LIST

[0049] A1: Austenitic transformation start temperature, A3: Austenitic transformation completion temperature, T1, T3: Temperature (equal to or higher than austenitic transformation completion temperature), and T2: Temperature (lower than austenitic transformation completion temperature)

Claims

1. A method for producing a steel member comprising:

a carburizing step of causing carbon to infiltrate into a steel member in an austenitized state by heating the steel member to a temperature equal to or higher than an austenitic transformation completion temperature, at a carbon concentration at which the steel member and the carbon have a hypoeutectoid composition, and slowly cooling the steel member in which the carbon has been caused to infiltrate; and a quenching step of, after the carburizing step, heating the steel member again to a temperature equal to or higher than the austenitic transformation completion temperature, and rapidly cooling the steel member that has been heated.

2. The method for producing a steel member according to claim 1, further comprising a nitriding step of, after the carburizing step and before the quenching step, causing nitrogen to infiltrate into the steel member in a state where the steel member is heated to a tem-

perature lower than the austenitic transformation completion temperature.

3. The method for producing a steel member according to claim 2, wherein the quenching step is a step of, immediately after the nitriding step, heating the steel member from the temperature lower than the austenitic transformation completion temperature to the temperature equal to or higher than the austenitic transformation completion temperature, and rapidly cooling the steel member that has been heated.
4. The method for producing a steel member according to claim 2, wherein the nitriding step is a step of causing the nitrogen to infiltrate into the steel member at a temperature equal to or higher than an austenitic transformation start temperature and lower than the austenitic transformation completion temperature.
5. The method for producing a steel member according to claim 2, wherein the nitriding step is a step of causing the nitrogen to infiltrate into the steel member such that a nitrogen concentration in a surface of the steel member is 0.5% or lower.
6. The method for producing a steel member according to claim 1, wherein the carburizing step is performed on the steel member that has been cold forged.

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FIG. 1

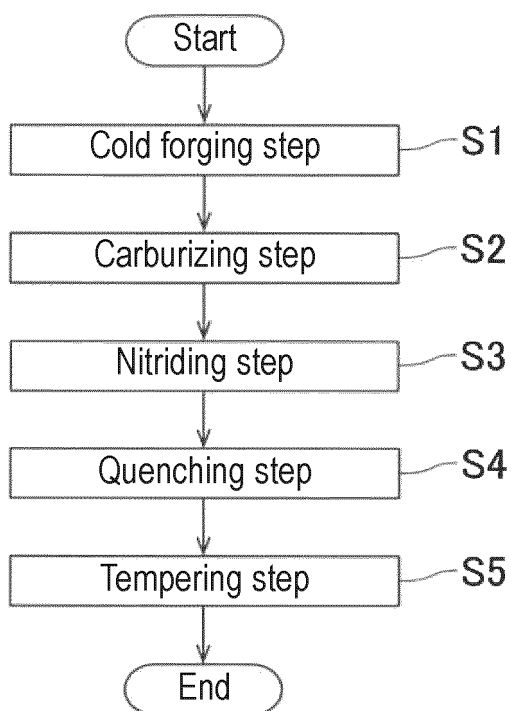


FIG. 2

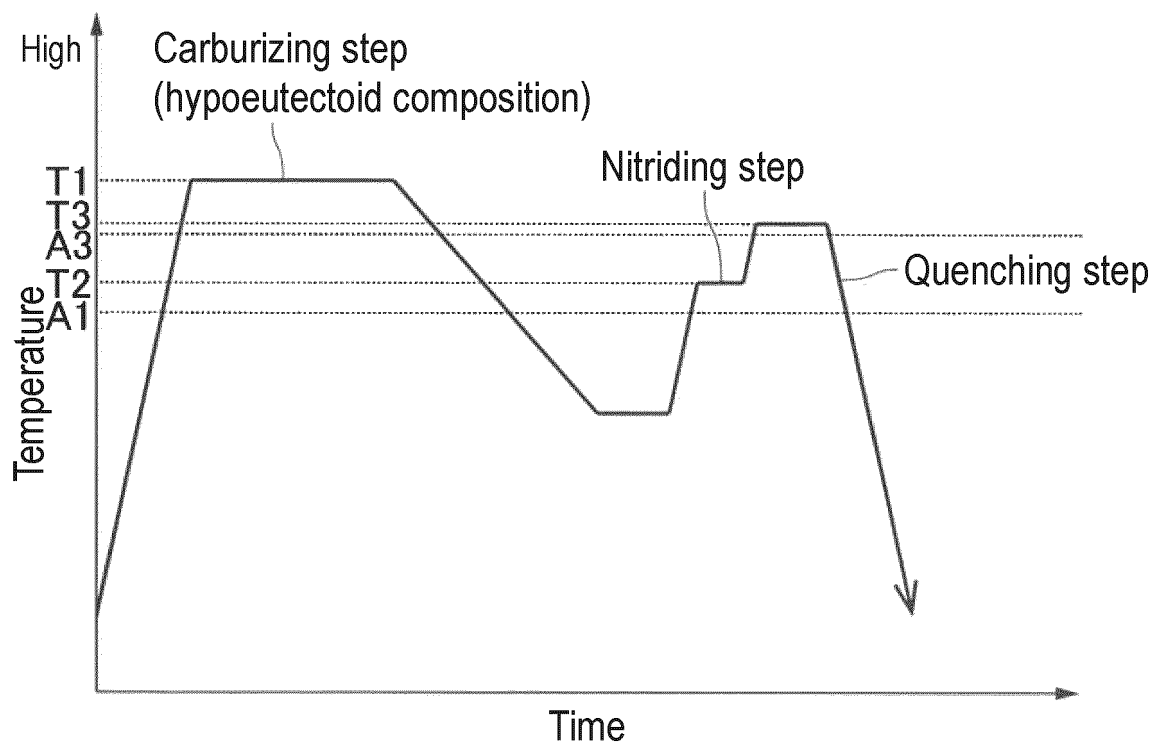


FIG. 3

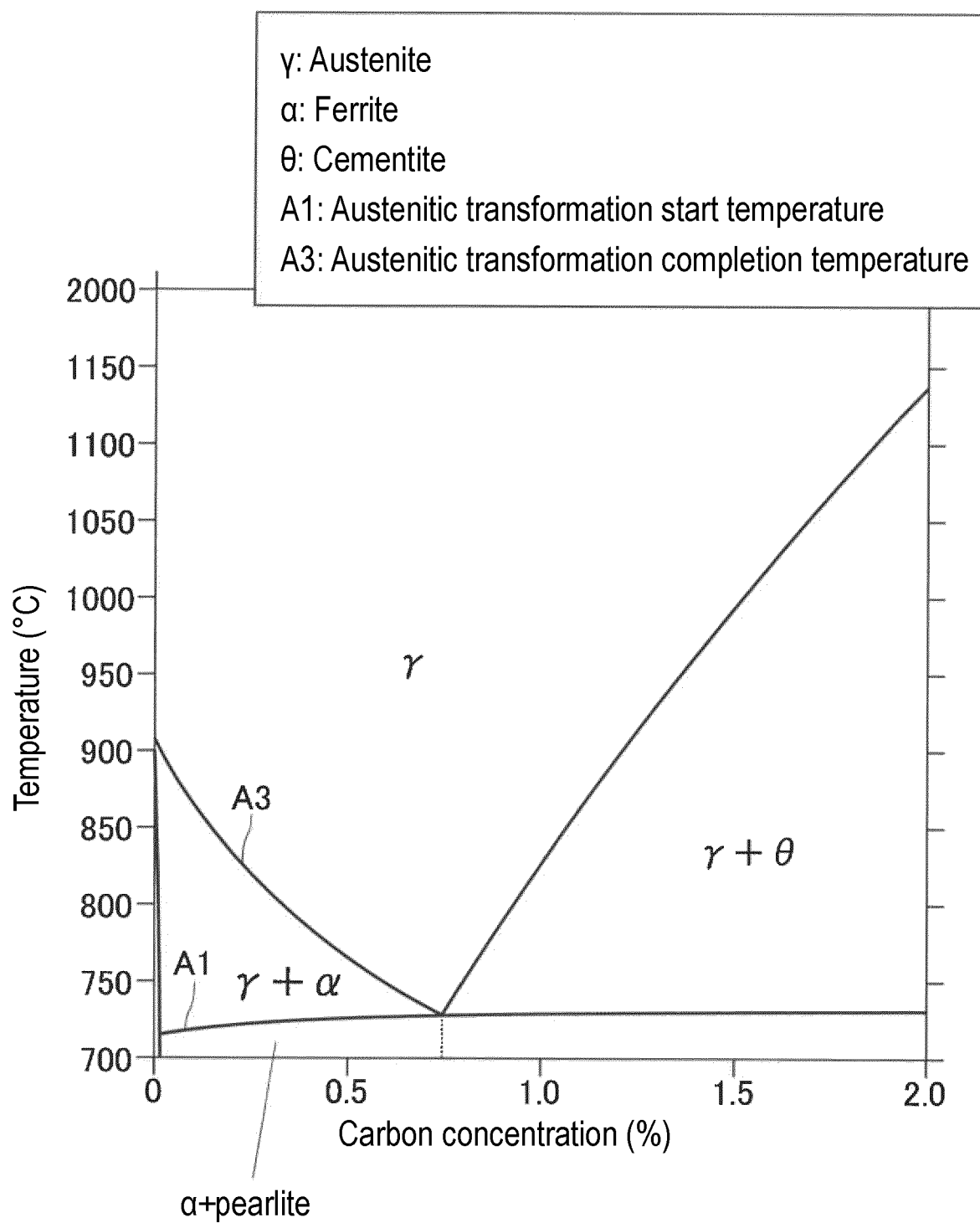


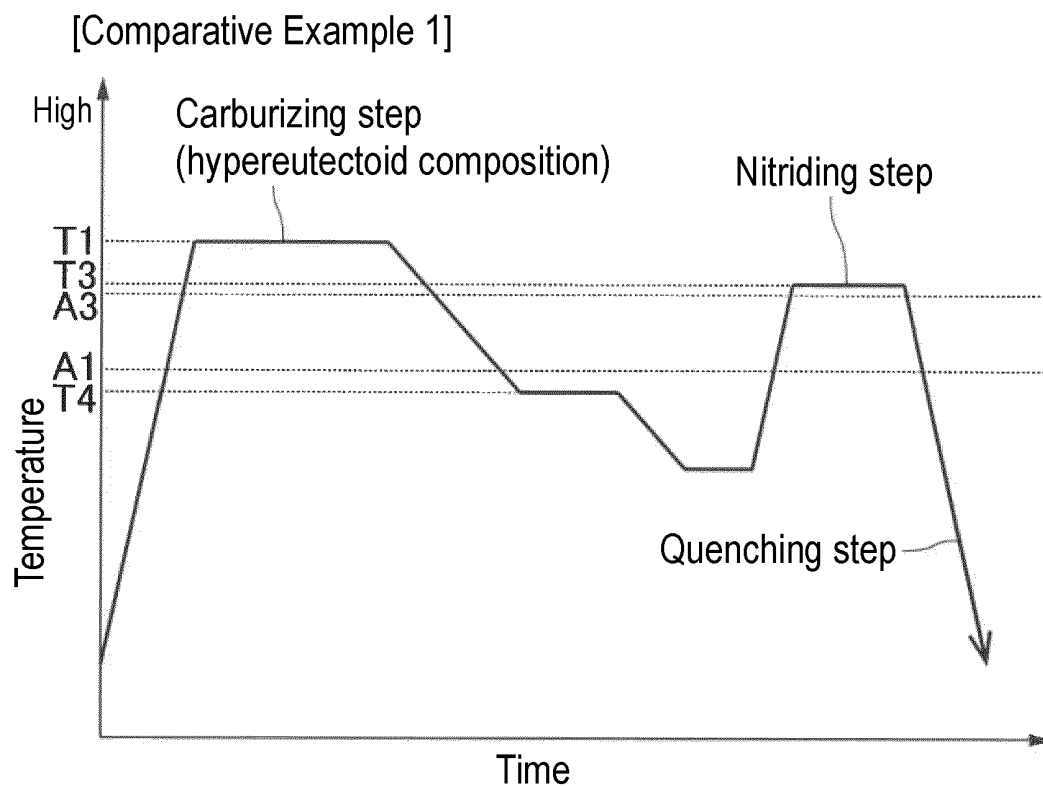
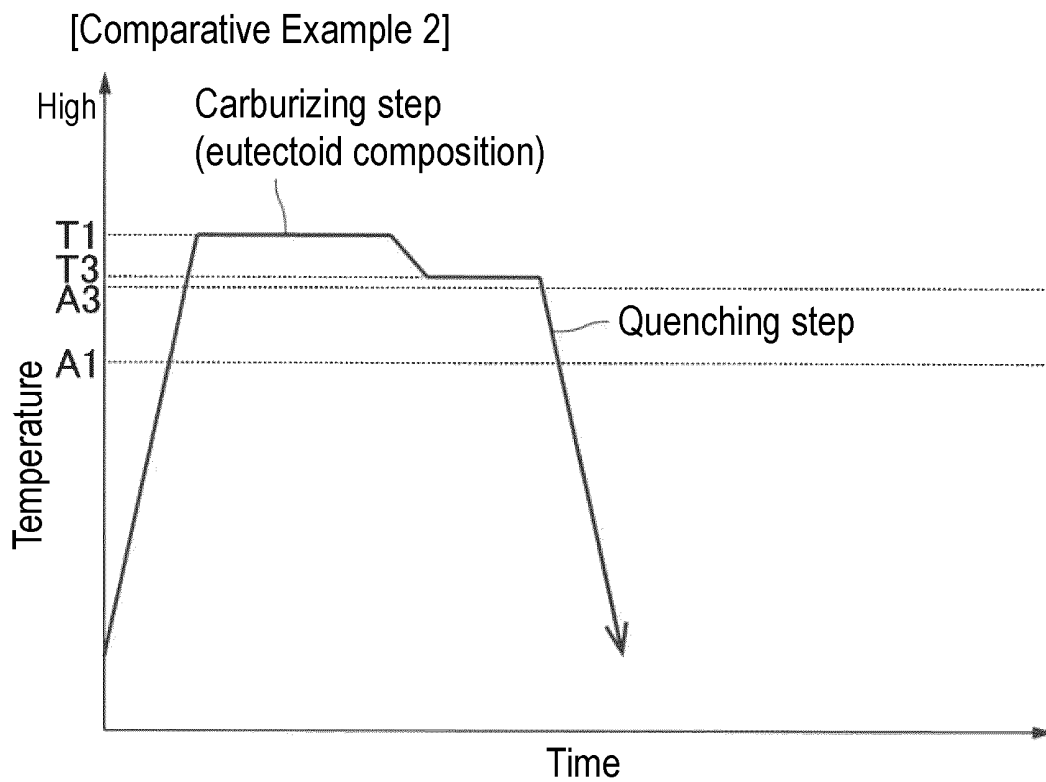
FIG. 4**FIG. 5**

FIG. 6

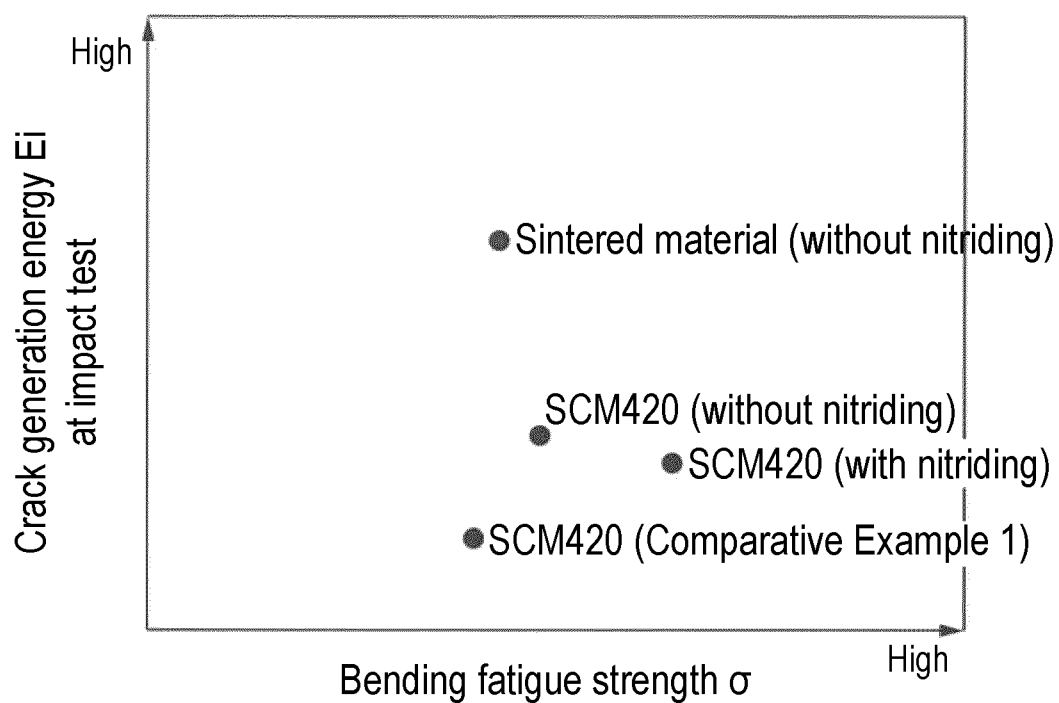


FIG. 7

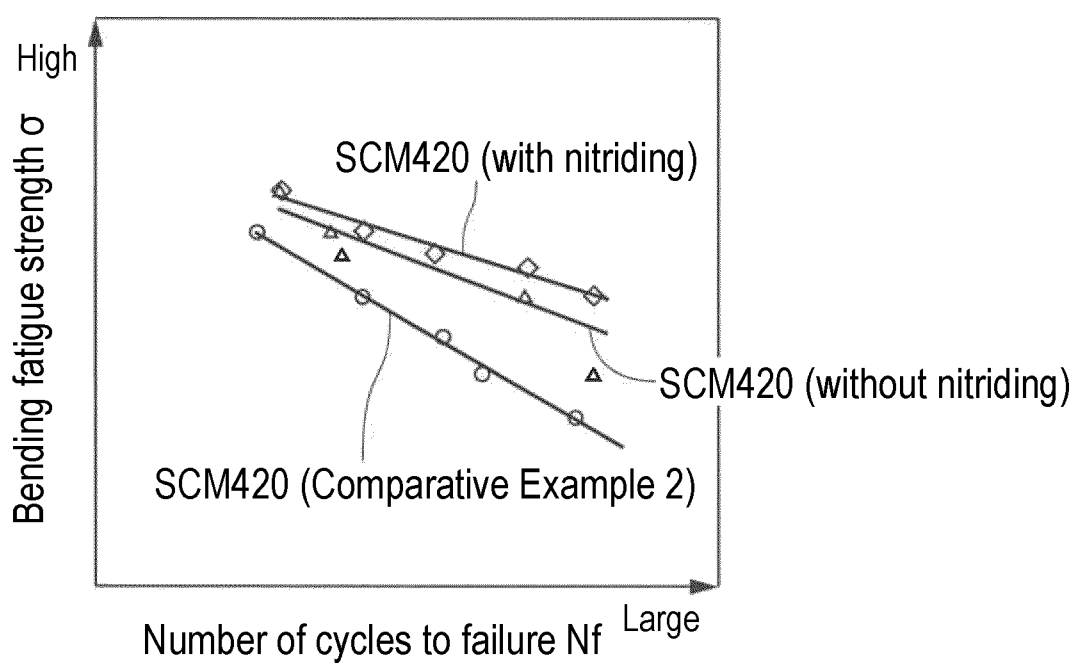
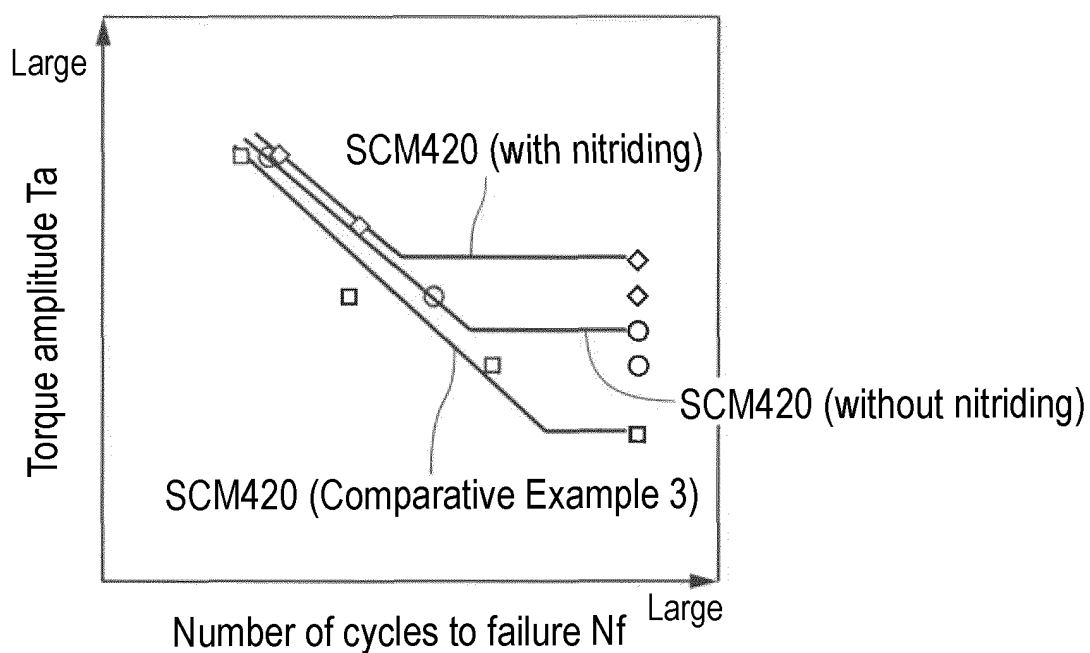


FIG. 8**FIG. 9**

	SCM420 (with nitriding)	SCM420 (without nitriding)	SCM420 (Comparative Example 2)
Surface hardness (HV)	770	771	760
Surface hardened layer depth (mm)	0.82	0.80	0.77
Carbon concentration in surface (wt%)	0.54	0.57	0.70
Total carburizing depth (mm)	1.4	1.4	1.4
Nitrogen concentration in surface (wt%)	0.34		
Total nitriding depth (mm)	0.3		

FIG. 10

	Grain boundary oxidation depth (μm)	Average crystal grain size (μm)
SCM420 (with nitriding)	5	14 (MIN: 10 to MAX: 22)
SCM420 (Comparative Example 2)	14	38 (MIN: 10 to MAX: 170)

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2023/001183

A. CLASSIFICATION OF SUBJECT MATTER

C21D 9/28(2006.01)i; **C21D 9/32**(2006.01)i; **C21D 9/40**(2006.01)i; **C21D 1/06**(2006.01)i; **C23C 8/22**(2006.01)i;
C23C 8/26(2006.01)i; **C23C 8/34**(2006.01)i

FI: C21D1/06 A; C23C8/26; C23C8/34; C21D9/32 A; C21D9/40 A; C21D9/28 A; C23C8/22

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)

C21D9/28; C21D9/32; C21D9/40; C21D1/06; C23C8/22; C23C8/26; C23C8/34

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.
X	WO 2009/131202 A1 (AISIN AW CO., LTD.) 29 October 2009 (2009-10-29) claims 1, 2, paragraphs [0002], [0016], [0027], [0051]-[0053], table 2, examples 1-2 of the present invention	1
Y	claims 1, 2, paragraphs [0002], [0016], [0027], [0051]-[0053], table 2, examples 1-2 of the present invention	6
Y	JP 10-99937 A (NISSAN MOTOR CO LTD) 21 April 1998 (1998-04-21) paragraph [0005]	6
X	JP 2017-137518 A (AISIN AW CO., LTD.) 10 August 2017 (2017-08-10) claims 1, 8, paragraphs [0004], [0053], fig. 2, 5	1
A	WO 2005/068862 A1 (NTN CORPORATION) 28 July 2005 (2005-07-28) paragraphs [0004], [0007], [0016], [0019], [0044]	1-6

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

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"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

17 March 2023

Date of mailing of the international search report

28 March 2023

Name and mailing address of the ISA/JP

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Authorized officer

Telephone No.

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2023/001183

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JP 10-99937 A	21 April 1998	(Family: none)	
JP 2017-137518 A	10 August 2017	(Family: none)	
WO 2005/068862 A1	28 July 2005	US 2007/0169850 A1 paragraphs [0007], [0010], [0023], [0033], [0054] EP 1710458 A1 CN 1910379 A	

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

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP 2019127624 A [0002] [0003] [0004] [0005]