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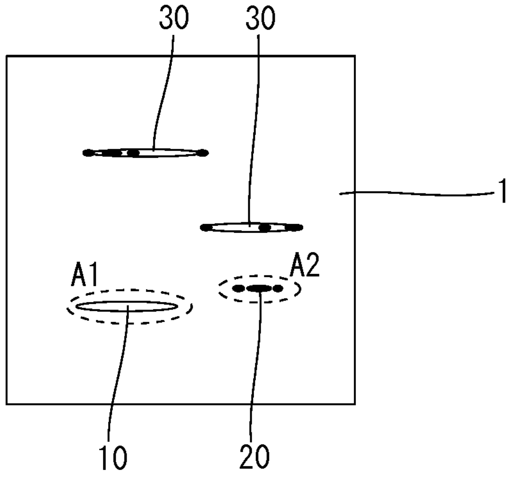
(54) FREE-CUTTING STEEL

(57) A free-cutting steel is provided that is excellent in machinability (surface roughness, tool life, chip treatability) and rusting characteristics. The free-cutting steel of this invention has a chemical composition that contains, in mass%, C: 0.005 to 0.150%, Si: less than 0.010%, Mn: 1.02 to 2.00%, P: 0.010 to 0.200%, S: 0.350 to 0.600%, Pb: 0.010 to 0.100%, N: 0.004 to 0.015%, O: 0.0080 to 0.0250%, Al: 0 to 0.003%, one or more types of element selected from a group consisting of Ca, Mg and Zr: 0 to 0.0005% in total, and B: 0 to 0.0200%, with the balance being Fe and impurities, the chemical composition satisfying Formula (1):

$$\mathrm{Mn/S} \geq 2.90 \qquad (1)$$

where, the content (mass%) of a corresponding element is substituted for each symbol of an element in Formula (1).

FIG. 1C



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Description

TECHNICAL FIELD

[0001] The present invention relates to free-cutting steel, and more specifically relates to free-cutting steel that is produced into components by cutting.

BACKGROUND ART

[0002] Surface quality is important for components that are to be used as small-size hydraulic components, shafts of office automation equipment, and axles of hinge parts and the like. To enhance the form accuracy and surface properties, these components are usually subjected to cutting and, as necessary, are thereafter subjected to a surface finishing treatment such as polishing or a plating process. To ensure the quality of the surface of components for such uses (hereunder, also referred to as "cut components"), free-cutting steel is used to produce these components. Among the various kinds of free-cutting steel, those based on low-carbon steel are defined, for example, in Standard No. JIS G 4804 (2008) that is published by the Japanese Industrial Standards Committee (Non Patent Literature 1). Among the free-cutting steels defined in JIS G 4804 (2008), those containing a large amount of Pb as typified by SUM24L is used for the aforementioned cut components for which surface quality is required.

[0003] A free-cutting steel that contains a large amount of Pb such as SUM24L is considered to be excellent with respect to ease of cutting of the steel material, that is, excellent in machinability. In particular, among the various aspects of machinability, in many cases the cut surface properties (surface roughness) are determined by a combination of the steel and the industrial tools, and a steel material containing a large amount of Pb is considered to be excellent in surface roughness.

[0004] However, because Pb has an adverse impact on the environment, it is highly possible that Pb will be designated as an environmentally hazardous substance. If Pb is designated as an environmentally hazardous substance, use thereof will be restricted. In such case, it will no longer be possible to use free-cutting steels that contain a large amount of Pb.

[0005] Instead of the free-cutting steels that contain a large amount of Pb, an alternative free-cutting steel is proposed in Japanese Patent Application Publication No. 2004-27297 (Patent Literature 1). In the free-cutting steel disclosed in Patent Literature 1, the Pb content is suppressed and a large amount of S is contained instead of Pb, and the shapes of inclusions such as MnS are controlled. By this means, machinability that is superior to the conventional lead free-cutting steel is secured.

CITATION LIST

PATENT LITERATURE

[0006] Patent Literature 1: Japanese Patent Application Publication No. 2004-27297

NON PATENT LITERATURE

[0007] Non Patent Literature 1: Japanese Industrial Standards Committee, Standard No.: JIS G 4804 (2008), Standard Name: Free-cutting Steels

SUMMARY OF INVENTION

TECHNICAL PROBLEM

[0008] When producing a cut component, the surface properties of the cut surface, such as the surface roughness, are important, and it is preferable from the aspects of both the performance of the component and the production cost if the cut component can be finished only by cutting. Even in a case where it is necessary to carry out a grinding process following a cutting process, if the cut surface has a large surface roughness or if defects remain, it is difficult to finish the cut component with the polishing process. Accordingly there is a need to suppress the surface roughness of the cut surface to a small amount.

[0009] In addition, in the case of producing cut components in a large amount with an automated equipment system, such as producing 1,000 or more components per day, excellent chip treatability is required. Chips that are discharged following cutting are preferably split into small pieces and discharged. In a case where chips remain connected in a long length, the chips are liable to become entwined around the cut component, and defects are liable to arise on the surface of the cut component. In a case where a chip is entwined around a cut component, it is also necessary to temporarily stop the production line to remove the chip entwined around the cut component. In this case, it is difficult to perform unattended production, and it is necessary to assign personnel to monitor production. Thus, chip treatability affects both the quality of cut components and the production cost.

[0010] In the case of cut components to be used for various kinds of precision instruments such as electronic components, hydraulic components and sliding components, in order to suppress the occurrence of rust during use and also improve wear resistance, the outermost surface of the component may be subjected to plating, and a treatment may also be performed for increasing the affinity to resin on the component surface.

[0011] After cutting, in some cases the components (cut components) are stored in a bucket or the like for a long time period before the next process after cutting. For example, in a case where components are cut in a certain country and the next process is performed in a separate factory in a different country, a period of several days to several months may pass after cutting until the cut components are subjected to the next process. In such a case, it is required to suppress the occurrence of rusting of the cut components.

[0012] An objective of the present invention is to provide a free-cutting steel that is excellent in machinability (surface roughness, tool life and chip treatability) and rusting characteristics.

SOLUTION TO PROBLEM

[0013] A free-cutting steel according to the present embodiment has a chemical composition that contains, in mass%: C: 0.005 to 0.150%, Si: less than 0.010%, Mn: 1.02 to 2.00%, P: 0.010 to 0.200%, S: 0.350 to 0.600%, Pb: 0.010 to 0.100%, N: 0.004 to 0.015%, O: 0.0080 to 0.0250%, Al: 0 to 0.003%, one or more types of element selected from a group consisting of Ca, Mg and Zr: 0 to 0.0005% in total, and B: 0 to 0.0200%, with the balance being Fe and impurities, the chemical composition satisfying Formula (1):

$$\mathrm{Mn/S} \geq 2.90 \qquad (1)$$

where, a content (mass%) of a corresponding element is substituted for each symbol of an element in Formula (1).

ADVANTAGEOUS EFFECTS OF INVENTION

[0014] The free-cutting steel according to the present invention is excellent in machinability (surface roughness, tool life and chip treatability) and rusting characteristics.

BRIEF DESCRIPTION OF DRAWINGS

[0015]

[FIG. 1A] FIG. 1A is a schematic diagram illustrating an S distribution in an observation surface, that is obtained by EPMA analysis.
[FIG. 1B] FIG. 1B is a schematic diagram illustrating a Pb distribution in the same observation surface as in FIG. 1A, that is obtained by EPMA analysis.
[FIG. 1C] FIG. 1C is a schematic diagram of an image obtained by combining FIG. 1A and FIG. 1B.
[FIG. 2] FIG. 2 is a schematic diagram for describing a criterion for determining whether or not to regard adjacent inclusions as a single inclusion.
[FIG. 3] FIG. 3 is a transverse sectional view of a starting material that was cast.
[FIG. 4] FIG. 4 is a schematic diagram of a cutting test machine for describing a cutting test.
[FIG. 5A] FIG. 5A is a perspective view of a chip.
[FIG. 5B] FIG. 5B is a planar photographic view of a chip.

DESCRIPTION OF EMBODIMENTS

[0016] The present inventors investigated and examined the machinability and rusting characteristics of free-cutting steel, and obtained the following findings.

[0017] Mn and Pb in steel form MnS inclusions, Pb inclusions, and composite inclusions that contain MnS inclusions and Pb. In the present description, the term "MnS inclusions" refers to inclusions that contain Mn and S with the balance being impurities. The term "Pb inclusions" refers to inclusions composed of Pb and impurities. The term "composite inclusions" refers to inclusions that contain MnS and Pb with the balance being impurities. There are cases where MnS and Pb are adjacent to each other and form a composite inclusion, and there are also cases where Pb dissolves into MnS to form a composite inclusion. In the following description, MnS inclusions, Pb inclusions and composite inclusions are referred to collectively as "specific inclusions".

[0018] MnS inclusions are already known as inclusions that enhance machinability. On the other hand, the fusing point of Pb inclusions is lower than the fusing point of MnS inclusions. Consequently, Pb inclusions exert a lubricating action during cutting, and as a result the machinability is enhanced.

[0019] In addition, it is considered that composite inclusions enhance machinability more than individual MnS inclusions and Pb inclusions. In a case where a fissure has arisen at the periphery of a composite inclusion, liquefied Pb enters into the open crack. By this means, propagation of the crack is promoted and machinability is enhanced. Accordingly, if specific inclusions that include composite inclusions are formed, the machinability is enhanced.

[0020] It is easier for Pb to move in liquid phase than in solid phase. Therefore, composite inclusions are not formed from MnS that precipitates after solidification, but are formed by Pb adhering to MnS that crystallized in molten steel. Accordingly, in order to form a large number of composite inclusions, it is preferable that MnS can be formed by crystallization.

[0021] On the other hand, these specific inclusions serve as the starting point for rust. The generation of rust depends on the number of specific inclusions, and does not depend on the size of the specific inclusions. As described above, in some cases MnS inclusions crystallize in the molten steel, and in some cases MnS inclusions precipitate after solidification. The size of MnS inclusions formed by crystallization is larger than the size of MnS inclusions formed by precipitation. Consequently, in a case where MnS inclusions are formed by precipitation, the number of MnS inclusions is markedly greater than the number of MnS inclusions formed by crystallization. Therefore, in order to decrease the starting points for rust while obtaining machinability, it is preferable to form MnS inclusions by crystallization as much as possible.

[0022] To form a large amount of MnS inclusions by crystallization, it is necessary to have a sufficient Mn content relative to the S content in the steel. Specifically, the Mn content and S content satisfy the following Formula (1):

$$\mathrm{Mn/S} \geq 2.90 \qquad (1)$$

where, the content (mass%) of a corresponding element is substituted for each symbol of an element in Formula (1).

[0023] Herein, it is defined F1 = Mn/S. If the Mn content is small relative to the S content, it is difficult for MnS to crystallize in the molten steel. As long as F1 is 2.90 or more, the Mn content is sufficiently large relative to the S content. In this case, it is easy for MnS to crystallize in the liquid phase. Therefore, composite inclusions of a sufficient amount for obtaining machinability are formed, and a sufficient amount of specific inclusions that include the composite inclusions is obtained. As a result, excellent machinability is obtained. In addition, because the number of fine MnS inclusions can be prevented from excessively increasing, the number of starting points for the occurrence of rust can be suppressed. As a result, the rusting characteristics can be enhanced.

[0024] A free-cutting steel according to the present invention that was completed based on the above findings has a chemical composition that contains, in mass%, C: 0.005 to 0.150%, Si: less than 0.010%, Mn: 1.02 to 2.00%, P: 0.010 to 0.200%, S: 0.350 to 0.600%, Pb: 0.010 to 0.100%, N: 0.004 to 0.015%, O: 0.0080 to 0.0250%, Al: 0 to 0.003%, one or more types of element selected from a group consisting of Ca, Mg and Zr: 0 to 0.0005% in total, and B: 0 to 0.0200%, with the balance being Fe and impurities, the chemical composition satisfying Formula (1):

$$\mathrm{Mn/S} \geq 2.90 \qquad (1)$$

where, the content (mass%) of a corresponding element is substituted for each symbol of an element in Formula (1).

[0025] The chemical composition of the free-cutting steel described above may contain Al: 0.001 to 0.003%. The chemical composition of the free-cutting steel described above may contain one or more types of element selected from a group consisting of Ca, Mg and Zr in a total content of 0.0001 to 0.0005%. The chemical composition of the free-cutting steel described above may contain B: 0.0005 to 0.0200%.

[0026] Preferably, in the free-cutting steel described above, a ratio of the number of Pb inclusions to the total number of specific inclusions is 17% or less.

[0027] In this case, the rusting characteristics are further enhanced.

[0028] Hereunder, the free-cutting steel according to the present invention is described in detail. The chemical composition of the free-cutting steel according to the present invention contains the following elements. The symbol "%" in relation to an element means "mass%" unless specifically stated otherwise.

[Chemical Composition]

[0029] The chemical composition of the free-cutting steel of the present embodiment contains the following elements.

C: 0.005 to 0.150%

[0030] Carbon (C) enhances the fundamental strength of the steel. A free-cutting steel that is produced into cut components is normally cut after being subjected to working such as wire drawing. If the C content is 0.005% or more, the strength of the free-cutting steel will be a strength suitable for the tool life of the cutting tool and the surface roughness after wire drawing. If the C content is less than 0.005%, the steel will be soft, and wire drawing and cutting will be difficult. In particular, tearing is liable to occur during cutting. On the other hand, if the C content is more than 0.150%, the steel will harden and the cold workability will decrease, and furthermore tool wear will be severe during cutting after wire drawing. Accordingly, the C content is 0.005 to 0.150%. A preferable lower limit of the C content is 0.06%. A preferable upper limit of the C content is 0.120%. If the C content is from 0.06 to 0.120%, the occurrence rate of rolling defects will decrease.

Si: less than 0.010%

[0031] Silicon (Si) usually deoxidizes steel. However, in the present invention it is necessary to cause oxygen (O) to remain in the steel to a certain extent to control the shape of MnS. If the Si content is too high, the O concentration in the steel will be too low. Further, if the Si content is too high, hard oxides such as SiO_2 will remain in the steel and the machinability will decrease. Furthermore, the oxygen amount contained in MnS is, on the contrary, decreased by formation of hard oxides. In this case, MnS is elongated by rolling and wire drawing, and MnS having a large aspect ratio is formed. The MnS having a large aspect ratio decreases the surface roughness (surface property). Therefore, the Si content is less than 0.010%.

Mn: 1.02 to 2.00%

[0032] Although manganese (Mn) deoxidizes the steel, the deoxidizing power thereof is weak compared to other deoxidizing elements such as Si or Al, and hence containment of a large amount of Mn is allowed. Mn also enhances the strength of the steel. In addition, Mn combines with S in the steel to form MnS, and thereby enhances the machinability. In free-cutting steel containing a large amount of S, MnS will not crystallize unless Mn is also contained in a large amount.

[0033] According to the present invention, in order to cause MnS to crystallize in the steel in the steel making process, a sufficient content of Mn relative to the S content is contained. If the Mn content is less than 1.02%, crystallization of MnS will be delayed because the Mn content is not sufficient relative to the S content. In this case, the amount of MnS that precipitates after solidification will increase. If MnS is caused to crystallize, the compositing ratio of MnS with Pb is higher than when MnS is caused to precipitate and the machinability is enhanced. Accordingly, if the Mn content is less than 1.02%, the machinability decreases. On the other hand, if the Mn content is more than 2.00%, the hardenability of the steel will be too high and the steel will become brittle. Consequently, surface defects will easily arise when rolling or wire drawing is performed. Accordingly, the Mn content is 1.02 to 2.00%. A preferable lower limit of the Mn content is 1.10%, and further preferably is 1.30%.

P: 0.010 to 0.200%

[0034] Phosphorus (P) embrittles the steel and enhances machinability. In the present invention, because the content of C that enhances the strength is low, P also enhances the strength of the steel together with Mn. If the P content is less than 0.010%, the machinability will be low and the surface roughness will be inferior. In addition, the strength of the steel will be insufficient. On the other hand, if the P content is more than 0.200%, the hot ductility of the steel will decrease, rolling defects will easily occur and manufacturing stability will be lost. Accordingly, the P content is 0.010 to 0.200%. A preferable lower limit of the P content is 0.050%. A preferable upper limit of the P content is 0.100%.

S: 0.350 to 0.600%

[0035] Sulfur (S) forms MnS in the steel and enhances the machinability. If the S content is less than 0.350%, sufficient machinability is not obtained. On the other hand, if the S content is more than 0.600%, grain boundary embrittlement is liable to occur due to grain-boundary segregation. Accordingly, the S content is 0.350 to 0.600%. A preferable lower limit of the S content is 0.400%. A preferable upper limit of the S content is 0.550%. In the case of prioritizing machinability, a preferable range of the S content is 0.450 to 0.500%. In the case of prioritizing producibility, a preferable range of the

S content is 0.400 to 0.450%.

Pb: 0.010 to 0.100%

[0036] Lead (Pb) enhances the machinability of the steel. If the Pb content is less than 0.010%, the machinability will be insufficient. On the other hand, if the Pb content is more than 0.100%, the steel will become brittle and the producibility will decrease, and rolling defects will easily occur. Furthermore, if the Pb content is more than 0.100%, a large amount of independently existing Pb inclusions (lead grains) will arise and the rusting characteristics will decrease. Therefore the Pb content is 0.010 to 0.100%. A preferable lower limit of the Pb content is 0.020%. A preferable upper limit of the Pb content is 0.040%. If the Pb content is 0.020 to 0.040%, a decrease in the rust characteristics is suppressed, and the machinability is further enhanced by Pb combining with MnS.

N: 0.004 to 0.015%

[0037] Although nitrogen (N) enhances the strength of the steel and increases the cutting resistance during cutting, N improves the surface roughness. If the N content is 0.004% or more, the aforementioned effects are obtained. Note that, if the N content is made less than 0.004%, the production cost will become too high and industrial production will be difficult. On the other hand, if the N content is made more than 0.015%, the steel material becomes brittle and surface defects are liable to occur during rolling and during wire drawing. Accordingly, the N content is 0.004 to 0.015%. In the case of prioritizing machinability, a preferable lower limit of the N content is 0.007%, and in the case of prioritizing producibility, a preferable upper limit of the N content is 0.012%. Note that, as used herein the term "N content" means the total content of N (T-N).

[0038] In a case where B that is described later is contained, N combines with B to form BN and thereby further enhance the machinability of the steel. In that case, the N content is preferably made equal to the B content.

O: 0.0080 to 0.0250%

[0039] Oxygen (O) forms oxides. O is also contained in sulfides, and controls the form of the sulfides. Specifically, O is contained in MnS, and suppresses elongation of MnS during rolling and during wire drawing. If the O content is less than 0.0080%, because the oxygen content in the MnS will be too low, the MnS will be elongated during rolling and during wire drawing, and the aspect ratio thereof will be too large. On the other hand, if the O content is more than 0.0250%, defects are liable to arise in the cast micro-structure. In addition, a large amount of oxides will be generated and the machinability of the steel will decrease. Generation of a large amount of oxides also promotes melting loss of the refractory of the production line and decreases the manufacturing stability. Accordingly, the O content is 0.0080 to 0.0250%. A preferable lower limit of the O content is 0.0120%, and further preferably is 0.0150%. A preferable upper limit of the O content is 0.0200%, and further preferably is 0.0180%. Note that, as used herein the term "O content" means the total content of O (T-O).

[0040] The balance of the chemical composition of the free-cutting steel according to the present invention is Fe and impurities. Here, the term "impurities" refers to elements which, during industrial production of the steel material, are mixed in from ore or scrap that is used as a raw material, or from the production environment or the like.

[Optional Elements]

[0041] The chemical composition of the free-cutting steel according to the present invention may further contain Al.

Al: 0 to 0.003%

[0042] Aluminum (Al) is an optional element. Al is a deoxidizing element of the steel. However, in the present invention, it is necessary to cause oxygen to remain in the steel to a certain extent to control the shape of MnS. If the Al content is more than 0.003%, the oxygen amount in the MnS will be too low, and the MnS will be elongated by rolling and wire drawing and the aspect ratio of the MnS will become too large and will deteriorate the surface roughness. If the Al content is more than 0.003%, alumina-based inclusions (hard oxides) will remain in the steel and the machinability of the steel will decrease. Accordingly, the Al content is 0 to 0.003%. A preferable lower limit of the Al content is 0.001%. Note that, as used herein the term "Al content" means the total content of Al (t-Al).

[0043] The chemical composition of the free-cutting steel according to the present invention may further contain one or more types of element selected from the group consisting of Ca, Mg and Zr. These elements are optional elements.

[0044] One or more types of element selected from Ca, Mg and Zr: 0 to 0.0005% in total

[0045] Calcium (Ca), magnesium (Mg) and zirconium (Zr) each control the form of inclusions and precipitates, and enhance the workability of the steel. Each of these elements is described hereunder.

[0046] Ca forms composite sulfides (Mn, Ca)S with MnS and CaS, and suppresses elongation of MnS during rolling and during wire drawing. By this means, the workability and machinability of the steel increase. However, if the Ca content is more than 0.0005%, the oxygen content in the MnS will decrease, and MnS having a large aspect ratio will be formed by rolling and wire drawing. Accordingly, the upper limit of the Ca content is 0.0005%, and more preferably is 0.0003%. A preferable lower limit of the Ca content is 0.0001%.

[0047] Magnesium (Mg) forms composite sulfides (Mn, Mg)S with MnS and MgS, and suppresses elongation of MnS. By this means, the workability and machinability of the steel increase. Mg also forms fine Mg oxides that serve as the product nuclei for sulfides such as MnS. By this means, the number of large MnS-based inclusions can be increased. On the other hand, if the Mg content is more than 0.0005%, the oxygen content in the MnS decreases and the MnS is liable to undergo elongation. In addition, a large amount of oxides are generated in the molten steel and adhere to the refractory or adhere to a nozzle and cause the nozzle to clog. Accordingly, the upper limit of the Mg content is 0.0005%. A preferable lower limit of the Mg content is 0.0001%.

[0048] Zirconium (Zr) forms oxides, sulfides and nitrides, and controls the form of inclusions and precipitates. A preferable lower limit of the Zr content for controlling the form of inclusions and increasing the workability and machinability of the steel is 0.0002%. On the other hand, if the Zr content is too high, the oxygen content in the MnS decreases and the MnS is liable to undergo elongation. In addition, a large amount of hard oxides are formed and the machinability decreases. Accordingly, the upper limit of the Zr content is 0.0005%, and more preferably is 0.0003%. A preferable lower limit of the Zr content is 0.0001%.

[0049] In the present invention, the content of the aforementioned one or more types of element selected from the group consisting of Ca, Mg and Zr is 0 to 0.0005% in total. In this case, as described above, the aforementioned one or more types of element controls the form of precipitates and inclusions, and increases the workability of the steel. Preferably, two or more types of element selected from the group consisting of Ca, Mg and Zr are contained. In this case, a large number of spherical sulfides can be dispersed, which further enhances the workability of the steel. A further preferable upper limit of the total content of these elements is 0.0003%. A preferable lower limit of the total content of these elements is 0.0001%.

[0050] The free-cutting steel of the present embodiment may also contain B. B is an optional element.

B: 0 to 0.0200%

[0051] Boron (b) combines with N to form BN, and thereby enhances the machinability of the steel. In a case where BN is present at the grain boundaries, BN enhances the machinability by embrittling the grain boundaries. In a case where BN is present at the periphery of MnS, an embrittlement effect caused by concentration of stress of the MnS is promoted as a result of BN suppressing deformation of the sulfides, and the machinability of the steel is enhanced. However, if the B content is more than 0.0200%, B oxides are generated and, on the contrary, the machinability of the steel decreases and the B oxides react with the refractory and promote melting loss. Accordingly, the B content is 0 to 0.0200%. A preferable lower limit of the B content for further effectively enhancing the machinability is 0.0005%, and more preferably is 0.0008%. A preferable upper limit of the B content is 0.0150%. To form a large amount of BN and further enhance the machinability of the steel, it is preferable to make the B content satisfy the formula $0.7 \leq B/N \leq 1.8$.

[Regarding Formula (1)]

[0052] The chemical composition of the aforementioned free-cutting steel further satisfies Formula (1):

$$\mathrm{Mn/S} \geq 2.90 \qquad (1)$$

where, the content (mass%) of a corresponding element is substituted for each symbol of an element in Formula (1).

[0053] Herein, it is defined that F1 = Mn/S. If the Mn content is small relative to the S content, it is difficult for MnS to crystallize in molten steel. As a result, dissolved S is liable to remain at the grain boundaries after solidification, and in many cases causes the hot ductility to deteriorate. In this case, MnS precipitates after solidification. The precipitated MnS is extremely fine compared to the crystallized MnS. In addition, the number of precipitated MnS is extremely large compared to the number of crystallized MnS. MnS can become a starting point for the occurrence of rust. Accordingly, the greater the number of MnS is, the more the rusting characteristics deteriorate. In addition, although Pb is liable to adhere to crystallized MnS in the liquid phase, it is difficult for Pb to adhere to precipitated MnS in the solid phase. Accordingly, it is difficult for composite inclusions to be formed.

[0054] If F1 is 2.90 or more, the Mn content is sufficiently large relative to the S content. In this case, it is easy for MnS to crystallize in the liquid phase. Consequently, specific inclusions of an adequate amount for obtaining machinability are obtained, and excellent machinability is obtained. In addition, the number density of fine MnS can be kept from becoming excessively large, and the generation of starting points for the occurrence of rust can be suppressed. As a result, the rusting characteristics can be enhanced. A preferable lower limit of F1 is 3.00, and further preferably is 3.30. The higher that F1 is, the greater the amount of MnS that can be crystallized in the liquid phase from the initial stage of solidification, and as a result, composite inclusions of MnS and Pb are liable to be formed.

[Number TN of coarse specific inclusions]

[0055] Preferably, in the free-cutting steel of the present embodiment, the total number of specific inclusions that are any of MnS inclusions, Pb inclusions and composite inclusions and that have an equivalent circular diameter of 10 μm or more is 200 to 10,000 per mm^2 or more. In this case, the rusting characteristics are further enhanced. Hereunder, specific inclusions having an equivalent circular diameter of 10 μm or more are referred to as "coarse specific inclusions"

[0056] Herein, the term "Pb inclusion" means an independent Pb grain. The composite inclusions contain MnS and Pb.

[0057] The coarse specific inclusions enhance machinability. In particular, MnS inclusions and composite inclusions of MnS and Pb, which have an equivalent circular diameter of 10 μm or more, enhance chip treatability. In the case of composite inclusions, because Pb that was softened by cutting heat penetrates into fissures that have arisen and promotes propagation of the fissures, the chip treatability is particularly enhanced.

[Ratio of number of Pb inclusions to number of coarse specific inclusions (Pb ratio) RA]

[0058] Further preferably, among the coarse specific inclusions, a ratio of the number of Pb inclusions to the total number of coarse specific inclusions (hereunder, referred to as "Pb ratio") RA is 17% or less. The higher the Pb ratio RA is, the greater the number of Pb inclusions will be. As described above, Pb inclusions lower the rusting characteristics. Accordingly, it is preferable for the proportion that the Pb inclusions occupy among the coarse specific inclusions to be low. If the Pb ratio RA is 17% or less, the number of Pb inclusions is sufficiently small. Therefore, the rusting characteristics are further enhanced. A preferable upper limit of the Pb ratio RA is 13%.

[Method of measuring number TN of coarse specific inclusions, and Pb ratio RA]

[0059] The number TN and the Pb ratio RA are measured by the following methods. A sample is taken from the free-cutting steel. For example, in a case where the free-cutting steel is a steel bar or a wire rod, from a transverse cross-section (a face perpendicular to the axial direction), a sample is taken at a central part (hereunder, referred to as "R/2 part") of a radius R that links the surface and the central axis. Using a scanning electron microscope (SEM), 20 visual fields at a transverse cross-section (surface) of the sample of the R/2 part are randomly observed at a magnification of ×1000. Specific inclusions (MnS inclusions, Pb inclusions and composite inclusions) are identified in the respective visual fields (referred to as "observation surfaces"). It is possible to distinguish specific inclusions and other inclusions by means of contrast. In addition, among the specific inclusions, MnS inclusions, Pb inclusions and composite inclusions are respectively identified by the following method.

[0060] For each observation surface, an image of the S distribution and Pb distribution in the observation surface is obtained by means of an X-ray spectroscopy wavelength dispersion device (EPMA). FIG. 1A is a schematic diagram illustrating the S distribution in an observation surface, which was obtained by EPMA analysis. FIG. 1B is a schematic diagram illustrating the Pb distribution in the same observation surface as in FIG. 1A, which was obtained by EPMA analysis.

[0061] Reference numeral 10 in FIG. 1A denotes a region in which S is present. Because S is almost entirely present as MnS, MnS can be regarded as being present at the locations indicated by each reference numeral 10 in FIG. 1A. Reference numeral 20 in FIG. 1B denotes a region in which Pb is present.

[0062] As illustrated in FIG. 1B, in some cases, as shown by reference numeral 20A, Pb is divided by rolling or the like and is arranged in the rolling direction. The same applies with respect to S. As illustrated in FIG. 2, in an image obtained by EPMA analysis, in a case where adjacent inclusions IN have an equivalent circular diameter of 5 μm or more, if a distance D between the adjacent inclusions IN is not more than 10 μm, these inclusions IN are regarded as a single inclusion. Note that, the area of the identified inclusion is determined, and the diameter of a circle of the same area as the determined area is defined as an "equivalent circular diameter" (μm). In the case of an inclusion group defined as a single inclusion, the equivalent circular diameter is taken as the diameter of a circle having the same total area as the inclusion group.

[0063] FIG. 1C is an image in which FIG. 1B is combined with FIG. 1A. Referring to FIG. 1C, in the case where the Pb inclusions 20 overlap with the MnS inclusions 10, the relevant inclusions are recognized as being composite inclusions 30. On the other hand, referring to FIG. 1C, in the case where the MnS inclusion 10 and the Pb inclusion 20 do not overlap (region A1 and region A2 and the like in FIG. 1C), the relevant inclusions are identified as an MnS inclusion and a Pb inclusion.

[0064] By the above method, MnS-based inclusions, Pb inclusions and composite inclusions are identified using a scanning microscope and EPMA. The area of the respective inclusions that are identified is determined, and the diameter of a circle with the same area is defined as the equivalent circular diameter (μm) for each of the inclusions.

[0065] Among the respective specific inclusions, coarse specific inclusions for which the equivalent circular diameter is 10 μm or more are identified. The total number (number in 20 visual fields) of the coarse specific inclusions that are identified is determined, and is converted to a number TN per mm^2 (inclusions/mm^2). The number TN is determined by the above method. In addition, among the coarse specific inclusions that are identified, a number MN of Pb inclusions (inclusions/mm^2) for which the equivalent circular diameter is 10 μm or more is determined, and the Pb ratio RA (%) is determined based on the following Formula (A).

$$RA = MN/TN \times 100 \qquad (A)$$

[Production Method]

[0066] The free-cutting steel of the present invention can be produced by a well-known production method. According to one example of a method for producing the free-cutting steel of the present invention, first, a molten steel satisfying the aforementioned chemical composition is made into a cast piece by a continuous casting process. Alternatively, the molten steel is made into an ingot by an ingot-making process (casting process). Next, the cast piece or ingot is subjected to hot working once or a plurality of times to produce free-cutting steel material (hot working process). It is sufficient to perform the casting process and the hot working process by well-known methods. Each process is described hereunder.

[Casting process]

[0067] First, molten steel is melted using a well-known method with a converter, an electric furnace, or the like. The produced molten steel is then cast to produce a cast piece or an ingot. Hereunder, the cast piece and the ingot are referred to generically as "starting material".

[0068] A solidification cooling rate RC during casting is not particularly limited, and it is sufficient for the solidification cooling rate RC to be a well-known rate. The solidification cooling rate RC is, for example, 150°C/min or less. To form an even larger amount of composite inclusions of MnS and Pb, it is preferable that the time period for which MnS is caused to crystallize in the liquid phase and for which Pb present in the liquid phase is caused to adhere to the MnS is a long period. Accordingly, it is preferable for the solidification cooling rate RC to be slow.

[0069] A preferable solidification cooling rate RC is 50°C/min or less. In this case, MnS inclusions sufficiently crystallize and grow in the molten steel. Consequently, it is easy for coarse specific inclusions to be formed, and the Pb ratio RA becomes 17% or less.

[0070] A further preferable solidification cooling rate RC is 20°C/min or less. In this case, it is easy for coarse MnS to crystallize and grow in the liquid phase. In addition, because the time until solidification is long, an adequate time period for Pb to move through the molten steel and adhere to the coarse MnS can be secured. Consequently, it is easy for composite inclusions containing MnS and Pb to form, and the Pb ratio RA becomes 13% or less.

[0071] The solidification cooling rate can be determined from the starting material that was cast. FIG. 3 is a transverse sectional view of a starting material that was cast. In the starting material having a thickness W (mm), a point P1 that is located at a position at a depth of W/4 towards the center of the starting material from the surface, the cooling rate from the liquidus temperature to the solidus temperature is defined as the solidification cooling rate RC (°C/min) in the casting process. The solidification cooling rate RC can be determined by the following method. After solidification, the starting material is cut in the transverse direction. In the transverse cross-section of the starting material, a secondary dendrite arm spacing λ2 (μm) in the thickness direction of the solidification structure at the point P1 is measured. Using the measurement value λ2, the cooling rate RC (°C/min) is determined based on the following Formula (3).

$$RC = (\lambda 2/770)^{-(1/0.41)} \qquad (3)$$

[0072] The secondary dendrite arm spacing λ2 depends on the solidification cooling rate. Accordingly, the solidification cooling rate RC can be determined by measuring the secondary dendrite arm spacing λ2.

[Hot working process]

[0073] In the hot working process, hot working is usually performed one or a plurality of times. The starting material is heated before each hot working is performed. Thereafter, the starting material is subjected to the hot working. The hot working is, for example, billeting or hot forging. After undergoing hot working, the starting material is cooled by a well-known cooling technique such as air-cooling. Next, as required, a second hot working is performed and the steel material is produced. For example, a continuous mill is used to roll the starting material and produce a steel bar or a wire rod. The free-cutting steel is produced by the above production processes.

[0074] As described above, the free-cutting steel of the present invention is excellent in enhancing machinability (surface roughness, tool life and chip treatability) and in rusting characteristics. Therefore, by using the free-cutting steel of the present invention, a complex-shaped component or a precision component that is to be produced by undergoing a plurality of processes can be produced with high accuracy and with a low defect rate. Accordingly, by using the free-cutting steel of the present invention, it is easy to implement automation and unattended operations with respect to component production processes, and even if the cut components that are produced are stored for an extended time period, it is difficult for rusting to occur in the cut components.

EXAMPLES

[0075] Molten steels having the chemical compositions shown in Table 1 were produced.

[Table 1]

[0076]

TABLE1

Test Number	Chemical Composition (unit is mass%; balance is Fe and impurities)														F1 = Mn/S	RC (°C/min)	RA (%)	Machinability			Rusting Characteristics	Surface Defects (Hot Ductility)	Remarks
	C	Si	Mn	P	S	Pb	N	O	Al	Ca	Mg	Zr	Ca+Mg+Zr	B				Surface Roughness	Tool Wear	Chip Treatability			
1	0.150	0.009	1.86	0.074	0.462	0.026	0.009	0.016	-	-	-	-	-	-	4.03	19.8	6	○	○	◎	◎	○	Inventive Example of Present Invention
2	0.120	0.005	1.65	0.088	0.480	0.038	0.008	0.016	0.001	-	-	-	-	-	3.44	16.8	12	○	◎	◎	◎	◎	Inventive Example of Present Invention
3	0.005	0.001	1.69	0.072	0.457	0.023	0.008	0.017	0.002	-	-	-	-	-	3.70	18.8	7	Δ	◎	○	◎	◎	Inventive Example of Present Invention
4	0.082	0.009	1.59	0.087	0.451	0.023	0.009	0.017	0.002	-	-	-	-	-	3.53	18.0	9	○	◎	◎	◎	◎	Inventive Example of Present Invention
5	0.083	0.008	2.00	0.092	0.473	0.030	0.011	0.015	0.001	-	-	-	-	-	4.23	17.2	5	○	◎	◎	◎	◎	Inventive Example of Present Invention
6	0.116	0.003	1.10	0.054	0.350	0.028	0.007	0.018	0.002	-	-	-	-	-	3.14	17.8	12	○	◎	◎	○	○	Inventive Example of Present Invention
7	0.102	0.004	1.02	0.099	0.350	0.035	0.010	0.017	0.001	-	-	-	-	-	2.91	18.5	13	○	◎	◎	○	Δ	Inventive Example of Present Invention
8	0.075	0.008	1.40	0.200	0.465	0.038	0.011	0.017	-	-	-	-	-	-	3.01	15.2	13	○	◎	◎	○	○	Inventive Example of Present Invention
9	0.064	0.003	1.31	0.050	0.452	0.031	0.009	0.016	0.001	-	-	-	-	-	2.90	18.4	12	○	◎	◎	○	○	Inventive Example of Present Invention
10	0.092	0.001	1.74	0.010	0.464	0.028	0.009	0.016	-	-	-	-	-	-	3.75	19.7	6	Δ	◎	◎	◎	◎	Inventive Example of Present Invention
11	0.117	0.003	1.91	0.068	0.600	0.025	0.011	0.017	0.001	-	-	-	-	-	3.18	19.8	11	○	◎	◎	○	○	Inventive Example of Present Invention
12	0.068	0.007	1.63	0.052	0.350	0.025	0.010	0.018	0.002	-	-	-	-	-	4.66	16.9	6	○	◎	◎	◎	◎	Inventive Example of Present Invention
13	0.101	0.007	1.44	0.053	0.462	0.100	0.010	0.015	0.001	-	-	-	-	-	3.12	18.1	13	○	◎	◎	○	Δ	Inventive Example of Present Invention
14	0.115	0.005	1.71	0.060	0.401	0.090	0.009	0.017	-	-	-	-	-	-	4.26	16.1	13	○	◎	◎	○	Δ	Inventive Example of Present Invention
15	0.102	0.002	1.36	0.057	0.459	0.040	0.007	0.016	0.001	-	-	-	-	-	2.96	17.4	12	○	◎	◎	○	○	Inventive Example of Present Invention
16	0.092	0.007	1.41	0.075	0.473	0.010	0.009	0.015	0.001	-	-	-	-	-	2.98	16.5	11	○	◎	◎	○	○	Inventive Example of Present Invention
17	0.100	0.007	1.85	0.073	0.470	0.032	0.011	0.016	0.003	-	-	-	-	-	3.94	17.1	7	○	○	○	◎	◎	Inventive Example of Present Invention
18	0.108	0.006	1.69	0.093	0.512	0.025	0.015	0.015	0.001	-	-	-	-	-	3.30	17.1	12	○	◎	◎	◎	◎	Inventive Example of Present Invention
19	0.071	0.007	1.27	0.096	0.360	0.021	0.004	0.017	-	-	-	-	-	-	3.53	16.9	8	○	◎	◎	◎	◎	Inventive Example of Present Invention
20	0.118	0.007	1.43	0.053	0.491	0.021	0.008	0.025	-	-	-	-	-	-	2.91	15.3	13	○	◎	○	○	○	Inventive Example of Present Invention
21	0.085	0.004	1.27	0.099	0.360	0.022	0.011	0.018	-	-	-	-	-	-	3.53	15.8	9	○	◎	◎	◎	◎	Inventive Example of Present Invention
22	0.107	0.008	1.70	0.072	0.467	0.032	0.011	0.015	0.002	-	-	-	-	-	3.64	16.4	9	○	◎	◎	◎	◎	Inventive Example of Present Invention
23	0.095	0.009	1.61	0.100	0.451	0.034	0.011	0.008	-	-	-	-	-	-	3.57	16.1	10	Δ	○	○	◎	◎	Inventive Example of Present Invention
24	0.081	0.002	1.83	0.054	0.483	0.031	0.011	0.017	0.001	0.0005	-	-	0.0005	-	3.79	17.1	7	○ - ◎	◎	◎	◎	◎	Inventive Example of Present Invention
25	0.096	0.003	1.70	0.066	0.485	0.039	0.009	0.018	-	-	0.0005	-	0.0005	-	3.51	18.7	11	○ - ◎	◎	◎	◎	◎	Inventive Example of Present Invention
26	0.085	0.006	1.71	0.079	0.474	0.029	0.009	0.017	-	-	-	0.0005	0.0005	-	3.61	18.9	9	○ - ◎	◎	◎	◎	◎	Inventive Example of Present Invention
27	0.090	0.004	1.91	0.072	0.487	0.032	0.010	0.017	-	0.0002	0.0003	-	0.0005	-	3.92	17.9	6	○ - ◎	◎	◎	◎	◎	Inventive Example of Present Invention
28	0.062	0.005	1.87	0.053	0.463	0.030	0.011	0.015	-	0.0004	-	0.0001	0.0005	-	4.04	18.5	5	○ - ◎	◎	◎	◎	◎	Inventive Example of Present Invention
29	0.115	0.007	1.90	0.072	0.481	0.026	0.010	0.015	-	-	0.0003	0.0001	0.0004	-	3.95	17.4	5	○ - ◎	◎	◎	◎	◎	Inventive Example of Present Invention
30	0.087	0.006	1.79	0.094	0.489	0.030	0.011	0.016	-	0.0001	0.0002	0.0001	0.0004	-	3.66	15.8	7	○ - ◎	◎	◎	◎	◎	Inventive Example of Present Invention
31	0.062	0.003	1.73	0.055	0.454	0.023	0.010	0.018	0.001	-	-	-	-	0.0180	3.80	17.0	6	◎	◎	◎	◎	◎	Inventive Example of Present Invention
32	0.095	0.006	1.82	0.072	0.488	0.038	0.012	0.017	-	-	-	-	-	0.0090	3.73	15.8	9	◎	◎	◎	◎	◎	Inventive Example of Present Invention
33	0.069	0.006	1.54	0.085	0.466	0.021	0.012	0.015	-	-	-	-	-	0.0010	3.30	17.1	12	○ - ◎	◎	◎	◎	◎	Inventive Example of Present Invention
34	0.076	0.006	1.62	0.099	0.460	0.031	0.010	0.017	-	0.0002	0.0001	0.0001	0.0004	0.0153	3.51	16.2	11	◎	◎	◎	◎	◎	Inventive Example of Present Invention
35	0.116	0.001	1.17	0.087	0.290	0.036	0.011	0.015	-	-	-	-	-	-	4.05	15.6	5	×	×	◎	◎	◎	Comparative Example
36	0.075	0.001	1.82	0.069	0.300	0.040	0.008	0.016	0.001	-	-	-	-	0.010	6.07	17.9	6	×	×	◎	◎	◎	Comparative Example
37	0.119	0.003	1.69	0.063	0.475	0.150	0.012	0.016	0.002	-	-	-	-	-	3.56	19.1	31	○	◎	◎	×	×	Comparative Example
38	0.060	0.004	1.48	0.073	0.488	0.130	0.007	0.017	0.002	-	-	-	-	0.008	3.03	15.3	34	◎	◎	◎	×	×	Comparative Example
39	0.087	0.005	1.02	0.067	0.460	0.035	0.011	0.016	0.002	-	-	-	-	-	2.17	18.6	28	○	◎	◎	×	×	Comparative Example
40	0.069	0.006	1.03	0.097	0.460	0.021	0.011	0.016	0.001	-	-	-	-	0.009	2.24	17.1	25	◎	◎	◎	×	×	Comparative Example
41	0.098	0.050	1.15	0.080	0.371	0.021	0.010	0.016	-	-	-	-	-	-	3.09	16.3	13	×	×	×	○	○	Comparative Example
42	0.068	0.002	1.55	0.086	0.465	0.039	0.010	0.016	0.004	-	-	-	-	-	3.34	19.6	11	×	×	×	◎	◎	Comparative Example
43	0.102	0.002	1.96	0.090	0.459	0.024	0.009	0.005	0.001	-	-	-	-	-	4.26	16.4	4	×	×	×	○	◎	Comparative Example
44	0.068	0.009	1.83	0.006	0.481	0.037	0.008	0.015	0.001	-	-	-	-	-	3.80	16.0	7	×	◎	◎	◎	◎	Comparative Example
45	0.190	0.002	1.56	0.076	0.469	0.036	0.010	0.015	0.001	-	-	-	-	-	3.33	17.6	12	○	×	◎	◎	◎	Comparative Example
46	0.131	0.004	1.61	0.072	0.466	0.034	0.008	0.015	0.001	-	-	-	-	-	3.45	48.5	16	○	◎	◎	○	◎	Inventive Example of Present Invention
47	0.135	0.007	1.59	0.051	0.479	0.036	0.007	0.016	0.001	-	-	-	-	-	3.32	122.6	19	○	◎	◎	Δ	◎	Inventive Example of Present Invention
48	0.133	0.006	1.66	0.068	0.449	0.037	0.008	0.017	0.001	-	-	-	-	-	3.70	252.7	25	○	◎	◎	Δ	◎	Inventive Example of Present Invention
49	0.092	0.006	1.39	0.051	0.445	0.004	0.010	0.015	0.001	-	-	-	-	-	3.12	18.1	19	×	×	×	◎	◎	Comparative Example
50	0.067	0.004	1.85	0.055	0.575	0.004	0.008	0.019	-	-	-	-	-	-	3.22	9.2	19	×	×	×	◎	◎	Comparative Example

[0077] Each molten steel was cast to produce a cast piece. The solidification cooling rate RC during casting was as described in Table 1. The produced cast piece was subjected to hot working to produce a steel bar with a diameter of 10 mm. The solidification cooling rate RC was obtained by measuring the secondary dendrite arm spacing of an ingot and using the aforementioned Formula (3). The steel bar was subjected to wire drawing and straightening to produce a steel bar having a diameter of 8 mm.

[Evaluation Test]

[Pb ratio RA]

[0078] A test specimen for observing the micro-structure was taken from the R/2 part of the steel bar of each test number. Among the entire surface of the test specimen, a cross-section that was parallel to the longitudinal direction (that is, the rolling direction or elongation direction) of the steel bar was defined as the observation surface. The Pb ratio RA (%) was determined based on the aforementioned method.

[Machinability]

[0079] The surface roughness, the tool life characteristics in the case of normal drilling, and the chip treatability were evaluated with respect to the machinability. For each of these evaluations, the symbol "×" in the table indicates "low machinability", and symbols other than "×" in the table indicate "good machinability".

[Cutting Test]

[0080] A steel bar having a diameter of 8 mm was cut to a predetermined length and adopted as a cutting test specimen. Outer circumferential lathe turning shown in FIG. 4 was performed on the test specimen. Specifically, a K10 carbide tool was used as a tool 10. A nose radius of the tool 10 was 0.4, and a rake angle thereof was 5°. Outer circumferential lathe turning was performed under conditions of cutting speed V1: 80 m/min, feed speed V2: 0.05 mm/rev, depth-of-cut amount D1: 1 mm, and cutting width L1: 10 mm per test specimen. An insoluble cutting oil was used during lathe turning. A lathe turning test under the aforementioned conditions was performed with respect to 1,000 test specimens.

[Surface roughness evaluation]

[0081] In the aforementioned cutting test, after the lathe turning of the 1,000th test specimen was completed, the surface roughness of the test specimens was measured. The surface roughness was determined using the ten-point surface roughness (Rz) defined in JIS B0601 (2001). The measurement results are shown in the "surface roughness" column in Table 1. In Table 1, the symbol "◎" means that the surface roughness was equal to or less than 10 μm Rz JIS. The symbol "○" means that the surface roughness was in the range of more than 10 to 15 μm Rz JIS. The symbol "Δ" means that the surface roughness was in the range of more than 15 to 20 μm Rz JIS. The symbol "×" means that the surface roughness was more than 20 μm Rz JIS. If the surface roughness was 20 μm Rz JIS or less, it was evaluated that excellent surface roughness was obtained. Note that the symbol "○ - ◎" in the table means that ◎ and ○ evaluations were obtained in a plurality of measurements.

[Service life evaluation]

[0082] The amount of tool wear (mm) of the front flank face was measured with respect to the tool 10 after lathe turning of the 1,000th test specimen was completed. The measurement results are shown in the "tool wear" column in Table 1. In Table 1, the symbol "◎" means that the amount of tool wear was 150 μm or less. The symbol "○" means that the amount of tool wear was in the range of more than 150 to 200 μm. The symbol "×" means that the amount of tool wear was more than 200 μm. The tool life was evaluated as being excellent if the amount of tool wear was 200 μm or less.

[Chip treatability evaluation]

[0083] In the lathe turning of the 1,000th test specimen, chips 20 illustrated in FIG. 5A and FIG. 5B were obtained. A length L20 and a diameter D20 of the chips 20 were measured. The chips 20 were categorized as shown in Table 2 based on the measurement results.

[Table 2]

[0084]

TABLE 2

		Chip Shape	
		Diameter ≤ 30 mm	Other Than In Left Column
Chip Length	≤ 20 mm	◎	○
	More Than 20 mm to 50 mm	○	Δ
	More Than 50 mm		×

[0085] Referring to Table 2, the chip treatability was evaluated as follows. The symbol "◎" means that the chip was a coil shape with a diameter of 30 mm or less, and the chip length was 20 mm or less. The symbol "○" means that the chip was a coil shape with a diameter of 30 mm or less, and the chip length was more than 20 mm, or that the chip was not a coil shape with a diameter of 30 mm or less, and the chip length was 20 mm or less. The symbol "Δ" means that the chip was not a coil shape with a diameter of 30 mm or less, and the chip length was in a range from more than 20 mm to less than 50 mm. The symbol "×" means that the chip was not a coil shape with a diameter of 30 mm or less, and the chip length was 50 mm or more. In the case where the measurement result for the chip was "◎", "○" or "Δ", the steel was evaluated as being excellent in chip treatability.

[Rusting characteristics (corrosion resistance) evaluation test]

[0086] A test specimen was prepared by cutting a steel bar having a diameter of 8 mm to a predetermined length. The test specimen was subjected to lathe turning working under similar conditions as in the aforementioned cutting test. The test specimen was stored for 24 hours in an atmosphere with a humidity of 70% and a temperature of 20°C while spraying tap water onto the cut surface. After storage, the cut surface of the test specimen was observed and the number of rust points was measured. The measurement results are shown in the "rusting characteristics" column in Table 1. The symbol "◎" means that there were less than 10 rust points. The symbol "○" means that there were 11 to 15 rust points. The symbol "Δ" means that there were 16 to 19 rust points. The symbol "×" means that there were 20 or more rust points.

[Evaluation test of surface defects during hot working]

[0087] A round bar specimen having a diameter of 10 mm and a length of 100 mm was prepared from a steel bar in which the aforementioned diameter was 10 mm. After both ends of the test specimen were subjected to screw machining, and the test specimen was mounted in a tension test jig, a hot tension test was performed by electrical heating. Specifically, the test specimen was heated to 1100°C by electrical heating, and held at that temperature for three minutes. Thereafter, the test specimen was cooled to 900°C by being allowed to cool. The tension test was executed at a time point at which the temperature of the test specimen became 900°C, and the ductility at the time of rupturing (reduction in area) was evaluated. For each test number, the aforementioned tension test was performed on three test specimens, and the average of the obtained values of reduction in area was determined. The results are shown in the "surface defects" column in Table 1. The symbol "◎" means that the average of the values of reduction in area was 60% or more. The symbol "○" means that the average of the values of reduction in area was in the range of 50% to less than 60%. The symbol "Δ" means that the average of the values of reduction in area was in the range of 40% to less than 50%. The symbol "×" means that the average of the values of reduction in area was less than 40%. If the average of the values of reduction in area was 40% or more, it was evaluated that the steel was excellent in ductility during hot working and that the occurrence of surface defects was suppressed.

[Test Results]

[0088] Referring to Table 1, for each of test numbers 1 to 34 and 46 to 48, the chemical composition was within the range of the present invention and satisfied Formula (1). Therefore, the steels of these test numbers were excellent in each of cutting accuracy (surface roughness), tool life and chip treatability, and were excellent in machinability. These steels were also excellent in rusting characteristics and ductility. Note that, in test numbers 1 to 34 and 46, the ratio of the number of Pb inclusions RA was 17% or less.

[0089] Among test numbers 1 to 34, in particular, the chemical compositions of test numbers 1 to 5, 10, 12, 17 to 19, and 21 to 34 were in a preferable range. Therefore, the steels of these test numbers were more excellent in rusting characteristics in comparison to test numbers 6 to 9, 11, 13 to 16 and 20.

[0090] Among test numbers 1 to 34, in particular, test numbers 24 to 34 contained optional elements (Ca, Mg, Zr and B). Therefore, for these test numbers, the cutting accuracy (surface roughness) was superior to test numbers 1 to 23.

[0091] Among test numbers 1 to 34 and 46 to 48, in particular, in test numbers 1 to 34 and 46 the cooling rate was 50°C/min or less. Therefore, the Pb ratio RA was 17% or less. As a result, the rusting characteristics were more excellent in comparison to test numbers 47 and 48.

[0092] Among test numbers 1 to 34 and 46 to 48, in particular, in test numbers 1 to 34 the cooling rate was 20°C/min or less. Therefore, the Pb ratio RA was 13% or less. As a result, the rusting characteristics were more excellent in comparison to test numbers 46 to 48.

[0093] On the other hand, in test numbers 35 and 36, the S content was less than the lower limit defined in the present invention. Consequently, the cutting accuracy and tool life were low and the machinability was low. It is considered that the reason was that there was little formation of MnS inclusions.

[0094] In test numbers 37 and 38, the Pb content was more than the upper limit defined in the present invention. Consequently, the rusting characteristics were low and the ductility was also low. It is considered that the reason was that the amount of Pb inclusions was large.

[0095] In test numbers 39 and 40, Formula (1) was not satisfied. Consequently, the rusting characteristics were low and the ductility was also low. It is considered that the reason was that the amount of composite inclusions of MnS and Pb was small, and the amount of Pb inclusions was large.

[0096] In test number 41 the Si content was more than the upper limit defined by the present invention, and in test number 42 the Al content was more than the upper limit defined by the present invention. Consequently, the machinability was low. It is considered that the reason was that a large amount of hard oxides were formed.

[0097] In test number 43, the O content was less than the lower limit defined by the present invention. Consequently, the machinability was low. It is considered that the reason was that MnS was elongated and the aspect ratio thereof was large.

[0098] In test number 44, the P content was less than the lower limit defined by the present invention. Consequently, the cutting accuracy (surface roughness) was low. It is considered that the reason was that, because the P content was too low, the embrittlement effect on the steel was insufficient and the machinability decreased.

[0099] In test number 45, the C content was more than the upper limit defined by the present invention. Consequently, the tool life was low. It is considered that the reason was that the C content was too high and the strength of the steel was high.

[0100] In test numbers 49 and 50, the Pb content was less than the lower limit defined by the present invention. Consequently, the machinability was low.

[0101] An embodiment of the present invention has been described above. However, the foregoing embodiment is merely an example for implementing the present invention. Accordingly, the present invention is not limited to the above embodiment, and the above embodiment can be appropriately modified within a range which does not deviate from the gist of the present invention.

REFERENCE SIGNS LIST

[0102]

10	MnS Inclusions
20	Pb Inclusions
30	Composite Inclusions

Claims

1. A free-cutting steel having a chemical composition that contains, in mass%:

C: 0.005 to 0.150%,
Si: less than 0.010%,
Mn: 1.02 to 2.00%,
P: 0.010 to 0.200%,
S: 0.350 to 0.600%,
Pb: 0.010 to 0.100%,
N: 0.004 to 0.015%,
O: 0.0080 to 0.0250%,
Al: 0 to 0.003%,

one or more types of element selected from a group consisting of Ca, Mg and Zr: 0 to 0.0005% in total, and
B: 0 to 0.0200%,
with the balance being Fe and impurities,
the chemical composition satisfying Formula (1):

$$\mathrm{Mn/S} \geq 2.90 \qquad (1)$$

where, a content (mass%) of a corresponding element is substituted for each symbol of an element in Formula (1).

2. The free-cutting steel according to claim 1, wherein the chemical composition contains:

Al: 0.001 to 0.003%.

3. The free-cutting steel according to claim 1 or claim 2, wherein the chemical composition contains:

one or more types of element selected from a group consisting of Ca, Mg and Zr in a total content of 0.0001 to 0.0005%.

4. The free-cutting steel according to any one of claims 1 to 3, wherein the chemical composition contains:

B: 0.0005 to 0.0200%.

5. The free-cutting steel according to any one of claims 1 to 4, wherein the ratio of a number of Pb inclusions to the total number of specific inclusions is 17% or less.

FIG. 1A

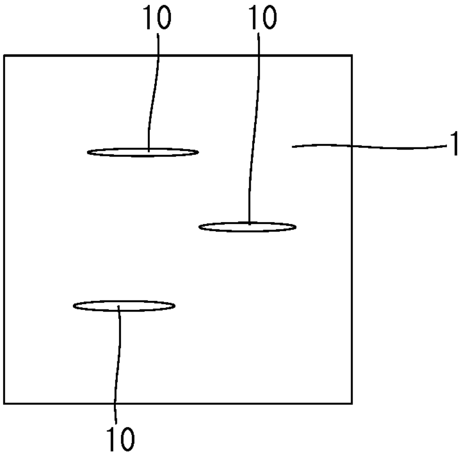


FIG. 1B

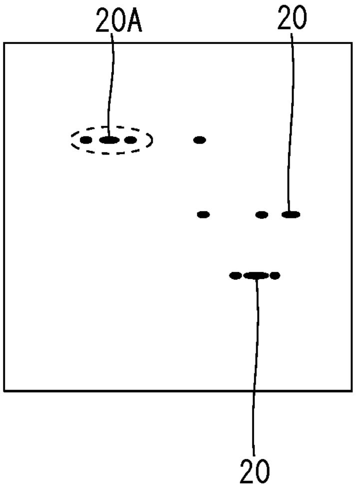


FIG. 1C

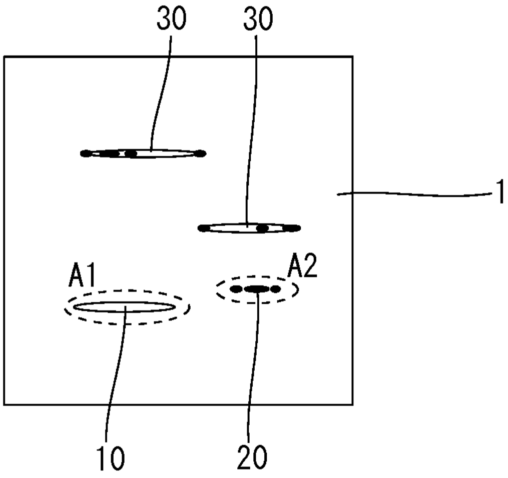


FIG. 2

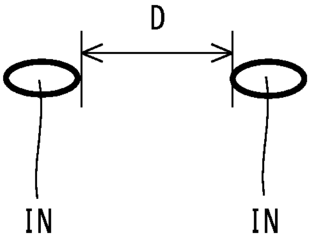


FIG. 3

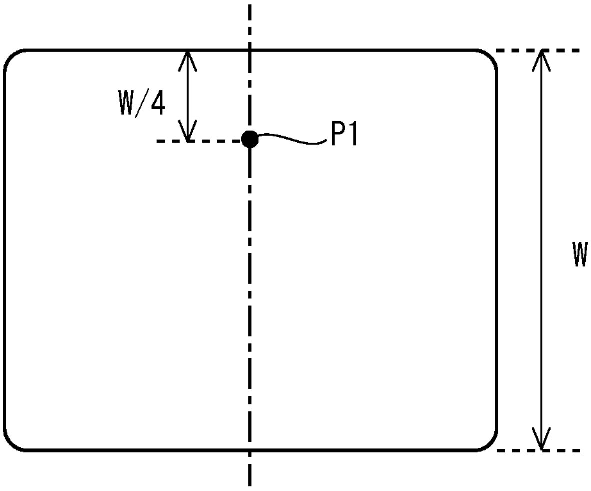


FIG. 4

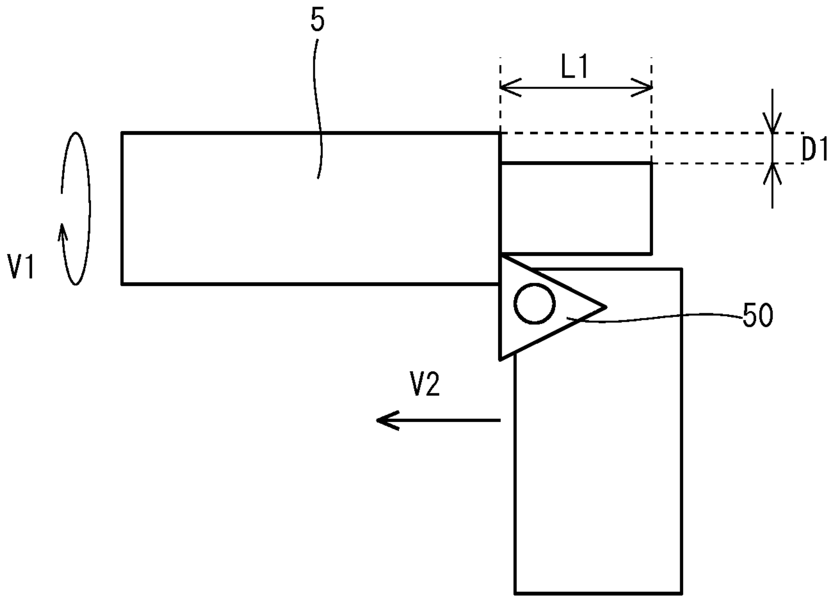


FIG. 5A

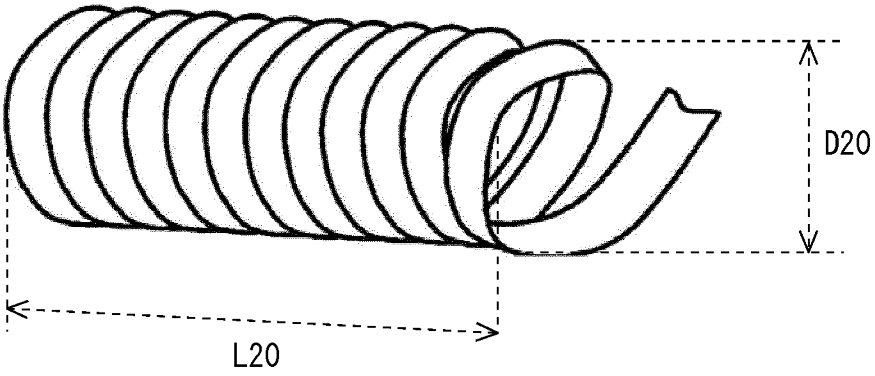
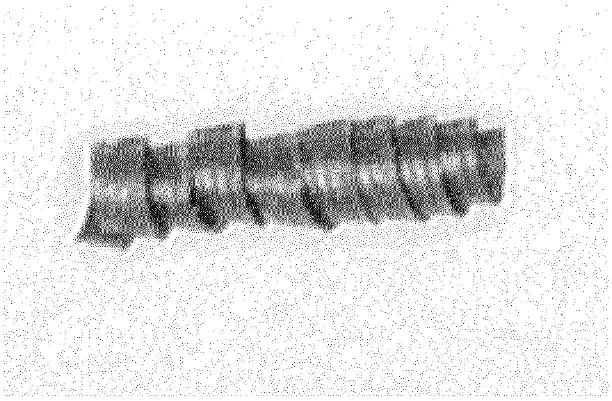


FIG. 5B



INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2016/067188

A. CLASSIFICATION OF SUBJECT MATTER
C22C38/00(2006.01)i, *C22C38/60*(2006.01)i

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

B. FIELDS SEARCHED

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

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

Jitsuyo Shinan Koho	1922-1996	Jitsuyo Shinan Toroku Koho	1996-2016
Kokai Jitsuyo Shinan Koho	1971-2016	Toroku Jitsuyo Shinan Koho	1994-2016

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.
Y	WO 2014/125770 A1 (Nippon Steel & Sumitomo Metal Corp.), 21 August 2014 (21.08.2014), claims; paragraphs [0031] to [0038], [0061] to [0070]; examples; table 1 & KR 10-2015-0092321 A & CN 104995324 A & TW 201437390 A	1-5

☒ 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 30 June 2016 (30.06.16)	Date of mailing of the international search report 12 July 2016 (12.07.16)
Name and mailing address of the ISA/ Japan Patent Office 3-4-3,Kasumigaseki,Chiyoda-ku, Tokyo 100-8915,Japan	Authorized officer Telephone No.

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2016/067188

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2008/066194 A1 (Nippon Steel Corp.), 05 June 2008 (05.06.2008), claims; page 7, line 8 to page 19, line 5; examples; tables 1 to 6 & JP 5212111 B2 & US 2010/0054984 A1 paragraphs [0056] to [0130]; examples; tables 1 to 6 & EP 2096186 A1 & AU 2007326255 A1 & KR 10-2009-0055648 A & CN 101573463 A & TW 200840875 A	1-5
Y	JP 7-252588 A (Nippon Steel Corp.), 03 October 1995 (03.10.1995), claims; paragraphs [0016], [0019], [0020]; examples; table 1, 2 (Family: none)	1-3,5
A	JP 62-196361 A (Daido Steel Co., Ltd.), 29 August 1987 (29.08.1987), (Family: none)	1-5
A	JP 2001-207240 A (Kobe Steel, Ltd.), 31 July 2001 (31.07.2001), & US 6635129 B1 & KR 10-2001-0051588 A	1-5

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- JP 2004027297 A **[0005] [0006]**