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(54) **METHOD OF PRODUCING A FREE-CUTTING STEEL**

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(57) **ABSTRACT**

A method of producing a free-cutting steel includes: rolling a rectangular cast steel at ≥1120° C. and an area reduction rate of ≥60% to obtain a billet; and hot working the billet at ≥1050° C. and an area reduction rate of ≥75%. The rectangular cast steel contains, in mass %: C: less than 0.09 %, Mn: 0.50% to 1.50%, S: 0.250% to 0.600%, 0: more than 0.010% and 0.050% or less, and Cr: 0.50% to 1.50%, with a balance consisting of Fe and inevitable impurities. An A value=2 ([Mn]+2[Cr])/[S] is 6.0 to 18.0, where [Mn], [Cr], and [S] respectively denote contents in mass % of elements Mn, Cr, and S. A side length of a cross section of the rectangular cast steel perpendicular to a longitudinal direction is ≥250 mm.

METHOD OF PRODUCING A FREE-CUTTING STEEL

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a divisional application of U.S. patent application Ser. No. 17/907,271 filed Sep. 26, 2022, which is a National Stage Application of PCT/JP2021/014049 filed Mar. 31, 2021, which claims priority of Japanese Patent Application No. 2020-063741 filed Mar. 31, 2020. The disclosures of the prior applications are hereby incorporated by reference herein in their entirety.

TECHNICAL FIELD

[0002] The present disclosure relates to a free-cutting steel, in particular a steel that is a substitute for a free-cutting steel containing sulfur and a small amount of lead as elements for improving machinability by cutting. The present disclosure relates to a free-cutting steel having machinability by cutting higher than or equal to that of a low carbon sulfur-lead composite free-cutting steel, and a method of producing the same.

BACKGROUND

[0003] Low carbon sulfur-lead free-cutting steel as represented by JIS SUM24L contains a large amount of lead (Pb) and sulfur (S) as free-cutting elements and thus has excellent machinability by cutting.

[0004] In steel materials, lead is useful for reducing tool wear and improving chip treatability in cutting work. Hence, lead is regarded as an important element that significantly improves the machinability by cutting of materials, and is used in many steel products produced by cutting work. With the rise of environmental awareness in recent years, however, there is a growing movement to abolish or restrict the use of environmentally hazardous substances worldwide. Lead is one of such environmentally hazardous substances, and restriction on the use of lead is required.

[0005] In view of this, for example, JP H9-25539 A (PTL 1) discloses a non-Pb-containing free-cutting non-heat-treated steel. Likewise, J P 2000-160284 A (PTL 2) discloses a non-Pb-containing free-cutting steel. Moreover, JP H2-6824 B (PTL 3) discloses a free-cutting steel containing Cr which can form a compound with S more easily than Mn to thereby cause a Mn—Cr—S-based inclusion to be present and ensure machinability by cutting.

CITATION LIST

Patent Literature

[0006] PTL 1: JP H9-25539 A

[0007] PTL 2: JP 2000-160284 A

[0008] PTL 3: JP H2-6824 B

SUMMARY

Technical Problem

[0009] The technique described in PTL 1 is intended for a non-heat-treated steel that contains 0.2% or more of C and thus is hard, and the use of Nd which is a special element requires high production costs. With the technique described in PTL 2, adding a large amount of S causes low hot ductility and induces cracking during continuous casting or hot rolling, which is problematic in terms of surface characteristics. With the technique described in PTL 3, Cr and S are added while reducing the amount of Mn. However, due to high Cr content of 3.5% or more, not only cost reduction is difficult but also a large amount of CrS forms, causing a production problem in that material smelting treatment in the steelmaking process is difficult.

[0010] It could therefore be helpful to provide a free-cutting steel that, despites not containing Pb, has machinability by cutting higher than or equal to that of a low carbon sulfur-lead composite free-cutting steel and does not need to contain Nd or a large amount of S or Cr as in PTL 1 to PTL 3, together with a method of producing the same.

Solution to Problem

[0011] Upon careful examination, we discovered the following:

[0012] (i) Adding appropriate amounts of Mn, Cr, and S and optimizing the ratio 2(Mn+2Cr)/S causes an appropriate amount of sulfide to have a Mn—Cr—S composite-based composition. The sulfides of the composite-based composition can be refined by hot working.

[0013] (ii) When the sulfides are finer, the lubricating action is greater, and the formation of hard phase adhering to the tool surface, called a built-up edge, can be prevented. Thus, machinability by cutting including chip treatability and surface roughness can be significantly improved.

[0014] (iii) It is conventionally known that machinability by cutting is improved with an increase in S content in steel. There is, however, an upper limit to the amount of S that can be added in steel, from the viewpoint of hot workability or mechanical property anisotropy. If sulfides in steel are fine, machinability by cutting including chip treatability and surface roughness is significantly improved. Hence, by finely distributing sulfides in steel, favorable machinability by cutting can be ensured within the upper limit of the S content imposed from the viewpoint of hot workability or mechanical property anisotropy.

[0015] The present disclosure is based on these discoveries. We thus provide:

[0016] 1. A free-cutting steel comprising: a chemical composition that contains (consists of), in mass %, C: less than 0.09%, Mn: 0.50% to 1.50%, S: 0.250% to 0.600%, 0: more than 0.0100% and 0.0500% or less, and Cr: 0.50% to 1.50%, with a balance consisting of Fe and inevitable impurities, and in which a A value defined by the following formula (1) is 6.0 to 18.0,

$$\text{A value} = 2([\text{Mn}] + 2[\text{Cr}])/[\text{S}] \quad (1)$$

[0017] where [Mn], [Cr], and [S] respectively denote contents in mass % of elements Mn, Cr, and S; and a steel microstructure in which at least 500 particles/mm^2 of sulfide of less than 1 μm in equivalent circle diameter and at least 2000 particles/mm^2 of sulfide of 1 μm to 5 μm in equivalent circle diameter are distributed.

[0018] 2. The free-cutting steel according to 1., wherein the chemical composition further contains, in mass %, one or more selected from the group consisting of Si: 0.50% or less, P: 0.10% or less, Al: 0.010% or less, and N: 0.0150% or less.

[0019] 3. The free-cutting steel according to 1, or 2., wherein the chemical composition further contains, in mass %, one or more selected from the group consisting of Ca: 0.0010% or less, Se: 0.30% or less, Te: 0.15% or less, Bi: 0.20% or less, Sn: 0.020% or less, Sb: 0.025% or less, B: 0.010% or less, Cu: 0.50% or less, Ni: 0.50% or less, Ti: 0.100% or less, V: 0.20% or less, Zr: 0.050% or less, and Mg: 0.0050% or less.

[0020] 4. A method of producing a free-cutting steel, the method comprising: rolling a rectangular cast steel at a heating temperature of 1120° C. or more and an area reduction rate of 60% or more to obtain a billet, the rectangular cast steel having a chemical composition that contains, in mass %, C: less than 0.09%, Mn: 0.50% to 1.50%, S: 0.250% to 0.600%, 0: more than 0.0100% and 0.0500% or less, and Cr: 0.50% to 1.50% with a balance consisting of Fe and inevitable impurities, and in which a A value defined by the following formula (1) is 6.0 to 18.0,

$$A\ \text{value} = 2([Mn] + 2[Cr])/[S] \quad (1)$$

[0021] where [Mn], [Cr], and [S] respectively denote contents in mass % of elements Mn, Cr, and S, and a side length of a cross section of the rectangular cast steel perpendicular to a longitudinal direction being 250 mm or more; and hot working the billet at a heating temperature of 1050° C. or more and an area reduction rate of 75% or more.

[0022] 5. The method of producing a free-cutting steel according to 4., wherein the chemical composition further contains, in mass %, one or more selected from the group consisting of Si: 0.50% or less, P: 0.10% or less, Al: 0.010% or less, and N: 0.0150% or less.

[0023] 6. The method of producing a free-cutting steel according to 4, or 5., wherein the chemical composition further contains, in mass %, one or more selected from the group consisting of Ca: 0.0010% or less, Se: 0.30% or less, Te: 0.15% or less, Bi: 0.20% or less, Sn: 0.020% or less, Sb: 0.025% or less, B: 0.010% or less, Cu: 0.50% or less, Ni: 0.50% or less, Ti: 0.100% or less, V: 0.20% or less, Zr: 0.050% or less, and Mg: 0.0050% or less.

Advantageous Effect

[0024] It is thus possible to obtain a free-cutting steel having excellent machinability by cutting without adding lead.

DETAILED DESCRIPTION

[0025] A free-cutting steel according to the present disclosure will be described in detail below. First, the reasons for limiting the content of each component in the chemical composition of the free-cutting steel will be described below. Herein, "%" with regard to components is mass % unless otherwise stated.

C: Less Than 0.09%

[0026] C is an important element that greatly influences the strength and the machinability by cutting of the steel. If the C content is 0.09% or more, the steel hardens and the strength increases excessively, and as a result the machinability by cutting degrades. The C content is therefore less than 0.09%. The C content is preferably 0.07% or less. From the viewpoint of ensuring the strength, the C content is preferably 0.01% or more, and more preferably 0.03% or more.

Mn: 0.50% to 1.50%

[0027] Mn is a sulfide forming element important for improvement in machinability by cutting. If the Mn content is less than 0.50%, the amount of sulfide is small, and sufficient machinability by cutting cannot be obtained. The lower limit is therefore 0.50%. The Mn content is preferably 0.70% or more. If the Mn content is more than 1.50%, sulfides not only coarsen but also extend long, causing a decrease in machinability by cutting. In addition, the mechanical properties decrease. The upper limit of the Mn content is therefore 1.50%. The Mn content is preferably 1.20% or less.

S: 0.250% to 0.600%

[0028] S is a sulfide forming element effective in improving the machinability by cutting. If the S content is less than 0.250%, fine sulfides are few, so that the machinability by cutting cannot be improved. If the S content is more than 0.600%, sulfides coarsen excessively and the number of fine sulfides decreases, as a result of which the machinability by cutting decreases. Moreover, the hot workability and the ductility which is an important mechanical property decrease. The S content is therefore in a range of 0.250% to 0.600%. The S content is preferably 0.300% or more. The S content is preferably 0.450% or less.

O: More than 0.0100% and 0.0500% or Less

[0029] O is an element that forms oxide and serves as a sulfide precipitation nucleus and also is effective in suppressing extension of sulfides during hot working such as rolling. This action can improve the machinability by cutting. If the O content is 0.0100% or less, the sulfide extension suppressing effect is insufficient and extended sulfides remain, so that the foregoing effect cannot be expected. The O content is therefore more than 0.0100%. If the O content is more than 0.0500%, not only the sulfide extension suppressing effect is saturated but also the amount of hard oxide-based inclusions increases. Adding an excessive amount of O is also economically disadvantageous. The upper limit of the O content is therefore 0.0500%.

Cr: 0.50% to 1.50%

[0030] Cr has an effect of forming sulfides and improving the machinability by cutting through lubricating action during cutting. Cr also suppresses extension of sulfides during hot working such as rolling, and thus can improve the machinability by cutting. If the Cr content is less than 0.50%, the formation of sulfides is insufficient and extended sulfides tend to remain, so that the foregoing effect cannot be expected. If the Cr content is more than 1.50%, not only the steel hardens but also sulfides coarsen. Moreover, the extension suppressing effect is saturated, and the machinability by cutting decreases. Besides, adding an excessive amount causes an increase in alloy costs, which is economically disadvantageous. The Cr content is therefore 0.50% to 1.50%. The Cr content is preferably 0.70% or more. The Cr content is preferably 1.30% or less.

[0031] The free-cutting steel contains the above-described components with the balance consisting of Fe and inevitable impurities, or contains the above-described components and further contains the below-described optional components. The free-cutting steel preferably contains the above-described components or preferably contains the above-described components and further the below-described optional components, with the balance consisting of Fe and inevitable impurities.

[0032] It is important that, in the above-described chemical composition, a A value defined by the following formula (1) is 6.0 to 18.0.

$$\text{A value} = 2([\text{Mn}] + 2[\text{Cr}])/[\text{S}] \quad (1)$$

[0033] where [M] is the content (mass %) of the corresponding element in brackets.

[0034] The A value is an important index that influences refinement of Mn—Cr—S-based sulfide during hot working such as rolling, and limiting the A value can improve the machinability by cutting. If the A value is less than 6.0, sulfide of Mn—S alone forms, which tends to be coarse. Consequently, the machinability by cutting degrades. If the A value is more than 18.0, not only the sulfide refining effect is saturated but also the amount of the sulfide forming elements is excessively large relative to sulfur, causing sulfides to coarsen. The A value is therefore 6.0 to 18.0. The A value is preferably 6.5 or more. The A value is preferably 17.0 or less.

[0035] The optional components will be described below. In addition to the above-described basic components, the free-cutting steel according to the present disclosure may optionally contain one or more selected from the group consisting of

[0036] Si: 0.50% or less,
[0037] P: 0.10% or less,
[0038] Al: 0.010% or less, and
[0039] N: 0.0150% or less.
[0040] Si: 0.50% or less

[0041] Si is a deoxidizing element. Moreover, Si oxide acts as a sulfide formation nucleus to promote the formation of sulfides and refine the sulfides and thus improve the cutting tool life. Accordingly, Si may be contained in the steel in order to further extend the tool life. If the Si content is more than 0.50%, the oxide increases in size and decreases in number. Such oxide is ineffective as a sulfide formation nucleus, and also hard oxide induces abrasive wear and leads to degradation in tool life. The Si content is therefore 0.50% or less. The Si content is preferably 0.03% or less. To achieve the foregoing action by Si, the Si content is preferably 0.001% or more.

P: 0.10% or Less

[0042] P is an element effective in suppressing the formation of built-up edges during cutting work to thus reduce finishing surface roughness. From this viewpoint, the P content is preferably 0.01% or more. If the P content is more than 0.10%, the material hardens, so that the machinability by cutting decreases and the hot workability and the ductility decrease significantly. The P content is therefore preferably 0.10% or less. The P content is more preferably 0.08% or less.

Al: 0.010% or Less

[0043] Al is a deoxidizing element as with Si, and may be contained in the steel. Al forms Al_2O_3 in the steel. This oxide is hard and causes degradation in cutting tool life due to abrasive wear. Hence, adding an excessive amount of Al needs to be avoided. From this viewpoint, the Al content is preferably 0.010% or less. The Al content is more preferably 0.005% or less. From the viewpoint of achieving the deoxidizing effect by Al, the Al content is preferably 0.001% or more.

N: 0.0150% or Less

[0044] N forms nitride with Cr and the like. As a result of the nitride decomposing due to temperature increase during cutting work, an oxide film called belag forms on the tool surface. Belag has an action of protecting the tool surface and thereby improving the tool life. Accordingly, N may be contained in the steel. To effectively achieve this action, the N content is preferably 0.0050% or more. If the N content is more than 0.0150%, not only the effect of belag is saturated but also the material hardens, as a result of which the tool life shortens. The N content is therefore preferably 0.0150% or less. The N content is more preferably 0.0060% or more. The N content is more preferably 0.0120% or less.

[0045] The free-cutting steel according to the present disclosure may optionally further contain one or more selected from the group consisting of

[0046] Ca: 0.0010% or less,
[0047] Se: 0.30% or less,
[0048] Te: 0.15% or less,
[0049] Bi: 0.20% or less,
[0050] Sn: 0.020% or less,
[0051] Sb: 0.025% or less,
[0052] B: 0.010% or less,
[0053] Cu: 0.50% or less,
[0054] Ni: 0.50% or less,
[0055] Ti: 0.100% or less,
[0056] V: 0.20% or less,
[0057] Zr: 0.050% or less, and
[0058] Mg: 0.0050% or less.

[0059] Ca, Se, Te, Bi, Sn, Sb, B, Cu, Ni, Ti, V, Zr, and Mg each have an action of improving the machinability by cutting, and accordingly may be added in the case where the machinability by cutting is considered important. In the case of adding these elements in order to improve the machinability by cutting, if their respective contents are Ca: less than 0.0001%, Se: less than 0.02%, Te: less than 0.10%, Bi: less than 0.02%, Sn: less than 0.003%, Sb: less than 0.003%, B: less than 0.003%, Cu: less than 0.05%, Ni: less than 0.50%, Ti: less than 0.003%, V: less than 0.005%, Zr: less than 0.005%, and Mg: less than 0.0005%, sufficient effect cannot be achieved. Accordingly, their respective contents are preferably Ca: 0.0001% or more, Se: 0.02% or more, Te: 0.10% or more, Bi: 0.02% or more, Sn: 0.003% or more, Sb: 0.003% or more, B: 0.003% or more, Cu: 0.05% or more, Ni: 0.05% or more, Ti: 0.003% or more, V: 0.005% or more, Zr: 0.005% or more, and Mg: 0.0005% or more.

[0060] If their respective contents are Ca: more than 0.0010%, Se: more than 0.30%, Te: more than 0.15%, Bi: more than 0.20%, Sn: more than 0.020%, Sb: more than 0.025%, B: more than 0.010%, Cu: more than 0.50%, Ni: more than 0.50%, Ti: more than 0.100%, V: more than 0.20%, Zr: more than 0.050%, and Mg: more than 0.0050%, the effect is saturated, and also adding such amounts is economically disadvantageous. Accordingly, their respective contents are preferably Ca: 0.0010% or less, Se: 0.30% or less, Te: 0.15% or less, Bi: 0.20% or less, Sn: 0.020% or less, Sb: 0.025% or less, B: 0.010% or less, Cu: 0.50% or less, Ni: 0.50% or less, Ti: 0.100% or less, V: 0.20% or less, Zr: 0.050% or less, and Mg: 0.0050% or less.

(Steel Microstructure)

[0061] Distribution of at least 500 particles/mm^2 of sulfide of less than 1 μm in equivalent circle diameter and at least 2000 particles/mm^2 of sulfide of 1 μm to 5 μm in equivalent circle diameter

[0062] Fine dispersion of sulfides in the microstructure of the free-cutting steel is advantageous in promoting the lubricating action between the tool and the work material during cutting work. To ensure the machinability by cutting of the free-cutting steel by such fine dispersion of sulfides, at least a predetermined amount of sulfides of less than 1 μm in equivalent circle diameter and at least a predetermined amount of sulfides of 1 μm to 5 μm in equivalent circle diameter need to be dispersed in the steel microstructure. Sulfides of less than 1 μm in equivalent circle diameter are mainly effective for lubrication between the tool and the work material. Sulfides of 1 μm to 5 μm in equivalent circle diameter not only have the foregoing lubrication effect but also are effective for chip partibility. Hence, the number of sulfides of less than 1 μm in equivalent circle diameter is at least 500 particles/mm^2, and the number of sulfides of 1 μm to 5 μm in equivalent circle diameter is at least 2000 particles/mm^2.

[0063] The conditions for producing the free-cutting steel according to the present disclosure will be described below.

[0064] A rectangular cast steel that has the above-described chemical composition and whose side length of a cross section perpendicular to the longitudinal direction is 250 mm or more is rolled at a heating temperature of 1120° C. or more and an area reduction rate of 60% or more to obtain a billet, and the billet is hot worked at a heating temperature of 1050° C. or more and an area reduction rate of 75% or more.

(Cast Steel)

[0065] Rectangular cross section whose side length of cross section perpendicular to longitudinal direction is 250 mm

[0066] First, a molten steel adjusted to the chemical composition is cast to obtain a cast steel. As the cast steel, a rectangular cast steel whose side length of a cross section perpendicular to the longitudinal direction is 250 mm or more is used.

[0067] The cast steel is produced as a cast steel having a rectangular cross section by continuous casting or ingot casting. If the side length of the rectangular cross section is less than 250 mm, sulfide particles increase in size in the solidification of the cast steel. Consequently, coarse sulfides remain even after the cast steel is subsequently rolled to obtain a billet, which is disadvantageous in terms of sulfide refinement after final hot working. The side length of the cast steel in the cross section is therefore 250 mm or more.

[0068] The side length of the cast steel in the cross section is more preferably 300 mm or more. Although no upper limit is placed on the side length of the cast steel in the cross section, the side length is preferably 600 mm or less from the viewpoint of the rollability in the hot rolling following the casting.

(Hot Rolling of Cast Steel into Billet)

Heating Temperature of Cast Steel: 1120° C. Or More

[0069] The cast steel is hot rolled into a billet. The heating temperature in the hot rolling needs to be 1120° C. or more. If the heating temperature is less than 1120° C., coarse sulfides crystallized during cooling-solidification in the casting stage do not dissolve, and remain even in the billet. Consequently, the sulfides remain coarse even after the hot working, and the desired fine sulfide distribution state cannot be achieved. Accordingly, the heating temperature when hot rolling the cast steel into the billet is 1120° C. or more, and is preferably 1150° C. or more. Although no upper limit is placed on the heating temperature of the cast steel, the heating temperature is preferably 1300° C. or less and more preferably 1250° C. or less from the viewpoint of preventing scale loss.

Area Reduction Rate in Hot Rolling of Cast Steel into Billet: 60% or More

[0070] Since the sulfide particles crystallized during the solidification are large in size, the sulfide particles need to be reduced in size to some extent in bloom rolling. If the area reduction rate in the hot rolling is low, the sulfide particles remain large in the billet. In such a case, it is difficult to refine the sulfide particles in heating/rolling when subsequently hot working the billet into a steel bar or a wire rod. In view of this, the area reduction rate in the hot rolling of the cast steel into the billet is 60% or more.

[0071] The area reduction rate (%) in the hot rolling can be calculated according to the following formula:

$$100 \times (S0 - S1)/S0$$

[0072] where S0 is the cross-sectional area of a cross section perpendicular to the hot rolling direction of the cast steel before the hot rolling, and S1 is the cross-sectional area of a cross section perpendicular to the hot rolling direction of the billet produced as a result of the hot rolling.

(Hot Working of Billet)

Heating Temperature: 1050° C. or More

[0073] The heating temperature when hot working the billet into a steel bar or a wire rod is an important factor. If the heating temperature is less than 1050° C., the sulfides do not disperse finely, so that the lubricating action during cutting work is poor. This facilitates tool wear, and shortens the tool life. The heating temperature of the billet is therefore 1050° C. or more. The heating temperature of the billet is more preferably 1080° C. or more. Although no upper limit is placed on the heating temperature of the billet, the heating temperature is preferably 1250° C. or less from the viewpoint of suppressing a yield rate decrease caused by scale loss.

Area Reduction Rate in Hot Working: 75% or More

[0074] The area reduction rate when hot working the billet into a steel bar or a wire rod is also an important factor for sulfide refinement. If the area reduction rate is less than 75%, sulfide refinement is insufficient. Accordingly, the lower limit of the area reduction rate is 75%. The area reduction rate is more preferably 80% or more. The area reduction rate in the hot working can be calculated according to the following formula:

$$100 \times (S1 - S2)/S1$$

[0075] where S1 is the cross-sectional area of a cross section perpendicular to the hot working direction of the billet before the hot working, and S2 is the cross-sectional area of a cross section perpendicular to the hot working direction (stretching direction) of the steel bar or wire rod produced as a result of the hot working.

[0076] By limiting the size and the heating temperature of the bloom, the size and the heating temperature of the billet, and the area reduction rates to the respective appropriate ranges, the sulfides can be refined and the machinability by cutting can be improved.

Examples

[0077] The presently disclosed technique will be described in detail below by way of examples.

[0078] Steels having the chemical compositions listed in Table 1 were cast into rectangular cast steels having the dimensions listed in Table 2-1 and Table 2-2 in a cross section perpendicular to the longitudinal direction, by a continuous casting machine. The obtained cast steels were rolled into steel bars under the production conditions listed in Table 2-1 and Table 2-2. Disclosed steels (conforming steels) and comparative steels were subjected to the following test. In detail, the cast steels were each hot rolled at the corresponding heating temperature and area reduction rate in Table 2-1 and Table 2-2, to obtain a square billet having the corresponding long side dimension and short side dimension in Table 2-1 and Table 2-2. The obtained billet was heated at the corresponding heating temperature in Table 2-1 and Table 2-2, and hot rolled into a steel bar having the corresponding diameter in Table 2-1 and Table 2-2. Each of the obtained steel bars (disclosed steels and comparative steels) was subjected to the following test.

TABLE 1

(mass %)

No.	C	Si	Mn	P	S	Cr	Al	Sb	N	O	Others	A value*	Category
1	0.05	—	0.67	0.072	0.412	0.80	0.001	0.0010	0.0110	0.0295	—	11.0	Conforming Example
2	0.06	0.05	0.55	0.036	0.450	0.55	0.003	0.0040	0.0095	0.0245	—	6.1	Conforming Example
3	0.08	0.02	1.25	0.065	0.356	1.25	0.002	0.0040	0.0123	0.0159	—	17.6	Conforming Example
4	0.03	0.09	0.75	0.051	0.255	0.86	0.001	—	0.0105	0.0163	—	16.0	Conforming Example
5	0.04	0.01	0.83	0.049	0.523	0.98	0.001	—	0.0088	0.0204	—	8.8	Conforming Example
6	0.08	—	1.44	0.007	0.375	0.99	0.002	0.0010	0.0090	0.0288	Ca: 0.0005	15.6	Conforming Example
7	0.05	—	0.86	0.055	0.406	1.23	0.002	—	0.0086	0.0369	Se: 0.12	13.3	Conforming Example
8	0.07	0.02	0.55	0.082	0.324	0.76	0.002	—	0.0120	0.0234	Te: 0.15	10.4	Conforming Example
9	0.06	0.06	1.45	0.091	0.554	1.16	0.002	—	0.0099	0.0254	Bi: 0.05, Sn: 0.010	11.5	Conforming Example
10	0.04	0.01	0.92	0.081	0.543	1.15	0.001	0.0102	0.0060	0.0265	Sb: 0.045	9.7	Conforming Example
11	0.07	0.02	1.05	0.065	0.368	1.15	0.002	—	0.0063	0.0316	B: 0.0035	15.1	Conforming Example
12	0.07	0.02	0.78	0.078	0.435	0.97	0.001	—	0.0077	0.0203	C: 0.25, Ni: 0.15	10.3	Conforming Example
13	0.06	0.03	1.44	0.075	0.366	1.11	0.001	—	0.0096	0.0314	TiO: 0.056	17.0	Conforming Example
14	0.05	—	0.76	0.068	0.370	0.54	0.003	0.0006	0.0089	0.0163	V: 0.008, Zr: 0.06	8.5	Conforming Example
15	0.06	0.02	1.24	0.074	0.399	1.23	0.001	0.0006	0.0123	0.0234	Mg: 0.0009	15.5	Conforming Example
16	0.05	0.01	0.78	0.008	0.399	0.99	0.003	0.0068	0.0040	0.0132	—	11.4	Conforming Example
17	0.09	0.01	0.85	0.055	0.403	0.95	0.003	0.0025	0.0088	0.0126	—	11.3	Comparative Example
18	0.08	0.51	1.15	0.016	0.435	0.88	0.001	0.0025	0.0123	0.0168	—	11.4	Comparative Example
19	0.08	0.02	0.45	0.045	0.352	0.56	0.002	0.0036	0.0098	0.0201	—	7.3	Comparative Example
20	0.05	0.01	2.13	0.060	0.301	0.55	0.003	0.0056	0.0076	0.0176	—	19.6	Comparative Example
21	0.09	—	0.84	0.120	0.406	0.25	0.001	0.0019	0.0089	0.0155	—	6.0	Comparative Example
22	0.08	0.01	0.75	0.096	0.241	0.65	0.001	0.0019	0.0112	0.0201	—	14.3	Comparative Example
23	0.07	0.02	0.53	0.012	0.611	1.09	0.002	0.0019	0.0098	0.0196	—	7.1	Comparative Example
24	0.05	0.01	1.36	0.003	0.352	0.04	0.003	0.0019	0.0053	0.0162	—	8.1	Comparative Example
25	0.07	0.02	0.94	0.065	0.463	1.59	0.001	0.0019	0.0123	0.0246	—	14.4	Comparative Example
26	0.05	0.01	1.00	0.013	0.349	1.06	0.013	—	0.0062	0.0222	—	14.8	Comparative Example
27	0.06	—	1.34	0.065	0.391	1.25	0.003	0.0068	0.0170	0.0116	—	16.4	Comparative Example
28	0.05	0.53	0.63	0.023	0.406	0.95	0.001	0.0088	0.0123	0.0091	—	10.1	Comparative Example
29	0.07	0.03	1.36	0.098	0.369	0.95	0.003	0.0088	0.0076	0.0523	—	15.1	Comparative Example
30	0.08	0.02	0.68	0.023	0.531	0.57	0.001	0.0088	0.0116	0.0165	—	5.8	Comparative Example
31	0.04	—	1.25	0.089	0.312	1.08	0.004	0.0088	0.0084	0.0203	—	18.4	Comparative Example

*Avalue = 2(Mn + 2Cr)/S ratio: conforming range (6.0 to 18.0).

"—" in composition table denotes less than 0.01 for Si, and less than 0.003 for Sb.

[0079] A test piece was collected from a cross section parallel to the rolling direction of the obtained steel bar, and the ¼ position in the radial direction from the peripheral surface of the cross section was observed with a scanning electron microscope (SEM) to investigate the equivalent circle diameter and number density of sulfide in the steel. Here, precipitate composition analysis was conducted by energy dispersive X-ray spectrometry (EDX). The obtained SEM images of precipitates determined as sulfide by EDX were analyzed and binarized to calculate the equivalent circle diameter and the number density.

[0080] The machinability by cutting was evaluated by an outer periphery turning test. BNC-34C5 produced by Citizen Machinery Co., Ltd. was used as a cutting machine, Carbide EX35 Tool TNGG160404R-N produced by Hitachi Tool Engineering, Ltd. was used as a turning tip, and DTGNR2020 produced by KYOCERA Corporation was used as a holder. As a lubricant, a 15-fold diluted emulsion of YUSHIROKEN FGE1010 produced by Yushiro Chemical Industry Co., Ltd. was used. The cutting conditions were cutting rate: 120 m/min, feed rate: 0.05 mm/rev, cut depth: 2.0 mm, and machining length: 10 m.

[0081] The machinability by cutting was evaluated based on the flank wear Vb of the tool after the end of the cutting test over a length of 10 m. In the case where the flank wear Vb after the end of the cutting test was 200 μm or less, the machinability by cutting was evaluated as "good". In the case where the flank wear was more than 200 μm, the machinability by cutting was evaluated as "poor".

[0082] The test results of the disclosed steels and the comparative steels are shown in Table 2-1 and Table 2-2. As is clear from Table 2-1 and Table 2-2, the disclosed steels had favorable machinability by cutting as compared with the comparative steels.

TABLE 2-1

No.	Steel sample No.	Cast steel rolling (rolling cast steel into billet): Long side of cross section of cast steel (mm)	Short side of cross section of cast steel (mm)	Cross-sectional area (mm²)	Heating temperature (° C.)	Area reduction rate in cast steel rolling (%)	Linear rod rolling (rolling billet into steelbar): Long side of cross section of billet (mm)	Short side of cross section of billet (mm)	Cross-sectional area (mm²)	Heating temperature (° C.)	Steel bar diameter (mm)	Area reduction rate in linear rod rolling (%)	Properties of steelbar (inclusion distribution, machinability by cutting test result): Number density of sulfides of less than 1 µm in equivalent circle diameter (particles/mm²)	Number density of sulfides of 1 to 5 µm in equivalent circle diameter (particles/mm²)	Tool life (machinability by cutting)	Remarks
1	1	400	300	120000	1180	79	160	160	25600	1080	25	98	1273	2896	Good	Example
2	2	400	300	120000	1180	79	160	160	25600	1080	25	98	1011	2299	Good	Example
3	3	400	300	120000	1180	79	160	160	25600	1080	25	98	1817	4134	Good	Example
4	4	400	300	120000	1180	79	160	160	25600	1080	25	98	810	2343	Good	Example
5	5	400	300	120000	1180	79	160	160	25600	1080	25	98	1986	4518	Good	Example
6	6	400	300	120000	1180	79	160	160	25600	1080	25	98	1746	3971	Good	Example
7	7	400	300	120000	1180	79	160	160	25600	1080	25	98	1835	4174	Good	Example
8	8	400	300	120000	1180	79	160	160	25600	1080	25	98	913	2077	Good	Example
9	9	400	300	120000	1180	79	160	160	25600	1080	25	98	2843	6467	Good	Example
10	10	400	300	120000	1180	79	160	160	25600	1080	25	98	2380	5414	Good	Example
11	11	400	300	120000	1180	79	160	160	25600	1080	25	98	1678	3817	Good	Example
12	12	400	300	120000	1180	79	160	160	25600	1080	25	98	1611	3664	Good	Example
13	13	400	300	120000	1180	79	160	160	25600	1080	25	98	1823	4148	Good	Example
14	14	400	300	120000	1180	79	160	160	25600	1080	25	98	927	2108	Good	Example
15	15	400	300	120000	1180	79	160	160	25600	1080	25	98	2009	4571	Good	Example
16	1	420	350	147000	1180	83	160	160	25600	1080	25	98	1444	3001	Good	Example
17	1	400	300	120000	1220	79	160	160	25600	1080	25	98	1564	3265	Good	Example
18	1	400	300	120000	1180	84	140	140	19600	1080	25	97	1654	3269	Good	Example
19	1	400	300	120000	1180	84	140	140	19600	1130	25	97	1312	2130	Good	Example
20	1	400	300	120000	1180	84	140	140	19600	1080	15	99	1273	3356	Good	Example
21	4	250	250	62500	1120	60	158	158	24964	1050	89	75	511	2021	Good	Example
22	16	400	300	120000	1180	79	160	160	25600	1080	30	97	1124	2558	Good	Example

*1 Underlines indicate outside applicable range.
*2 Number density of sulfides of less than 1 µm in equivalent circle diameter: conforming range (at least 500 particles/mm^2).
*3 Number density of sulfides of 1 to 5 µm in equivalent circle diameter: conforming range (at least 2000 particles/mm^2).
*4 Tool life (machinability by cutting) good: tool wear of 200 µm or less, poor: tool wear of more than 200 µm.

TABLE 2-2

No.	Steel sample No.	Cast steel rolling (rolling cast steel into billet): Long side of cross section of cast steel (mm)	Short side of cross section of cast steel (mm)	Cross-sectional area (mm^2)	Heating temperature (° C.)	Area reduction rate in cast steel rolling (%)	Linear rod rolling (rolling billet into steel bar): Long side of cross section of billet (mm)	Short side of cross section of billet (mm)	Cross-sectional area (mm^2)
23	1	257	240	61680	1120	60	158	158	24964
24	1	230	230	52900	1180	52	160	160	25600
25	1	400	300	120000	1100	79	160	160	25600
26	1	250	250	62500	1180	59	160	160	25600
27	1	400	300	120000	1180	79	160	160	25600
28	1	400	300	120000	1180	79	160	160	25600
29	17	400	300	120000	1180	79	160	160	25600
30	18	400	300	120000	1180	79	160	160	25600
31	19	400	300	120000	1180	79	160	160	25600
32	20	400	300	120000	1180	79	160	160	25600
33	21	400	300	120000	1180	79	160	160	25600
34	22	400	300	120000	1180	79	160	160	25600
35	23	400	300	120000	1180	79	160	160	25600
36	24	400	300	120000	1180	79	160	160	25600
37	25	400	300	120000	1180	79	160	160	25600
38	26	400	300	120000	1180	79	160	160	25600
39	27	400	300	120000	1180	79	160	160	25600
40	28	400	300	120000	1180	79	160	160	25600
41	29	400	300	120000	1180	79	160	160	25600
42	30	400	300	120000	1180	79	160	160	25600
43	31	400	300	120000	1180	79	160	160	25600

No.	Linear rod rolling (rolling billet into steel bar): Heating temperature (° C.)	Steel bar diameter (mm)	Area reduction rate in linear rod rolling (%)	Properties of steel bar (inclusion distribution, machinability by cutting test result): Number density of sulfides of less than 1 μm in equivalent circle diameter (particles/mm^2)	Number density of sulfides of 1 to 5 μm in equivalent circle diameter (particles/mm^2)	Tool life (machinability by cutting)	Remarks
23	1050	89	75	483	2034	Poor	Comparative Example
24	1080	25	98	324	1804	Poor	Comparative Example
25	1080	25	98	514	1589	Poor	Comparative Example
26	1080	25	98	569	1756	Poor	Comparative Example
27	1030	25	98	1023	1465	Poor	Comparative Example
28	1080	95	72	468	1786	Poor	Comparative Example
29	1080	30	97	1131	2574	Poor	Comparative Example
30	1080	30	97	1292	2940	Poor	Comparative Example
31	1080	30	97	456	1114	Poor	Comparative Example
32	1080	30	97	356	1375	Poor	Comparative Example
33	1080	30	97	756	2146	Poor	Comparative Example
34	1080	30	97	467	1805	Poor	Comparative Example
35	1080	30	97	444	1769	Poor	Comparative Example
36	1080	30	97	324	1657	Poor	Comparative Example
37	1080	30	97	1156	2146	Poor	Comparative Example
38	1080	30	97	1112	2529	Poor	Comparative Example
39	1080	30	97	1533	3487	Poor	Comparative Example
40	1080	30	97	1154	2179	Poor	Comparative Example
41	1080	30	97	1232	2217	Poor	Comparative Example
42	1080	30	97	430	1567	Poor	Comparative Example
43	1080	30	97	398	1765	Poor	Comparative Example

*1 Underlines indicate outside applicable range.
*2 Number density of sulfides of less than 1 μm in equivalent circle diameter: conforming range (at least 500 particles/mm^2).
*3 Number density of sulfides of 1 to 5 μm in equivalent circle diameter: conforming range (at least 2000 particles/mm^2).
*4 Tool life (machinability by cutting) good: tool wear of 200 μm or less, poor: tool wear of more than 200 μm

1. A method of producing a free-cutting steel, the method comprising:

rolling a rectangular cast steel at a heating temperature of 1120° C. or more and an area reduction rate of 60% or more to obtain a billet, the rectangular cast steel having a chemical composition that contains, in mass %,

C: less than 0.09%,

Mn: 0.50% to 1.50%,

S: 0.250% to 0.600%,

O: more than 0.010% and 0.050% or less, and

Cr: 0.50% to 1.50%

with a balance consisting of Fe and inevitable impurities, and in which a A value defined by the following formula (1) is 6.0 to 18.0,

$$\text{A value} = 2([\text{Mn}] + 2[\text{Cr}])/[\text{S}] \tag{1}$$

where [Mn], [Cr], and [S] respectively denote contents in mass % of elements Mn, Cr, and S, and a side length of a cross section of the rectangular cast steel perpendicular to a longitudinal direction being 250 mm or more; and

hot working the billet at a heating temperature of 1050° C. or more and an area reduction rate of 75% or more.

2. The method of producing a free-cutting steel according to claim 1, wherein the chemical composition further contains, in mass %, one or more selected from the group consisting of

Si: 0.50% or less,

P: 0.10% or less,

Al: 0.010% or less, and

N: 0.0150% or less.

3. The method of producing a free-cutting steel according to claim 1, wherein the chemical composition further contains, in mass %, one or more selected from the group consisting of

Ca: 0.0010% or less,

Se: 0.30% or less,

Te: 0.15% or less,

Bi: 0.20% or less,

Sn: 0.020% or less,

Sb: 0.025% or less,

B: 0.010% or less,

Cu: 0.50% or less,

Ni: 0.50% or less,

Ti: 0.100% or less,

V: 0.20% or less,

Zr: 0.050% or less, and

Mg: 0.0050% or less.

4. The method of producing a free-cutting steel according to claim 2, wherein the chemical composition further contains, in mass %, one or more selected from the group consisting of

Ca: 0.0010% or less,

Se: 0.30% or less,

Te: 0.15% or less,

Bi: 0.20% or less,

Sn: 0.020% or less,

Sb: 0.025% or less,

B: 0.010% or less,

Cu: 0.50% or less,

Ni: 0.50% or less,

Ti: 0.100% or less,

V: 0.20% or less,

Zr: 0.050% or less, and

Mg: 0.0050% or less.

* * * * *