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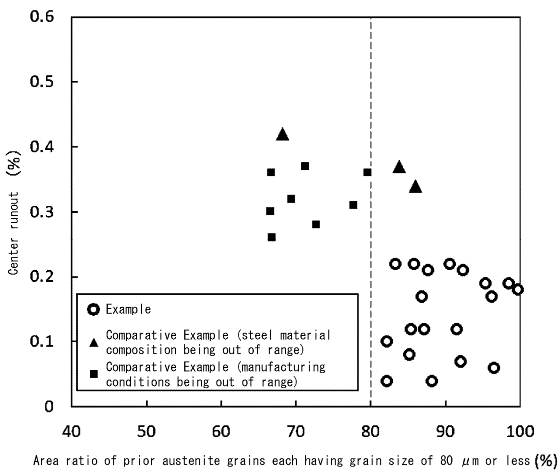
(54) MECHANICAL STRUCTURAL PART AND METHOD FOR MANUFACTURING SAME

(57) It is provided a mechanical structural part and a method of manufacturing the same. The mechanical structural part comprises a chemical composition containing C: 0.45 % to 0.51 %, Si: 0.15 % to 0.35 %, Mn: 0.60 % to 0.90 %, P: 0.030 % or less, S: 0.025 % or less, Al: 0.040 % to 0.059 %, Cr: 0.10 % to 0.50 %, and N: 0.0060 % to 0.0100 %, with the balance being Fe and inevitable impurities, and a hardened layer by induction hardening and tempering treatment, wherein an area ratio of crystal grains each having a prior austenite grain size of 80 μm or less in the hardened layer is 80 % or more, and a number ratio of grains each having a grain size twice or more than a mode of grain size in the hardened layer is 5 % or less.

FIG. 1



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Description

TECHNICAL FIELD

[0001] This disclosure relates to a mechanical structural part having a hardened layer by induction hardening and tempering treatment, which is used in the fields of construction industrial machinery and automobiles, in particular, a mechanical structural part having a shaft-shaped portion, and a method for manufacturing the same.

BACKGROUND

[0002] Alloy steels for mechanical structural use, such as JIS standard SCr420 and SCM420, are used for power transmission parts such as drive shafts and axle shafts used in automobiles, construction machinery, etc. The outline of the method for manufacturing this type of parts is as follows. That is, a steel bar or wire rod using the alloy steel for mechanical structural use as material is roughly formed into a part shape by hot forging and/or cold forging, and then finely formed by cutting work. The formed body is then subjected to surface hardening treatment, such as induction hardening and tempering treatment (induction heat treatment) or carburizing-quenching and tempering treatment (carburizing heat treatment) to be a product. Induction heat treatment and carburizing heat treatment harden the target member using transformation of steel microstructure, by heating and holding at 900 °C or more and then cooling the target member. Therefore, heat treatment strain is generated due to the transformation of steel microstructure during heating. In particular, for parts with a large aspect ratio, such as shafts and other parts with shaft-shaped portions, the eccentricity of the parts due to strain cannot be ignored, and the correction process is required according to the degree of eccentricity, leading to increased costs.

[0003] To address these problems, for example, techniques disclosed in PTLs 1-5 have been proposed. That is, JPS61-261427A (PTL 1) proposes a method for manufacturing steel in which the coarsening of austenite grains is suppressed by precipitating AlN, thereby reducing the heat treatment strain during carburizing heat treatment.

[0004] JPH08-199316A (PTL 2) proposes controlling the size and precipitation density of AlN by controlling the cooling speed in the specified temperature range after hot working, thereby reducing the heat treatment strain during carburizing heat treatment.

[0005] JP2004-204263A (PTL 3) proposes a steel in which decarburization is reduced by controlling the post-casting heating and hot rolling temperatures, thereby reducing coarse grain generation and heat treatment strain during carburizing heat treatment, and a method for manufacturing the same.

[0006] JP2006-265703A (PTL 4) proposes a steel in which coarse grain generation and heat treatment strain during carburizing heat treatment are reduced by controlling TiN precipitation by adding Ti and the finishing temperature of hot rolling, and a method for manufacturing the same.

[0007] JP2013-151719A (PTL 5) proposes suppressing the occurrence of nonuniform martensite transformation by controlling the variation of martensite transformation temperature in the longitudinal cross section of a steel bar, thereby reducing the heat treatment strain generated during carburizing-quenching or carbonitriding-quenching.

CITATION LIST

Patent Literature

[0008]

PTL 1: JPS61-261427A
PTL 2: JPH08-199316A
PTL 3: JP2004-204263A
PTL 4: JP2006-265703A
PTL 5: JP2013-151719A

SUMMARY

(Technical Problem)

[0009] Here, comparing carburizing heat treatment and induction heat treatment, the strain generated after heat treatment is larger in carburizing heat treatment. Therefore, reducing strain after carburizing heat treatment is conventionally emphasized. Therefore, the techniques disclosed in PTLs 1-5 are effective in reducing the strain generated by carburizing heat treatment, but they are not sufficient to reduce the smaller strains generated by induction heat treatment.

[0010] This disclosure was made in consideration of the above situation, and it could be helpful to provide a mechanical structural part in which the problem of eccentricity in, in particular, a part with a large aspect ratio having a shaft-shaped portion has been resolved, by reducing strain after induction heat treatment.

(Solution to Problem)

[0011] The inventors investigated the effects of steel material composition and steel material manufacturing conditions on strain after induction heat treatment in order to reduce strain in members after induction heat treatment. As a result, the inventors found that the following (a) and (b) are important for strain reduction after induction heat treatment.
(a) To reduce the variation of prior austenite grain size in the hardened layer after induction heat treatment. (b) In the hardened layer after induction heat treatment, to cause prior austenite grains with smaller grain size to occupy a large area.
[0012] This disclosure is based on the aforementioned findings and primary features thereof are described below.

1. A mechanical structural part comprising:

    a chemical composition containing (consisting of), in mass%,
    C: 0.45 % to 0.51 %,
    Si: 0.15 % to 0.35 %,
    Mn: 0.60 % to 0.90 %,
    P: 0.030 % or less,
    S: 0.025 % or less,
    Al: 0.040 % to 0.059 %,
    Cr: 0.10 % to 0.50 %, and
    N: 0.0060 % to 0.0100 %,

    with the balance being Fe and inevitable impurities, and
    a hardened layer by induction hardening and tempering treatment, wherein an area ratio of crystal grains each having a prior austenite grain size of 80 μm or less in the hardened layer is 80 % or more, and a number ratio of grains each having a grain size twice or more than a mode of grain size in the hardened layer is 5 % or less.

2. The mechanical structural part according to 1. above, wherein the part has a shaft-shaped portion.

3. A method for manufacturing a mechanical structural part, the method comprising subjecting a steel material having a chemical composition containing (consisting of), in mass%,

    C: 0.45 % to 0.51 %,
    Si: 0.15 % to 0.35 %,
    Mn: 0.60 % to 0.90 %,
    P: 0.030 % or less,
    S: 0.025 % or less,
    Al: 0.040 % to 0.059 %,
    Cr: 0.10 % to 0.50 %, and
    N: 0.0060 % to 0.0100 %,

    with the balance being Fe and inevitable impurities to hot rolling at a rolling speed VSL satisfying the following formula (1) to form a steel bar or wire rod, and forging the steel bar or wire rod to be subjected to induction hardening at 900 °C to 1150 °C and then tempering:

$$VSL \leq 100/DL \text{ (m/s)} \ldots (1),$$

    where VSL is a rolling speed (m/s) just before passing through a final stage of rolling, and DL is a diameter (mm) of a rolled material after the rolling is completed.

(Advantageous Effect)

[0013] According to the present disclosure, a mechanical structural part with low residual strain can be provided. In particular, the reduction of strain is achieved in a mechanical structural part having a shaft-shaped portion, and this disclosure thus produces the effect of suppressing eccentricity in this type of mechanical structural part.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] In the accompanying drawings:
FIG. 1 is a graph illustrating a correlation between the area ratio of prior austenite grains each having a grain size of 80 μm or less and the center runout (eccentricity) in the hardened layer.

DETAILED DESCRIPTION

[0015] In the following, one form for implementing this disclosure will be described in detail, starting with the chemical composition of the steel applied to a mechanical structural part of this disclosure. Here, "%" indicating the content of each element is "mass%", unless otherwise stated.

C: 0.45 % to 0.51 %

[0016] C is an essential element to ensure the strength of the hardened layer of the part when the part is subjected to induction heat treatment. When the C content is less than 0.45 %, the strength of the part is insufficient. On the other hand, when the C content exceeds 0.51 %, the amount of strain after induction heat treatment increases. For the above reasons, the C content is specified to be in the range of 0.45 % to 0.51 %. From the viewpoint of balancing strength and amount of strain, the C content is desirably 0.47 % or more. Similarly, the C content is desirably 0.49 % or less.

Si:0.15 % to 0.35 %

[0017] Si has actions of reducing oxygen inclusions by deoxidation action of the steel and suppressing hardness reduction in tempering heat treatment. That is, Si has an effect of improving the mechanical properties of the product. On the other hand, excessive addition of Si will reduce cold workability due to hardening of the material. For the above reasons, the Si content is specified to be in the range of 0.15 % to 0.35 %. A more desirable range of the Si content is 0.20 % or more. A more desirable range of the Si content is 0.30 % or less.

Mn: 0.60 % to 0.90 %

[0018] Mn has an action of greatly improving hardenability. Thus, Mn needs to be added at 0.60 % or more. On the other hand, an increase in amount of addition of Mn increases hardness of the material and decreases cold workability. However, the Mn content is allowed up to 0.90 %. For the above reasons, the Mn content is specified to be in the range of 0.60 % to 0.90 %. A more desirable range of the Mn content is 0.70 % or more. A more desirable range of the Mn content is 0.80 % or less.

P: 0.030 % or less (including 0 %)

[0019] P has an action of segregating at the prior austenite grain boundary after induction hardening, thereby reducing fatigue resistance of the hardened layer. Therefore, it is preferable to keep the P content as low as possible. For the above reason, the P content is specified to be in the range of 0.030 % or less. The P content is more preferably decreased to 0.012 % or less. Of course, the P content may be 0 %.

S: 0.025 % or less (including 0 %)

[0020] S exists as sulfur inclusions and is an effective element for improving machinability by cutting. However, the addition exceeding 0.025 % of S adversely affects manufacturability during casting. Thus, the upper limit of the S content is 0.025 %. When improvement in machinability by cutting is required, 0.010 % or more of S may be added. The preferred range of the S content is 0.010 % to 0.015 %. When the machinability by cutting is not a consideration, the S content may be 0 %.

Al: 0.040 % to 0.059 %

[0021] Al combines with N to form AlN. Thus, Al has an action of suppressing the coarsening of austenite grains during rolling and induction hardening of a steel bar and a wire rod. Al is an important element in this disclosure because austenite grain size control during rolling and induction hardening of the steel bar and wire rod is effective in strain control. When the Al content is low, the above effect is not expected. On the other hand, excessive Al content leads to an increase in inclusions, which increases the number of initiation points of fatigue fracture and causes a reduction in fatigue strength. For the above reasons, the Al content is specified to be in the range of 0.040 % to 0.059 %. The Al content is preferably 0.045 % or more. The Al content is preferably 0.055 % or less.

Cr: 0.10 % to 0.50 %

[0022] Cr effectively improves the hardenability and strength of steel. On the other hand, as the Cr content increases, a decrease in workability due to increased hardness is inevitable. For the above reasons, the Cr content is specified to be in the range of 0.10 % to 0.50 %. The Cr content is preferably 0.10 % or more. The Cr content is preferably 0.20 % or less.

N: 0.0060 % to 0.0100 %

[0023] N combines with Al to form AlN. Thus, N is an important element in this disclosure as is Al. An N content of 0.0060 % or more is necessary to control austenite grain size during rolling and induction hardening of the steel bar and wire rod. On the other hand, an increase in the N content generates cracks during solidification. The cracks will remain as defects in subsequent processes. If the defects remain, the steel cannot be used as a product because the defects open up to make cracks be significantly more likely to be generated. For the above reasons, the N content is specified to be in the range of 0.0060 % to 0.0100 %. The N content is preferably 0.0060 % or more. The N content is preferably 0.0080 % or less.

[0024] In the mechanical structural part of this disclosure, the balance of the chemical composition is Fe and impurities. Impurities are those that are introduced during the industrial manufacture of steel material, from ores and scrap as raw materials or from manufacturing environment, etc., and are acceptable to the extent that they do not adversely affect the properties of this embodiment.

[0025] The following describes the specification in this disclosure regarding the prior austenite grain size of the hardened layer by induction heat treatment.

[0026] The mechanical structural part of this disclosure is formed into a part shape, such as a shape having a shaft portion, using steel with the above-described chemical composition, and then subjected to induction heat treatment of induction hardening and tempering. In the hardened layer formed by this induction heat treatment, it is necessary that the area ratio of crystal grains each having a prior austenite grain size of 80 μm or less is 80 % or more, and that the number ratio of grains each having a grain size twice or more than the mode of grain size is 5 % or less.

[Hardened layer]

[0027] In the mechanical structural part of this disclosure, the formed body that has become the part shape is subjected to induction heat treatment of induction hardening and tempering to form a hardened layer on the surface layer. This hardened layer is a portion hardened by induction heat treatment. Specifically, the hardness (e.g., Vickers hardness) distribution is measured from the surface toward the center of the part after induction heat treatment, and in the resulting hardness distribution, a depth position where a predetermined hardness (e.g., HV 450) is maintained is defined as an effective hardened case depth (ECD). The region of this effective hardened case depth is defined as a hardened layer.

[Area ratio of crystal grains each having prior austenite grain size of 80 μm or less being 80 % or more]

[0028] This specification regarding the prior austenite grain size is an indicator of the properties of prior austenite grains that can suppress strain after induction heat treatment. As FIG. 1 illustrates a relationship between the area ratio of prior austenite grains each having a grain size of 80 μm or less and the center runout (a center runout of 0.25 % or less achieves suppression of strain in the part) in the example described below, when the area ratio of crystal grains each having a prior austenite grain size of 80 μm or less satisfies 80 % or more, the center runout can be effectively suppressed, i.e., strain in the part can be suppressed. The reason why the crystal grains each having a prior austenite grain size of 80 μm or less is targeted is that prior austenite grains each having a grain size of larger than 80 μm have a significant impact on center runout suppression, and the desired center runout suppression capability can be obtained by regulating the crystal grains of more than 80 μm. Therefore, the area ratio of crystal grains each having a prior austenite grain size of more than 80 μm is specified to be less than 20%. In other words, the area ratio of crystal grains each having a prior austenite grain size of 80 μm or less is specified to be 80% or more.

[0029] Here, the prior austenite grain size can be obtained by properly corroding and observing the part after induction heat treatment. For example, after corroding the hardened layer formed on the part surface layer with a picric acid solution to reveal the prior austenite grain boundary, the prior austenite grain microstructure can be photographed and processed by image processing software to obtain the equivalent circle diameter of each prior austenite grain and determine the area ratio of the crystal grains of 80 μm or less.

[Number ratio of grains each having grain size twice or more than mode of grain size being 5 % or less]

[0030] By specifying the number ratio of grains each having a grain size twice or more than the mode of grain size to 5% or less in the hardening layer, strain and eccentricity of the part after induction hardening can be suppressed. Even when the area ratio of prior austenite grains in the previous section is satisfied, if a certain small number of prior austenite grains are significantly coarsened than the other grains (specifically, twice or more than the mode of grain size), eccentricity is not suppressed to the desired degree. Thus, the inventors found that the above conditions are appropriate as the criteria for suppressing eccentricity.
[0031] Here, the mode of grain size can be obtained by properly corroding and observing the part after induction heat treatment. For example, the mode of grain size can be obtained by, after corroding the hardened layer formed on the part surface layer with a picric acid solution to reveal the prior austenite grain boundary, photographing and processing the prior austenite grain microstructure by image processing software to obtain a histogram of grain size. Furthermore, the histogram can be used to determine the number ratio of grains each having a grain size twice or more than the mode of grain size.
[0032] The following describes a method for manufacturing a mechanical structural part of this disclosure.
[0033] That is, a steel material having the above chemical composition is subjected to hot rolling at a rolling speed that satisfies the following formula (1) to form a steel bar or wire rod, and the bar or wire is forged to a part shape and then subjected to induction hardening at 900 °C to 1150 °C to manufacture a mechanical structural part. The steel material is, for example, cast steel, slab, etc., with a billet as a typical example, but is not limited to these.
[0034] Here, in order to satisfy the above-mentioned specification regarding the prior austenite grain size in the hardened layer, in addition to the adjustment of the above-mentioned chemical composition, it is necessary to subject a steel material, for example, cast steel, to hot rolling at a rolling speed that satisfies the following formula (1) to form a steel bar or wire rod:
note

$$\mathrm{VSL} \leq 100/\mathrm{DL}\ (\mathrm{m/s}) \ldots (1),$$

where VSL is a rolling speed (m/s) just before passing through the final stage of rolling, and DL is a diameter (mm) of the rolled material after the rolling is completed.
[0035] Formula (1) above is an indicator that indicates the rolling speed at which cast steel is subjected to hot rolling to be a steel bar or wire rod, which will be a forged material to form a mechanical structural part. Appropriate rolling speed according to the diameter of the steel bar or wire rod can reduce the temperature gradient inside the rolled material and control the microstructure of the rolled material. By using a rolling speed that satisfies this formula, the time required for cooling the inside of the rolled material can be guaranteed, and the temperature difference between the surface layer and the inside of the rolled material can be suppressed, resulting in a homogeneous post-rolling microstructure. Therefore, when the rolling speed and diameter of the rolled material do not satisfy Formula (1) above, the prior austenite grain size in the final part will not satisfy the above conditions even if the heat treatment conditions during induction heat treatment described below are satisfied.
[0036] Furthermore, from the viewpoint of strain suppression, it is preferable to use a rolling speed where the constant on the right side of Formula (1) is specified to be from 100 to 90. In other words, hot rolling at a rolling speed that satisfies the following formula (2) is preferable for suppressing strain:
note

$$\mathrm{VSL} \leq 90/\mathrm{DL}\ (\mathrm{m/s}) \ldots (2),$$

where VSL is a rolling speed (m/s) just before passing through the final stage of rolling, and DL is a diameter (mm) of the rolled material after the rolling is completed.
[0037] Incidentally, it is basically appropriate to use the diameter of the rolled material just before the final stage of rolling as an indicator that indicates the rolling speed. However, the final stage of rolling of a steel bar or wire rod is usually a minor rolling reduction for arranging dimensions, and the change in diameter is minute. Thus, the diameter after the rolling is completed can be used as an indicator that indicates the rolling speed.
[0038] The steel bar or wire rod manufactured as above is subjected to hot forging and/or cold forging, cutting, or other processing to finish it into a part shape, and are then subjected to induction heat treatment to be a part. In order for the prior austenite grains in the hardened layer after induction heat treatment to satisfy the above grain size conditions, the temperature of induction hardening needs to be 900 °C to 1150 °C.
[0039] The above temperature range is specified on the basis that, within the chemical composition range of this disclosure, complete austenite transformation occurs during heating and that no significant austenite grain growth occurs

during heating. The commonly known conditions for tempering heat treatment after induction hardening are acceptable.

EXAMPLES

[0040] The following describes the structures and function effects of the present disclosure in more detail, by way of examples. However, this disclosure is not limited to the following examples and may be changed appropriately within the scope conforming to the purpose of this disclosure, all of such changes being included within the technical scope of this disclosure.

[0041] Continuous-cast steel produced through continuous casting by smelting steel having each chemical composition presented in Table 1 was processed into billets and then hot-rolled into round bars with various diameters. The hot rolling conditions are as follows: diameter DL of the rolled material after the rolling is completed = 30 mm; and rolling speed VSL just before passing through the final stage of rolling = 3.0 m/s. The properties required for steel for mechanical structural use were investigated for the resulting round bars. The hardness of each round bar after hot rolling was measured as a property required for the steel for mechanical structural use, i.e., a property of the steel itself. Furthermore, the hardness distribution was measured after induction heat treatment, as described below, of the round bar to evaluate the hardenability.

[Table 1]

[0042]

[Table 1]

Steel No.	Chemical composition (mass%)								Remarks
	C	Si	Mn	P	S	Al	Cr	N	
1	0.50	0.17	0.63	0.011	0.011	0.048	0.31	0.0069	Conforming Example
2	0.51	0.15	0.84	0.010	0.011	0.045	0.47	0.0098	Conforming Example
3	0.51	0.33	0.82	0.012	0.015	0.052	0.41	0.0074	Conforming Example
4	0.47	0.33	0.80	0.030	0.023	0.056	0.42	0.0068	Conforming Example
5	0.50	0.17	0.73	0.029	0.018	0.040	0.25	0.0083	Conforming Example
6	0.45	0.21	0.64	0.029	0.020	0.052	0.48	0.0087	Conforming Example
7	0.49	0.22	0.85	0.016	0.018	0.052	0.41	0.0085	Conforming Example
8	0.49	0.18	0.67	0.012	0.012	0.042	0.32	0.0060	Conforming Example
9	0.46	0.25	0.65	0.007	0.024	0.053	0.30	0.0085	Conforming Example
10	0.45	0.30	0.75	0.016	0.023	0.048	0.27	0.0098	Conforming Example
11	0.45	0.15	0.67	0.024	0.019	0.042	0.50	0.0073	Conforming Example
12	0.50	0.26	0.60	0.030	0.018	0.057	0.38	0.0071	Conforming Example
13	0.47	0.28	0.80	0.012	0.010	0.052	0.14	0.0098	Conforming Example
14	0.47	0.23	0.79	0.012	0.014	0.056	0.20	0.0094	Conforming Example
15	0.45	0.24	0.86	0.013	0.022	0.053	0.46	0.0070	Conforming Example
16	0.50	0.30	0.79	0.026	0.025	0.043	0.37	0.0088	Conforming Example
17	0.51	0.35	0.79	0.011	0.024	0.047	0.24	0.0065	Conforming Example
18	0.45	0.25	0.73	0.020	0.011	0.049	0.29	0.0078	Conforming Example
19	0.50	0.26	0.88	0.015	0.021	0.049	0.10	0.0095	Conforming Example
20	0.53	0.28	0.86	0.018	0.015	0.050	0.48	0.0086	Comparative Example
21	0.44	0.26	0.74	0.013	0.011	0.048	0.49	0.0082	Comparative Example
22	0.48	0.12	0.72	0.025	0.015	0.059	0.30	0.0099	Comparative Example
23	0.51	0.34	0.58	0.028	0.011	0.052	0.43	0.0061	Comparative Example

(continued)

Steel No.	Chemical composition (mass%)								Remarks
	C	Si	Mn	P	S	Al	Cr	N	
24	0.46	0.24	0.84	0.033	0.021	0.040	0.41	0.0068	Comparative Example
25	0.48	0.17	0.83	0.010	0.024	0.063	0.16	0.0077	Comparative Example
26	0.48	0.16	0.66	0.024	0.017	0.039	0.37	0.0088	Comparative Example
27	0.46	0.23	0.82	0.018	0.020	0.044	0.09	0.0093	Comparative Example
28	0.46	0.19	0.73	0.017	0.025	0.049	0.47	0.0059	Comparative Example

[0043] As the hardness measurement, the Vickers hardness was measured at 300 gf, at a depth position of 1/4 of the diameter of the round bar from the peripheral surface of the round bar. The measurement was taken at 10 arbitrary points, and the average value was calculated and evaluated. The Vickers hardness here is desirably HV 195 or less from the viewpoint of cold workability.

[0044] The hardness distribution measurement after induction heat treatment was performed by subjecting each round bar to induction heat treatment. The induction heat treatment was performed at a frequency of 8.5 kHz, a maximum heating temperature of 1000 °C, and by mobile quenching. Tempering was performed using a heating furnace under a set of conditions including a temperature at 180 °C and a time for 30 minutes. The Vickers hardness measurement was then performed at 300 gf on the vertical cross section of the axis of the round bar from the surface to the center. That is, the depth position of 1 mm from the surface of the round bar to the inside in the radial direction was set as a first point, and the Vickers hardness was then measured in 1 mm intervals to the inside in the radial direction to evaluate the hardness distribution in the radial direction. Based on the results, the layer from the surface to the position where the Vickers hardness reaches HV 450 or more was evaluated as an effective hardened case depth (ECD). The region of this effective hardened case depth is the hardened layer of this disclosure. To ensure the strength of the part, the ECD is desirably 10 % or more of the diameter of the round bar.

[0045] The measurement results are presented in Table 2.

[Table 2]

[0046]

[Table 2]

Test No.	Steel No.	Properties of material as rolled	
		Hardness (HV)	ECD (mm)
1A	1	183	3.3
2A	2	183	3.2
3A	3	188	3.3
4A	4	180	3.0
5A	5	185	3.1
6A	6	180	3.0
7A	7	184	3.2
8A	8	185	3.0
9A	9	180	3.0
10A	10	185	3.0
11A	11	185	3.1
12A	12	188	3.2
13A	13	195	3.1
14A	14	193	3.1

(continued)

Test No.	Steel No.	Properties of material as rolled	
		Hardness (HV)	ECD (mm)
15A	15	182	3.3
16A	16	183	3.2
17A	17	184	3.1
18A	18	185	3.1
19A	19	187	3.0
20A	20	217	3.1
21A	21	176	2.9
22A	22	182	2.7
23A	23	177	2.7
24A	24	187	3.0
25A	25	186	3.1
26A	26	193	3.0
27A	27	182	2.7
28A	28	195	3.0

[0047] Furthermore, using the same continuous-cast steel as that provided for the above hardness measurement and hardness distribution measurement, a billet produced from each continuous-cast steel was subjected to hot rolling and induction hardening heat treatment in the part manufacturing conditions presented in Table 3 to produce a shaft part. The part shape was a round bar with 20 % area reduction rate extrusion from the steel bar after hot rolling. Each induction heat treatment was performed after adjusting the conditions so that the ECD (i.e., thickness of the hardened layer) was about 10 % of the shaft diameter.

[0048] The number ratio of grains each having a grain size twice or more than the mode of grain size and the area ratio of crystal grains each having a prior austenite grain size of 80 μm or less, in the hardened layer of the resulting part, were investigated.

[Number ratio of grains each having grain size twice or more than mode of grain size]

[0049] Observation of the prior austenite grains in the hardened layer of the part was performed by cutting out a sample from the above shaft part with the vertical cross section of the axis as the observation plane. The cut sample was corroded in a 3 % picric acid solution, and an optical microscopy was used to capture 10 views of the prior austenite grain microstructure at 200x at the half position of the ECD. Based on the photographs, the prior austenite grain boundary was traced, the traced image was processed by image processing software Image J, and the diameter of each prior austenite grain was calculated by rounding it to the nearest whole number as the equivalent circle diameter. From the obtained grain size data, the grain size with the largest number of grains was defined as the mode, and the number ratio of grains each having a grain size larger twice or more than the mode to the total grain number was calculated. When there were a plurality of candidates for the mode, the smallest value among them was treated as the mode.

[Area ratio of crystal grains each having a prior austenite grain size of 80 μm or less]

[0050] The area ratio of prior austenite grains each having a grain size of 80 μm or less was calculated by image analysis of the traced image, obtained in the same manner as above.

[0051] Furthermore, the resulting part was evaluated for torsional fatigue life and part center runout.

[Torsional fatigue life]

[0052] Torsional fatigue life was measured using an electric servo type torsional fatigue test machine. The load was applied at 2 Hz so that the maximum shear stress was 300 MPa, and the number of repetitions until fracture was measured. When a part exhibits a fracture life of 15,000 times or more in this test, it can be said that the part has sufficient fatigue strength.

[Part center runout]

[0053] The strain of the part was measured using an eccentricity tester. That is, the center runout (%) was calculated by dividing the range of displacement change (difference between the maximum displacement value and the minimum displacement value) when the part was made to go around with holes, which had been drilled in the center of both ends before induction heat treatment, being supported, by the diameter of the measured portion. In this test, it can be said that the strain of the part is sufficiently suppressed when the center runout is 0.25 % or less.

[0054] The obtained evaluation results are presented together in Table 3. FIG. 1 also illustrates the relationship between the area ratio of prior austenite grains each having a grain size of 80 μm or less and the center runout in an organized way. In the figure, only examples where fatigue life is in the preferred range are illustrated.

[Table 3]

[0055]

[Table 3]

Test No.	Steel No.	Part manufacturing conditions			Number ratio of grains each having grain size twice or more than mode	Area ratio of prior austenite grains each having grain size of 80 μm or less	Part properties		Remarks
		D_L (mm)	V_{SL} (m/s)	Induction hardening temperature (°C)	(%)	(%)	Torsional fatigue life (*) (times)	Center runout (%)	
1B	1	20	4.6	930	1.7	85.8	2.0E+04	0.22	Example
2B	2	20	4.7	1010	4.6	99.7	3.5E+04	0.18	Example
3B	3	20	4.8	1010	1.7	95.3	3.4E+04	0.19	Example
4B	4	20	5.0	1110	1.9	98.4	3.3E+04	0.19	Example
5B	5	20	4.9	920	2.0	86.8	2.2E+04	0.17	Example
6B	6	20	4.8	1000	1.0	87.6	3.7E+04	0.21	Example
7B	7	40	2.5	960	1.6	92.3	2.6E+04	0.21	Example
8B	8	40	2.0	1000	1.0	83.3	2.8E+04	0.22	Example
9B	9	40	1.8	970	4.7	96.1	1.9E+04	0.17	Example
10B	10	40	1.6	1020	4.7	90.5	1.6E+04	0.22	Example
11B	11	40	2.0	1150	0.3	82.1	3.0E+04	0.04	Example
12B	12	40	1.8	1030	0.9	87.1	2.9E+04	0.12	Example
13B	13	40	2.2	1060	1.0	85.1	3.9E+04	0.08	Example
14B	14	20	4.5	1130	0.5	92.0	4.1E+04	0.07	Example
15B	15	20	3.6	1010	1.0	85.3	2.9E+04	0.12	Example
16B	16	40	1.3	980	0.5	91.5	2.7E+04	0.12	Example
17B	17	40	1.4	920	0.8	82.1	4.3E+04	0.10	Example
18B	18	40	1.7	1130	1.0	96.5	3.6E+04	0.06	Example
19B	19	20	3.9	990	3.9	88.2	2.1E+04	0.04	Example

(continued)

Test No.	Steel No.	Part manufacturing conditions			Number ratio of grains each having grain size twice or more than mode	Area ratio of prior austenite grains each having grain size of 80 μm or less	Part properties		Remarks
		D_L (mm)	V_{SL} (m/s)	Induction hardening temperature (°C)	(%)	(%)	Torsional fatigue life (*) (times)	Center runout (%)	
20B	20	20	4.1	1050	4.8	83.8	2.3E+04	0.37	Comparative Example
21B	21	20	4.6	1020	2.5	93.1	1.3E+04	0.21	Comparative Example
22B	22	20	4.6	1060	3.2	90.7	1.2E+04	0.17	Comparative Example
23B	23	20	4.5	980	2.7	97.0	1.3E+04	0.17	Comparative Example
24B	24	20	4.7	900	2.7	97.6	1.3E+04	0.23	Comparative Example
25B	25	40	1.9	970	4.9	83.0	1.2E+04	0.17	Comparative Example
26B	26	40	1.6	1130	5.9	86.0	2.1E+04	0.34	Comparative Example
27B	27	40	1.6	970	2.0	82.0	1.0E+04	0.17	Comparative Example
28B	28	40	2.3	1100	2.7	68.2	2.8E+04	0.42	Comparative Example
29B	2	20	5.4	1010	2.2	71.3	3.3E+04	0.37	Comparative Example
30B	3	20	5.4	1000	2.3	66.8	1.6E+04	0.26	Comparative Example
31B	4	20	5.2	1020	4.9	69.4	3.1E+04	0.32	Comparative Example
32B	6	40	2.7	1050	2.1	66.6	3.3E+04	0.30	Comparative Example
33B	8	40	3.0	930	3.2	77.7	2.5E+04	0.31	Comparative Example
34B	9	40	3.0	1110	4.8	79.6	3.8E+04	0.36	Comparative Example
35B	11	20	4.9	890	3.0	84.6	1.3E+04	0.18	Comparative Example
36B	13	20	4.1	880	3.7	83.4	1.0E+04	0.24	Comparative Example
37B	15	40	1.8	1170	2.3	72.7	2.2E+04	0.28	Comparative Example

(continued)

Test No.	Steel No.	Part manufacturing conditions			Number ratio of grains each having grain size twice or more than mode	Area ratio of prior austenite grains each having grain size of 80 μm or less	Part properties		Remarks
		D_L (mm)	V_{SL} (m/s)	Induction hardening temperature (°C)	(%)	(%)	Torsional fatigue life (*) (times)	Center runout (%)	
38B	17	40	2.5	1180	3.2	66.7	2.3E+04	0.36	Comparative Example
*: "E+04" in Torsional fatigue life indicates "×10^4".									

Claims

1. A mechanical structural part comprising:

a chemical composition containing, in mass%,
C: 0.45 % to 0.51 %,
Si: 0.15 % to 0.35 %,
Mn: 0.60 % to 0.90 %,
P: 0.030 % or less,
S: 0.025 % or less,
Al: 0.040 % to 0.059 %,
Cr: 0.10 % to 0.50 %, and
N: 0.0060 % to 0.0100 %,

with the balance being Fe and inevitable impurities, and
a hardened layer by induction hardening and tempering treatment, wherein an area ratio of crystal grains each having a prior austenite grain size of 80 μm or less in the hardened layer is 80 % or more, and a number ratio of grains each having a grain size twice or more than a mode of grain size in the hardened layer is 5 % or less.

2. The mechanical structural part according to claim 1, wherein the part has a shaft-shaped portion.

3. A method for manufacturing a mechanical structural part, the method comprising subjecting a steel material having a chemical composition containing, in mass%,

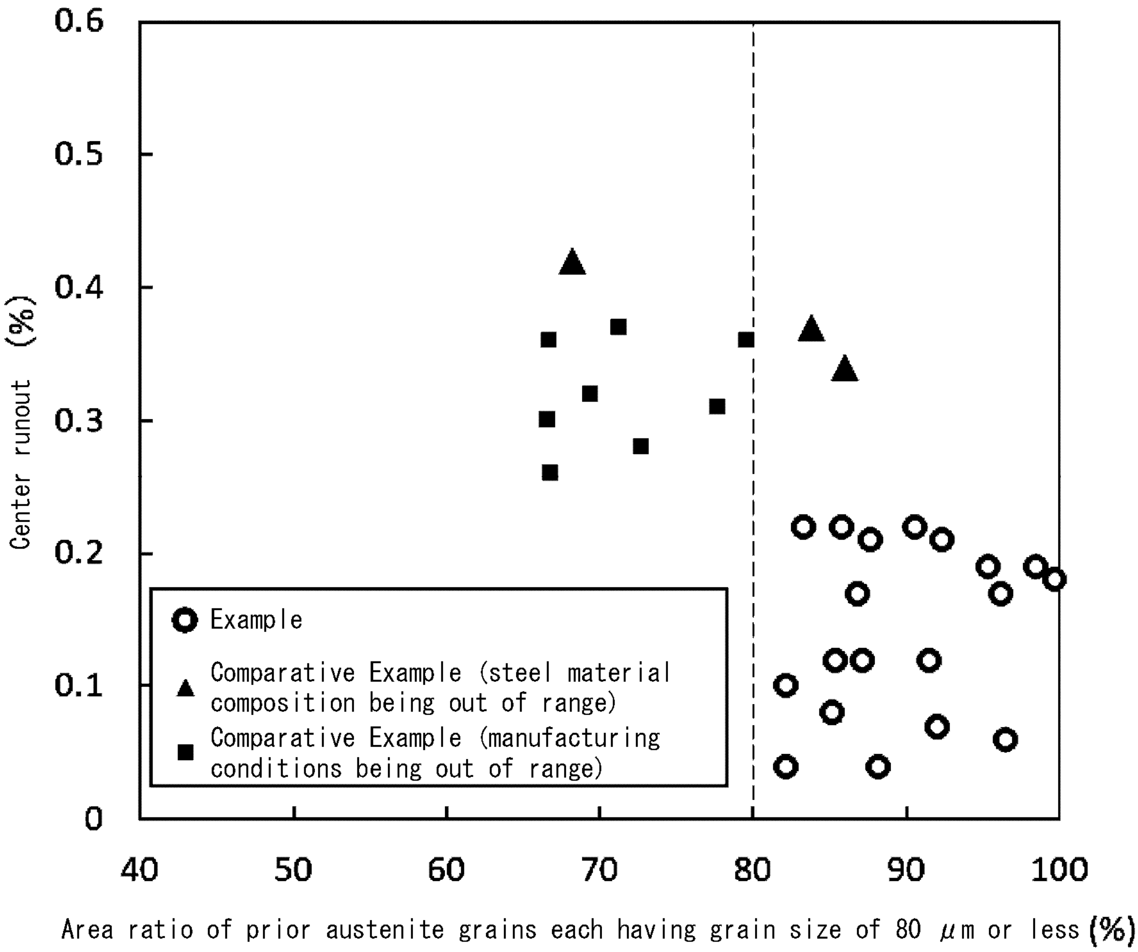
C: 0.45 % to 0.51 %,
Si: 0.15 % to 0.35 %,
Mn: 0.60 % to 0.90 %,
P: 0.030 % or less,
S: 0.025 % or less,
Al: 0.040 % to 0.059 %,
Cr: 0.10 % to 0.50 %, and
N: 0.0060 % to 0.0100 %,

with the balance being Fe and inevitable impurities to hot rolling at a rolling speed VSL satisfying the following formula (1) to form a steel bar or wire rod, and forging the steel bar or wire rod to be subjected to induction hardening at 900 °C to 1150 °C and then tempering:

$$VSL \leq 100/DL\ (m/s)\ \ldots\ (1),$$

where VSL is a rolling speed (m/s) just before passing through a final stage of rolling, and DL is a diameter (mm) of a rolled material after the rolling is completed.

FIG. 1


0.6
0.5
0.4
0.3
0.2
0.1
0
Center runout (%)
Example
Comparative Example (steel material composition being out of range)
Comparative Example (manufacturing conditions being out of range)
40
50
60
70
80
90
100
Area ratio of prior austenite grains each having grain size of 80 μm or less (%)

INTERNATIONAL SEARCH REPORT

International application No. **PCT/JP2023/012333**

A. CLASSIFICATION OF SUBJECT MATTER

C22C 38/00(2006.01)i; ***C21D 8/06***(2006.01)i; ***C21D 9/28***(2006.01)i; ***C22C 38/18***(2006.01)i
FI: C22C38/00 301Z; C21D8/06 A; C21D9/28 A; C22C38/18

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C22C38/00; C21D8/06; C21D9/28; C22C38/18

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

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2011/049006 A1 (NIPPON STEEL CORP.) 28 April 2011 (2011-04-28) entire text, all drawings	1-3
A	JP 2008-133530 A (JFE STEEL CORP.) 12 June 2008 (2008-06-12) entire text, all drawings	1-3
A	JP 2010-236062 A (JFE STEEL CORP.) 21 October 2010 (2010-10-21) entire text	1-3

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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
05 June 2023	**20 June 2023**

Name and mailing address of the ISA/JP	Authorized officer
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Form PCT/ISA/210 (second sheet) (January 2015)

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2023/012333

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
WO 2011/049006 A1	28 April 2011	US 2012/0193000 A1 entire text, all drawings KR 10-2012-0047303 A CN 102575328 A	
JP 2008-133530 A	12 June 2008	KR 10-2008-0039284 A entire text, all drawings	
JP 2010-236062 A	21 October 2010	(Family: none)	

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REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP S61261427 A **[0003] [0008]**
- JP H08199316 A **[0004] [0008]**
- JP 2004204263 A **[0005] [0008]**
- JP 2006265703 A **[0006] [0008]**
- JP 2013151719 A **[0007] [0008]**