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(54) LOW-CARBON FREE CUTTING STEEL

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(57) **ABSTRACT**

The invention provides a low-carbon free cutting steel containing no lead and is at least comparable in machinability to the conventional leaded free cutting steels and composite free cutting steels and furthermore has excellent finished surface characteristics. The steel is a low-carbon free cutting steel which comprises, on the percent by mass basis, C: 0.05 to under 0.20%, Mn: 0.4-2.0%, S: 0.21-1.0%, Ti: 0.002-0.10%, P: 0.001-0.30%, Al: not higher than 0.2%, 0: 0.001-0:03% and N: 0.0005-0.02%, with the balance being Fe and impurities, and which satisfies the relations (a) and (b) given below concerning the inclusions contained in the steel:

$$(A+B)/C \geqq 0.8 \quad \text{(a)},$$

$$N_A \geqq 5 \quad \text{(b)},$$

wherein, A: the total area occupied by substantial MnS with Ti carbide and/or Ti carbonitride included therein among the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling;

B: the total area occupied by substantial MnS with neither Ti carbide nor Ti carbonitride included therein among the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling;

C: the total area occupied by all the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling;

N_A: the number of substantial MnS inclusions with Ti carbide and/or Ti carbonitride included therein among the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling.

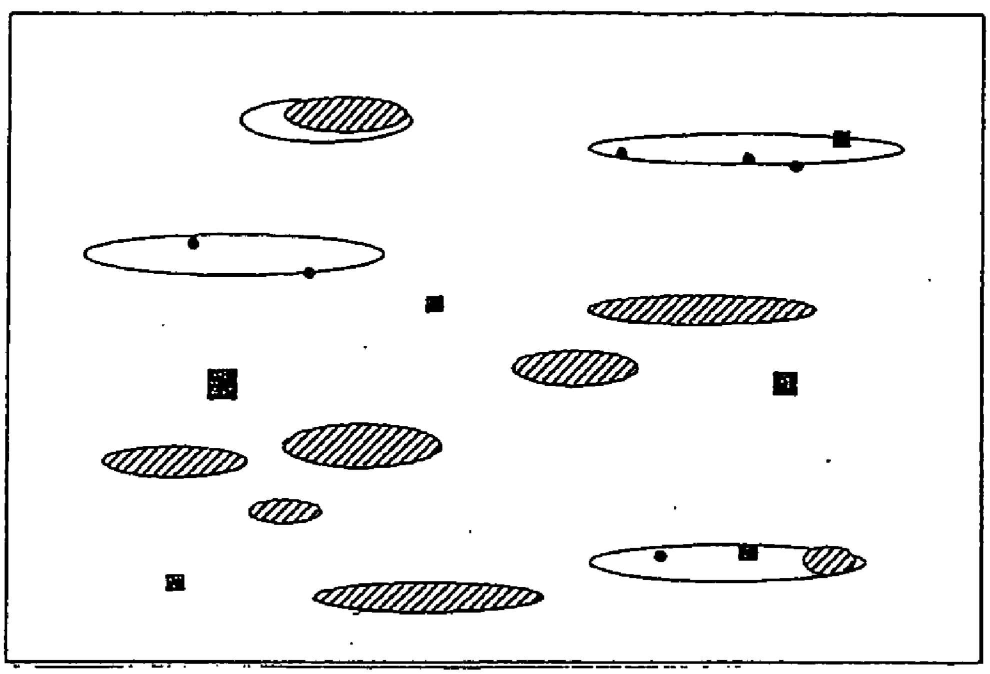


Fig. 1A

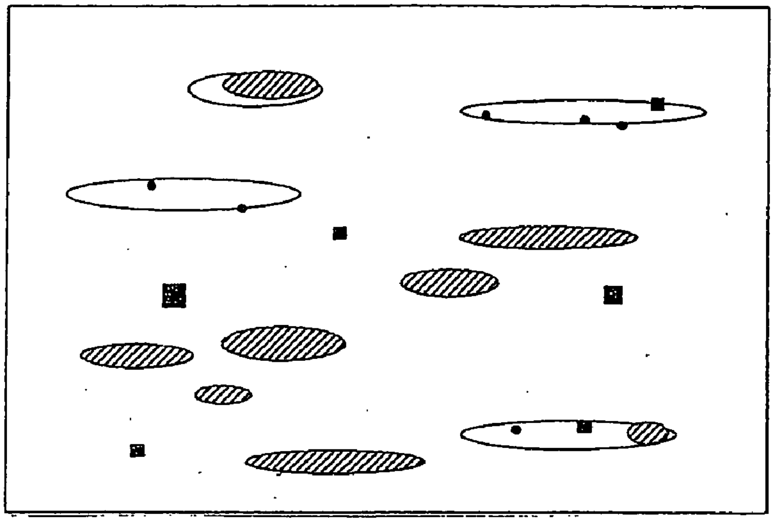
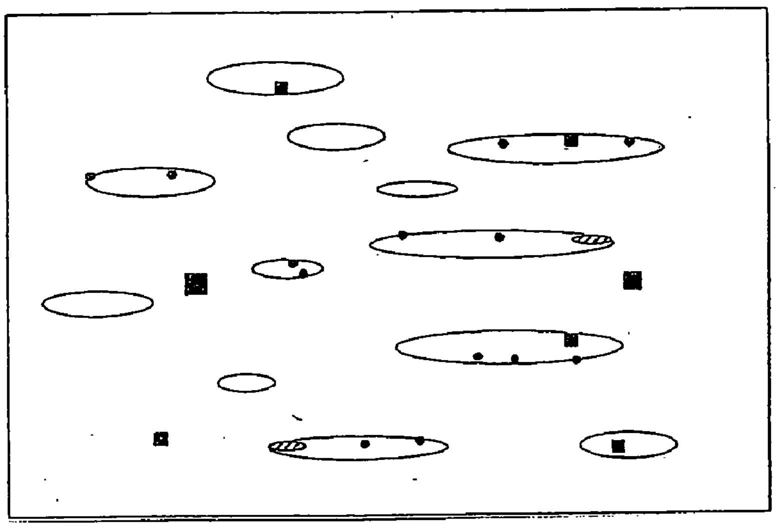


Fig. 1B



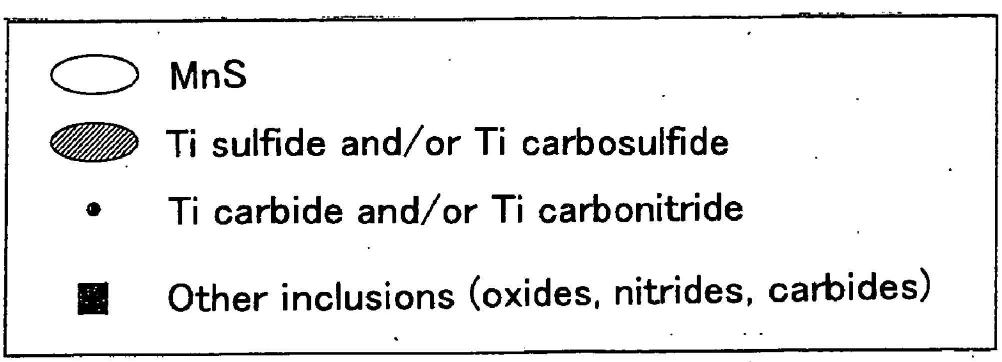

MnS
Ti sulfide and/or Ti carbosulfide
Ti carbide and/or Ti carbonitride
Other inclusions (oxides, nitrides, carbides)

Fig. 2

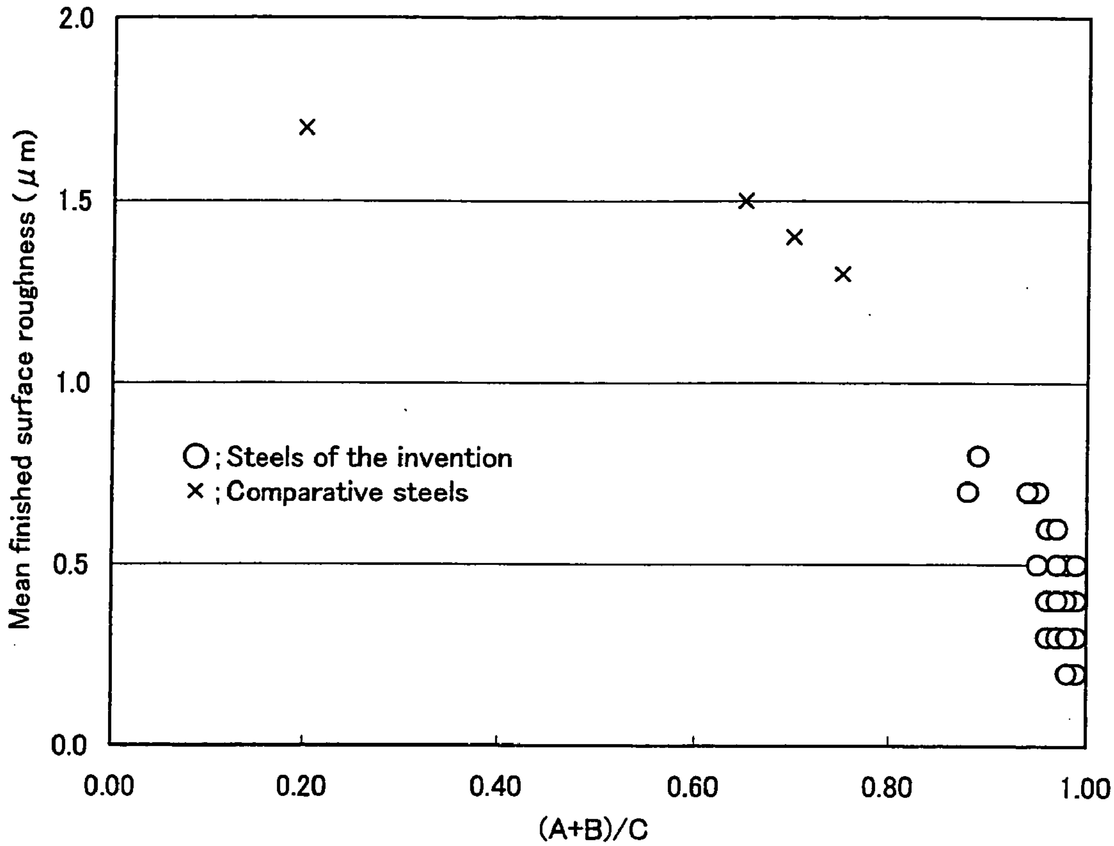
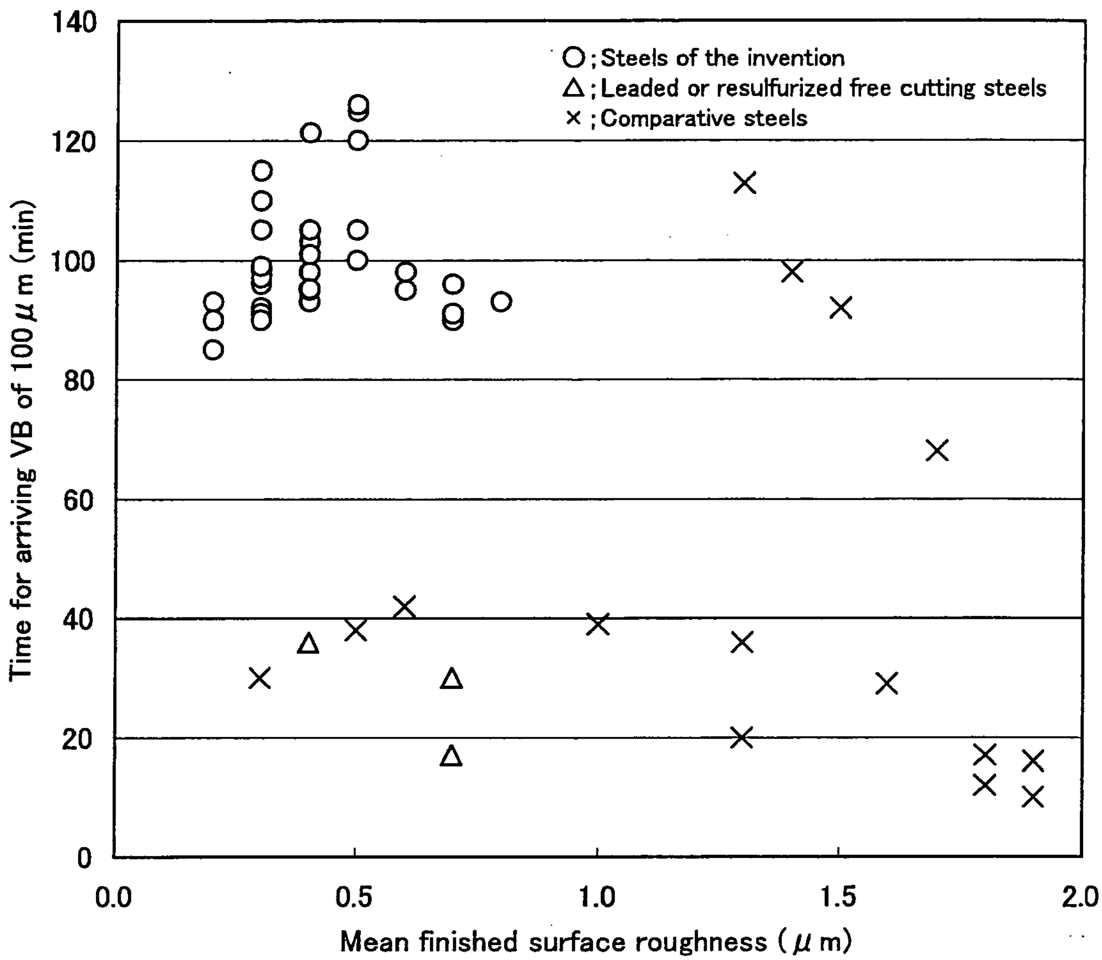
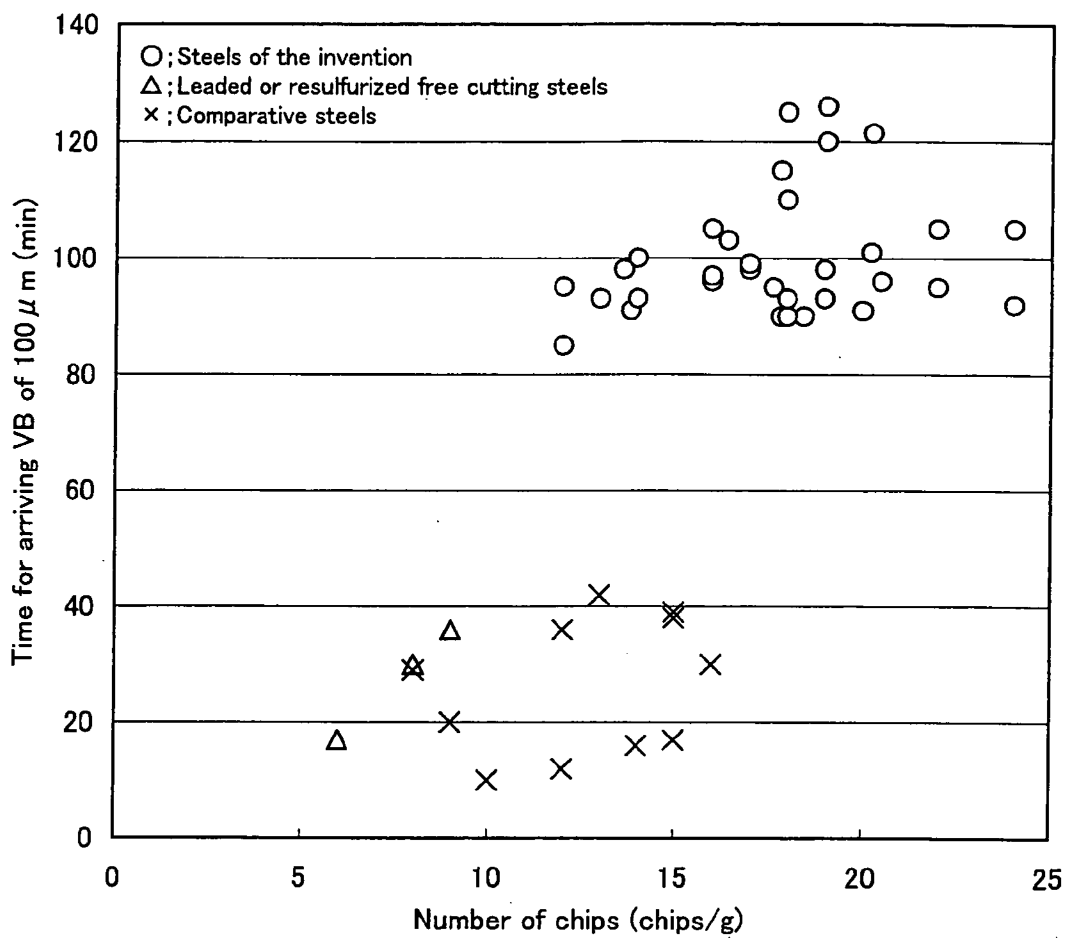

2.0
1.5
1.0
0.5
0.0
Mean finished surface roughness (μm)
○; Steels of the invention
×; Comparative steels
0.00
0.20
0.40
0.60
0.80
1.00
(A+B)/C

Fig. 3



140
120
100
80
60
40
20
0
0.0
0.5
1.0
1.5
2.0
Time for arriving VB of 100 μ m (min)
Mean finished surface roughness (μ m)
○; Steels of the invention
△; Leaded or resulfurized free cutting steels
×; Comparative steels

Fig. 4



○ ; Steels of the invention
△ ; Leaded or resulfurized free cutting steels
× ; Comparative steels
Time for arriving VB of 100 μ m (min)
0
20
40
60
80
100
120
140
0
5
10
15
20
25
Number of chips (chips/g)

LOW-CARBON FREE CUTTING STEEL

[0001] The disclosure of Japanese Patent Application No. 2003-285463 filed in Japan on Aug. 1, 2003 including specification, drawings and claims is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] This invention relates to a low-carbon free cutting steel which is free of lead (Pb). In particular, it relates to a low-carbon free cutting steel which, when machined with a carbide tool, has superior machinability compared to conventional leaded free cutting steels and composite free cutting steels in which lead and one or more machinability improving elements are used together, in spite of its being free of lead, and also which has excellent hot workability and finished surface characteristics after machining, and can be produced at a low cost. The present invention also relates to a low-carbon free cutting steel excellent, not only in the above-mentioned characteristics, but also in carburizing characteristics.

BACKGROUND OF THE INVENTION

[0003] In manufacturing soft small articles, not required to have very high strength, steel materials excellent in machinability, namely the so-called free cutting steels, have so far been used for the improvement of productivity. The best known free cutting steels include resulfurized free cutting steels which are improved in machinability by MnS due to the addition of a large amount of S; leaded free cutting steels obtained by an addition of Pb; and composite free cutting steels containing both of S and Pb. In particular, leaded free cutting steels are characterized in that they contribute toward prolonging the tool life and are excellent in chip disposability and also in that the steel products after machining are excellent in surface roughness, etc. Further, there are free cutting steels containing Te (tellurium) and/or Bi (bismuth) for the purpose of machinability improvement. These steels are used in large amounts in small parts such as automotive breaks, personal computers and their accompanying parts, and other various machine parts such as electric appliance parts and molds.

[0004] In recent years, the ability of cutting machines has been improved and, as a result, it has become possible to increase the speed of machining. Accordingly, steel materials, used as raw materials in the above-mentioned parts, are also intensely requested to show further improved machinability in high-speed machining.

[0005] Furthermore, in some instances, such parts as mentioned above, after being completed to a desired shape and form by machining, are subjected to carburizing in order to secure a desired level of surface strength. Therefore, the steel material to be used in manufacturing such parts is sometimes required, not only to have high machinability, but also to be excellent in carburizing characteristics.

[0006] Steels to be used as materials of such parts as mentioned above are required to have good machinability. As for such machinability, a special emphasis is placed not only on prolonging of the tool life but also on the properties, such that chips are separated in small pieces or, in other words, "chip disposability". The chip disposability is indispensable for working line automation and also essential for increasing productivity. Further, in addition to the tool life and chip disposability requirements, it is desired, from the working precision viewpoint, that the steel surface after machining should be good in finished surface characteristics, namely the finished surface roughness should be as low as possible. Among the free cutting steels mentioned above, leaded cutting steels and composite free cutting steels, containing Pb and one or more machinability improving elements, are superior due to such characteristics and are deemed the best in machinability among the currently available steels.

[0007] In view of the recent increasing concern about the environmental problems, a non-leaded free cutting steel is earnestly desired because those steels which contain Pb, which is hazardous to human beings and the global environment, require installation of large-scaled exhausters for the process of production and, further, the trend toward suppression of the use of Pb for the preservation of the environment is increasing.

[0008] To meet the above demand, various proposals have been made concerning non-leaded low-carbon resulfurized free cutting steels, which are to serve as alternatives to leaded free cutting steels. However, any free cutting steel capable of contributing to prolonging the life of the tool and having, to a satisfying extent, all the characteristic of the Pb-containing free cutting steels, such as good chip disposability and low levels of surface roughness, has not yet been developed.

[0009] In Japanese Patent Laid-open Application (JP Kokai) 2003-49240 (Patent Document 1), there is disclosed a free cutting steel improved in machinability, by causing Ti and/or Zr carbosulfide type inclusions to exist therein. Since the Ti carbosulfide or the Zr carbosulfide is dispersed, together with MnS, in this free cutting steel, the pseudo lubricating effect of the MnS can hardly be obtained and the frictional force between the tool and the work material increases. As a result, the cutting force increases and a built-up edge formation on the edge of cutting tool is facilitated. Once a built-up edge has been formed, the finished surface roughness after finish machining increases and the working precision of the parts is impaired.

[0010] In Patent Document 1, no example is given of the case where the Ti content is 0.1% or less. This indicates that the invention disclosed in Patent Document 1 aims at forming Ti carbosulfide inclusions by causing a large amount of Ti to be contained in the steel. Actually, it is described therein that the Ti carbosulfide type inclusions, together with MnS, are dispersed in a granular form in the matrix. In this case, those performance characteristics, such as tool life, chip disposability and low-level finished surface roughness, which are required in the steel to be used in manufacturing the parts mentioned above, cannot be acquired.

[0011] JP Kokai 2003-49241 (Patent Document 2) discloses a free cutting steel containing Ti and/or Zr within the content range of $(Ti+0.52\,Zr)/S<2$, containing Ti or Zr carbosulfide as an inclusion component and contributing to a prolonged tool life in turning and drilling. The invention described in Patent Document 2 aims at improving the tool life in turning by causing a formation of Ti carbosulfide in the steel. This technology can indeed improve the tool life to a certain extent but the presence of Ti or Zr carbosulfide makes it difficult to obtain the lubricating effect of the MnS, hence the frictional force between the tool and the work material increases. As a result, the cutting force increases and a built-up edge formation on the edge of cutting tool is facilitated. Once a built-up edge has been formed, the finished surface roughness after cutting increases, with the result that the working precision of the parts is impaired.

[0012] In Patent Document 2, there is no example found of the free cutting steel containing S in the range of not lower than 0.21% and Ti at a level not higher than 0.1%, as specified later herein in relation to the present invention. Due to this, it is evident that the invention in Patent Document 2 is not an invention aiming at improving the finished surface roughness and/or chip disposability. According to the invention in Patent Document 2, Ti or Zr carbosulfide, together with MnS, is dispersed in the matrix and, therefore, the desired level of finished surface roughness and of chip disposability cannot be attained.

[0013] In JP Kokai 2000-319753, there is disclosed a low-carbon resulfurized free cutting steel in which the amount of MnS is increased through an S content exceeding 0.4% to which Pb is not added. However, this steel is low in improving the tool life of carbide tools. Further, there is no improvement in chip disposability, which is important, nor in performance characteristics, as compared with the conventional resulfurized free cutting steels.

[0014] JP Kokai H09-53147 discloses a free cutting steel excellent in carbide tool machinability and, in particular, in tool life, which contains C: 0.01-0.2%, Si: 0.10-0.60%, Mn: 0.5-1.75%, P: 0.005-0.15%, S: 0.15-0.40%, O (oxygen): 0.001-0.010%, Ti: 0.0005-0.020% and N: 0.003-0.03%. This invention aims at improving the carbide tool life only due to the content of 0.1-0.6% of Si, together with Ti, as the essential components. Accordingly, this invention does not aim at improving the tool life or the chip disposability or the finished surface roughness level because of the "substantial MnS with Ti carbide and/or Ti carbonitride included therein" exists in the steel without adding Si, as included in the present invention.

[0015] Japanese Patent No. 3390988 discloses an invention relating to a low-carbon resulfurized free cutting steel improved in mechanical anisotropy which contains C: 0.02-0.15%, Mn: 0.3-1.8%, S: 0.225-0.5%, Ti: 0.1-0.6% and Zr: 0.1-0.6%, with the proviso that Ti+Zr: 0.3-0.6% and (Ti+Zr)/S ratio: 1.1-1.5. The steel of this invention is improved in mechanical anisotropy and machinability by employing the above composition to cause a formation of Ti and/or Zr sulfide, which are high in hot deformation resistance. However such sulfides, high in deformation resistance, can hardly afford a sulfide-due lubricating effect during machining, hence the cutting force increases, the deterioration of the tool life takes place and the finished surface roughness after finish machining increases.

SUMMARY OF THE INVENTION

[0016] It is an objective of the present invention to provide a low-carbon free cutting steel which is free of Pb, which is hazardous to the environment, shows superior machinability, in particular when carbide tools are used, as compared with the conventional leaded free cutting steels and composite free cutting steels containing Pb and one or more machinability improving elements, is excellent in hot workability and further in surface characteristics after machining, and can be produced at a low cost. Another objective of the present invention is to provide a low-carbon free cutting steel, having good carburizing characteristics, in addition to the characteristics mentioned above.

[0017] As is well known, the states of inclusions, such as sulfides, exert great influences on the machinability of steels. Various inclusions are observed in steels containing C, Ti, S, N and O. For example, this includes Ti sulfide, Ti carbosulfide, Ti carbide, Ti carbonitride, Ti nitride and Ti oxide. When Mn is further contained, Mn sulfide represented by the chemical formula "MnS" is also present. When Al and/or Si are contained in addition to those elements mentioned above, the oxides thereof are also present. The states of these inclusions are diverse, and the compositions and the states of these inclusions greatly influence the machinability and other mechanical characteristics of steels.

[0018] Previously, the present inventors filed a patent application in Japan under Application No. 2002-26368 concerning a non-leaded, low-carbon resulfurized free cutting steel. This free cutting steel is characterized in that it contains C, Mn, S, Ti, Si, P, Al, O and N in respective specified proportions and satisfies the expressions (A) below concerning the contents of Ti and S, and the expression (B) given below concerning the atomic ratio between Mn and S, and contains MnS with Ti sulfide and/or Ti carbonsulfide included therein.

$$\text{Ti (\% by mass)/S (\% by mass)} < 1 \quad \text{(A)}$$

$$\text{Mn/S} \geqq 1 \quad \text{(B)}$$

[0019] The steel according to this senior invention is much better in tool life than leaded free cutting steels and shows good chip disposability. This steel, however, still has some drawbacks with respect to its surface characteristics after machining. Namely, it has been revealed that when the finish machining was carried out, the finished surface roughness became large in some instances.

[0020] It is considered that when substantial Ti sulfide and/or Ti carbosulfide exist in the matrix, it becomes difficult to obtain the pseudo lubricating effect of MnS, hence the cutting force increases and a built-up edge is formed on the edge of cutting tool, which results in the steel surface after machining, loses brightness and that the finished surface smoothness is deteriorated. The term "substantial Ti sulfide and/or Ti carbosulfide" as used herein means those inclusions in each of which the total area in percent occupied by Ti sulfide and Ti carbosulfide amounts to not less than 50%. Some of them are shown in **FIG. 1A** attached hereto.

[0021] The present inventors made investigations to solve this problem and, as a result, obtained new findings as mentioned below.

[0022] (1) When a steel in which "substantial Ti sulfide and/or Ti carbosulfide" existing in the matrix is machined, a built-up edge is formed on the edge of cutting tool, resulting in a deteriorated finished surface smoothness.

[0023] (2) When the formation of "substantial Ti sulfide and/or Ti carbosulfide" are prevented as far as possible and a large amount of MnS is allowed to exist in the steel, the built-up edge formation can be prevented and the finished surface can be improved from the roughness viewpoint.

[0024] (3) However, with steels not containing Ti but containing only MnS, the carbide tool life is deteriorated. For improving the carbide tool life, it is necessary to add Ti and, at the same time, allow the existence of "substantial MnS with Ti carbide and/or Ti carbonitride included therein".

[0025] (4) The "substantial MnS with Ti carbide and/or Ti carbonitride included therein" improves the tool life, while it does not impair the pseudo lubricating effect of MnS.

[0026] Based on the above findings, the relation between the chemical composition and the states of existence of inclusions was investigated in detail. As a result, a low-carbon free cutting steel, specified below, was invented. This low-carbon free cutting steel is comparable or superior in machinability to the leaded free cutting steels and composite free cutting steels. The "%" indicating the content of each individual component means "% by mass".

[0027] A low-carbon resulfurized free cutting steel, that is characterized by comprising C: 0.05 to under 0.20%, Mn: 0.4-2.0%, S: 0.21-1.0%, Ti: 0.002-0.10%, P: 0.001-0.30%, Al: not higher than 0.2%, O (oxygen): 0.001-0.03% and N: 0.0005-0.02%, with the balance being Fe and impurities, and which satisfies the relations (a) and (b) given below concerning the inclusions contained in the steel.

$$(A+B)/C \geqq 0.8 \qquad (a),$$

$$N_A \geqq 5 \qquad (b),$$

[0028] where A, B, C and NA denote as follows:

[0029] A: The total area occupied by substantial MnS with Ti carbide and/or Ti carbonitride included therein, among the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling.

[0030] B: The total area occupied by substantial MnS with neither Ti carbide nor Ti carbonitride included therein, among the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling.

[0031] C: The total area occupied by all the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling.

[0032] N_A: The number of substantial MnS inclusions with Ti carbide and/or Ti carbonitride included therein, among the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling.

[0033] The above low-carbon free cutting steel may contain one or more components selected from at least one group out of the following first to third groups:

[0034] First group:

[0035] Se: 0.0005-0.10%, Te: 0.0005-0.10%, Bi: 0.01-0.3%, Sn: 0.01-0.3%, Ca: 0.0001-0.01%, Mg: 0.0001-0.005%, B: 0.0002-0.02% and rare earth elements: 0.0005-0.02%.

[0036] Second group:

[0037] Cu: 0.01-1.0%, Ni: 0.01-2.0%, Mo: 0.01-0.5%, V: 0.005-0.5% and Nb: 0.005-0.5%.

[0038] Third group:

[0039] Si: 0.1-2.0% and Cr: 0.03-1.0%.

[0040] The term "substantial MnS with Ti carbide and/or Ti carbonitride included therein" as used herein means those inclusions in each of which the area percentage of MnS amounts to not less than 50% and Ti carbide and/or Ti carbonitride are included (i.e. coexist). On the other hand, the term "substantial MnS with neither Ti carbide nor Ti carbonitride included therein" means those inclusions in each of which the area percentage of MnS amounts to not less than 50% and neither Ti carbide nor Ti carbonitride are included (i.e. coexist). In each of these "substantial MnS with Ti carbide and/or Ti carbonitride included therein" and "substantial MnS with neither Ti carbide nor Ti carbonitride included therein", there may be included any of sulfides, carbosulfides, carbides, nitrides and other compounds other than Ti carbide and Ti carbonitride.

[0041] The main characteristic features of the low-carbon free cutting steel of the present invention are as follows:

[0042] (1) It contains C at a level of 0.05 to under 0.20%, S at a level within the range of 0.21-1.0%, and Ti at a content level of 0.002-0.1%.

[0043] (2) Ti binds to C, S, N and O to form the sulfide, carbosulfide, carbide, carbonitride and oxide. Ti, which shows a stronger tendency toward sulfide formation than Mn, readily forms Ti sulfide and Ti carbosulfide. However, when the content balance among Mn, Ti, S and N is carefully considered and adjusted, it is possible to allow the abundant existence of "substantial MnS with Ti carbide and/or Ti carbonitride included therein" and "substantial MnS with neither Ti carbide nor Ti carbonitride included therein" while not allowing the abundant formation of "substantial Ti carbosulfide and/or Ti sulfide".

[0044] (3) When the chemical composition given above (1) is employed and the state of existence of inclusions as specified above (2) are obtained, "substantial MnS" capable of softening and producing a lubricating effect during machining accounts for most of all the inclusions existing in the matrix, and the content of other sulfides other than this "substantial MnS", namely "substantial Ti sulfide and/or Ti carbosulfide", becomes nearly zero. For attaining a favorable finished surface roughness level on that occasion, the amount of "substantial MnS" formed must account for most of all the inclusions formed. More specifically, it is necessary, for the total area occupied by "substantial MnS" inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a sectional surface for observation in the direction of rolling, to amount to not less than 80% of the total area of all the inclusions not smaller than 1 μm in circle-equivalent diameter. Only in that case, the built-up edge formation on the edge of cutting tool, which is caused by the existence of "substantial Ti sulfide and/or Ti carbosulfide", can be prevented and the good finished surface roughness features can be obtained.

[0045] The above-mentioned "substantial MnS" comprises those inclusions in each of which the area percentage of MnS is not less than 50%, including "substantial MnS with Ti carbide and/or Ti carbonitride included therein" and "substantial MnS with neither Ti carbide nor Ti carbonitride included therein".

[0046] As shown in the expression (a) given above, it is "A+B" in expression (a) that "accounts for at not less than 80%". And, A and B are respectively defined as the area occupied by "substantial MnS with Ti carbide and/or Ti carbonitride included therein" and the area occupied by "substantial MnS with neither Ti carbide nor Ti carbonitride included therein" among the sulfides not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling.

[0047] And, C in the expression (a) is the total area of "substantial MnS with Ti carbide and/or Ti carbonitride included therein", "substantial MnS with neither Ti carbide nor Ti carbonitride included therein", "substantial Ti sulfide and/or Ti carbosulfide", other sulfides, carbosulfides, carbides, nitrides, oxides, Al_2O_3, SiO_2, and so forth.

[0048] (4) When the steel containing such inclusions as specified above term

[0049] (3), namely a steel in which almost no "substantial Ti sulfide and/or Ti carbosulfide" is present and the inclusions contained therein mostly comprise "substantial MnS" but there exists "substantial MnS with Ti carbide and/or Ti carbonitride included therein", is machined in the high-speed range where the cutting temperature increases, a hard TiN film is formed on the tool surface and the prolonged tool life can be obtained accordingly.

[0050] (5) In the steel in which "substantial MnS with Ti carbide and/or Ti carbonitride included therein" exists, that "substantial MnS" is finer in size, hence larger in number of inclusions, than the MnS contained in the conventional JIS SUM 22L to 24L composite free cutting steels. In this case, such fine "substantial MnS" inclusions serve as stress concentration points in chips during machining and promote crack propagation, so that such a level of chip disposability that is at least comparable to that of the composite free cutting steels can be obtained.

[0051] (6) The steel in which "substantial MnS with Ti carbide and/or Ti carbonitride included therein" exists is no problem about its hot workability and, therefore, the content of S, which is effective in machinability improvement, can be increased and, in that case, there is no trouble in producing the same in a continuous casting plant, for instance. As for the level of an addition amount of Ti, a small amount thereof can produce satisfactory effects, hence the production cost can remain at a low level and the steel can be applied as an inexpensive one.

[0052] As mentioned hereinabove, good machinability can be obtained by restricting the ranges of the respective alloying elements and adjusting the morphology of inclusions. However, the steels to be used in manufacturing automotive parts are desired to be excellent not only in machinability but also in carburizing characteristics in some cases. Therefore, the influences of Si and Cr on such steel characteristics were investigated and, as a result, it was revealed that the carburizing characteristics can be improved by adjusting the Si content and Cr content without impairing the above-mentioned morphology of inclusions, hence without deteriorating the machinability of the steel.

[0053] Si and Cr are dissolved in austenite and this increases the hardenability of steels and thereby increases the depth of carburizing and the hardness of the carburized layer in the carburizing treatment. In addition to Si and Cr, there are other hardenability increasing elements, for example Mn, Mo and P. However, from the machinability or hot workability viewpoint, Mn is required to be added at a sufficiently high level relative to the content of S. In that case, the addition of a further amount of Mn for hardenability improvement only means an additional cost. Mo is effective in increasing the hardenability of the steels but is more expensive than Si or Cr, hence the addition of Mo in an equally effective amount results in an increase in production cost. P also has the same effect but the addition thereof results in a rapid increase in hardness of the steels themselves, hence in the deterioration in machinability. However, in cases where there is no restriction in the material cost these elements may be added at levels not leading to deterioration in machinability or in mechanical properties. On the other hand, Si and Cr are desirous as carburization characteristics improving elements when the desired steels are to be produced at a low cost without deterioration in machinability.

BRIEF DESCRIPTION OF THE DRAWINGS

[0054] **FIG. 1A** is a schematic representation of the morphology of inclusions in a steel for comparison, and **FIG. 1B** in a steel according to the present invention.

[0055] **FIG. 2** is a graphic representation of the relationship between ratio (A+B)/C and mean finished surface roughness for steels according to the present invention and for steels for comparison.

[0056] **FIG. 3** is a graphic representation of the relationship between mean finished surface roughness and tool life for steels according to the present invention and for steels for comparison.

[0057] **FIG. 4** is a graphic representation of the relationship between chip disposability and tool life for steels according to the present invention and for steels for comparison.

DETAILED DESCRIPTION OF THE INVENTION

[0058] 1. "Substantial MnS with Ti Carbide and/or Ti Carbonitride Included Therein"

[0059] Ti binds to S, C, N and O to form Ti sulfide and Ti carbosulfide represented by the chemical formulas such as TiS and $Ti_4C_2S_2$, as well as Ti-based inclusions such as Ti carbide, Ti carbonitride, Ti nitride and Ti oxide represented by the chemical formulas TiC, Ti(CN), TiN and TiO, respectively. In some cases, Ti is dissolved in MnS and exists as (Mn, Ti)S; since, however, the solubility of Ti in MnS is low, this sulfide is substantially MnS.

[0060] On the other hand, at times Ti is not dissolved in MnS but exists as a phase distinct from MnS. Then Ti exists in the form of TiC and/or Ti(C, N), namely in a form distinctly different in composition from MnS, and the mode of existence thereof is diversified, for example in the vicinity around one sulfide, or surrounded by MnS.

[0061] **FIG. 1A** is a schematic representation of inclusions existing in a Ti-containing free cutting steel for comparison, and **FIG. 1B** in a free cutting steel according to the present invention. In the steel shown in **FIG. 1A**, the independently existing Ti sulfide and/or Ti carbosulfide inclusions and those inclusions in each of which the area percentage of Ti sulfide and/or Ti carbosulfide is not less than 50%, even when they coexist with MnS, and which can be regarded substantially as Ti sulfide and/or Ti carbosulfide, namely the above-mentioned "substantial Ti sulfide and/or Ti carbosulfide", exist in large numbers.

[0062] On the other hand, in the steel of the present invention as shown in **FIG. 1B**, those inclusions with Ti carbide and/or Ti carbonitride taken up on the periphery or in the inside of MnS, namely "substantial MnS with Ti carbide and/or Ti carbonitride included therein", and "substantial MnS with neither Ti carbide nor Ti carbonitride included therein" exist in large numbers.

[0063] In case Ti sulfide, Ti carbosulfide, Ti carbide, Ti carbonitride, Ti nitride, Ti oxide and other inclusions are included in the steel shown in **FIG. 1B** each in a form resulting from distinct phase separation from MnS, those in which the area percentage of MnS is not less than 50%, are each judged as substantially one MnS inclusion, namely "substantial MnS" inclusion. Conversely, those inclusions in each of which the area percentage of such a Ti-based inclusion compound or some other element-based oxide, nitride, carbide, etc. amounts to not less than 50% are each regarded not as "substantial MnS" but as substantially one Ti-based inclusion or other element-based oxide, nitride, carbide or the like.

[0064] Among the MnS inclusions mentioned above, those in which Ti carbide and/or Ti carbonitride, in particular, are included in a form resulting from the distinct phase separation from MnS, and the area percentage of MnS is not less than 50%, are defined as "substantial MnS with Ti carbide and/or Ti carbonitride included therein". On the other hand, "substantial MnS with neither Ti carbide nor Ti carbonitride included therein" includes MnS in those inclusions in each of which such a Ti-based inclusion other than Ti carbide and Ti carbonitride as mentioned above, or some other element-based oxide, nitride, carbide or like compound and MnS exist in distinctly separate phases, and the area percentage of MnS is not less than 50%, and which substantially play the role as MnS, and MnS entirely free of the above-mentioned Ti-based inclusions or other element-based oxide, nitride, carbide, etc. Thus, the sum of "substantial MnS with Ti carbide and/or Ti carbonitride included therein" and "substantial MnS with neither Ti carbide nor Ti carbonitride included therein" represents the sum of inclusions regarded substantially as MnS (the above-mentioned "substantial MnS" species) while the other inclusions include Ti-based inclusions such as Ti sulfide, Ti carbosulfide, Ti carbide, Ti carbonitride, Ti nitride, and Ti oxide, and other element-based oxides, carbides and nitrides, etc.

[0065] The above-mentioned area percentage of MnS and Ti-based inclusions in one inclusion can be understood by area analysis and quantitative analysis, using an EPMA (electron probe microanalyzer), an EDX (energy dispersive X-ray microanalyzer) or the like, of a microstructure test specimen cut out from a round bar to be subjected to a machining test. The existence of "substantial MnS with Ti carbide and/or Ti carbonitride included therein", "substantial MnS with neither Ti carbide nor Ti carbonitride included therein" and other inclusions can be confirmed by the same methods, and the total area and numbers of inclusions can be determined by such a technique as image analysis and, on that occasion, measurements are made in a plurality of fields of view so that the sum of all the observation areas may exceed 1 mm^2, and the total areas and numbers of respective inclusions per mm^2 are converted into the mean total areas and mean numbers, respectively.

[0066] 2. Reasons Why the Expression $(A+B)/C \geqq 0.8$ Should be Satisfied

[0067] In the above-mentioned expression (a), A is the total area occupied by "substantial MnS with Ti carbide and/or Ti carbonitride included therein" among the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling. B is the total area occupied by "substantial MnS with neither Ti carbide nor Ti carbonitride included therein" among the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling. The term "circle-equivalent diameter" indicates the diameter resulting from the conversion of the area of one inclusion as determined by the technique mentioned above, for example by image analysis, to a circle having the same area. The restriction "not smaller than 1 μm in circle-equivalent diameter" is applied since those inclusions which are smaller than 1 μm exert little influence on the machinability.

[0068] The expression (a) given above indicates that it is necessary for the sum of A and B to be not less than 80% of the total area occupied by all the inclusions not smaller than 1 μm in circle-equivalent diameter. Although good machinability can be obtained within this range, a more preferred lower limit is 90%. Further, as mentioned above, the inclusions other than the inclusions represented by A and B include independently existing nitrides, carbides, oxides, "substantial Ti sulfide and/or Ti carbosulfide", etc. Thus, the expression (a) indicates that the total area of such inclusions other than "substantial MnS" should be lower than 20% of the total area (i.e. C in expression (a)) occupied by all inclusions. More preferably, the total area in question is less than 10%.

[0069] When Ti is added to a steel containing a large amount of S for the purpose of machinability improvement; Ti, which has a stronger tendency toward sulfide formation than Mn, readily forms Ti sulfide and/or Ti carbosulfide. However, the expression (a), specified in accordance with the present invention, aims at preventing the formation of Ti sulfide and Ti carbosulfide on the assumption that Ti is added. This is because Ti sulfide and Ti carbosulfide interfere with the pseudo lubricating effect of MnS during machining. If the pseudo lubricating effect of MnS is weakened, it is presumable that the frictional force between the tool and work material increase and a built-up edge is formed on the edge of cutting tool, it results in the deterioration of the finished surface roughness characteristics. Therefore, the formation of Ti sulfide and Ti carbosulfide must be prevented. Thus, as shown in expression (a), when independently existing "substantial Ti sulfide and/or Ti carbosulfide" are almost absent in the steel and "substantial MnS" accounts for not less than 80% of the inclusions contained in the steel, the pseudo lubricating effect can be obtained during machining.

[0070] Thus, when the steel composition range specified in accordance with the present invention is employed and the expression (a) is satisfied, the steel can be at least comparable in the finished surface roughness level in finish machining to the conventional leaded free cutting steels and composite free cutting steels. On the other hand, when the expression (a) is not satisfied even if the chemical composition is within the range specified in accordance with the present invention, good machinability cannot be obtained.

[0071] 3. Reasons Why the Expression $N_A \geqq 5$ Should be Satisfied

[0072] In the above-mentioned expression (b), NA is "the number of substantial MnS inclusions with Ti carbide and/or Ti carbonitride included therein among the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling". The term "substantial MnS inclusions with Ti carbide and/or Ti carbonitride included therein" indicates those inclusions in each of the area percentage of MnS is not less than 50%, as mentioned hereinabove. The "substantial MnS with Ti carbide and/or Ti carbonitride included therein" does not substantially impair the pseudo lubricating effect, hence the built-up edge hardly forms and the finished surface roughness feature of the machined material will not deteriorate.

[0073] When a steel containing "substantial MnS with Ti carbide and/or Ti carbonitride included therein" was machined in a high-speed range exceeding 100 m/min using a carbide tool, and the tool surface was observed in detail, it was found that TiN had formed on the tool surface. Presumably, the hard TiN in a laminar form, having a thickness of several micro-meters to scores of micro-meters, is formed on the tool surface which come into contact with the work material as a result of the reaction and the change in quality occurring with the increase of temperature due to friction. The existence of the hard TiN in a laminar form can be confirmed by an area analysis and a point quantitative analysis, by AES (Auger electron spectroscopy) or using an EPMA (electron probe microanalyzer), of the tool surface deprived of carbon-containing contaminants (e.g. oils and fats etc.) by Ar sputtering or the like after completion of machining. As a result, it was found that the surface area of TiN, adhering to the tool which covers 10 to 80% of the contact area between the work material and the tool. The remainder of the contact area between the work material and the tool being covered by MnS or Fe resulting from adhesion thereof on the occasion of machining or being the tool surface as such without any adhering matter. Presumably, the hard TiN formed on the tool surface prevents tool wear, such as a thermal diffusion wear and a mechanical friction wear due to the hard inclusions, so that a markedly superior tool life, compared with the conventional resulfurized free cutting steels and Pb-containing composite free cutting steels, can be obtained.

[0074] In order to obtain such effects as mentioned above, it is only necessary that not less than 5 inclusions, preferably not less than 10 inclusions, consisting of "substantial MnS with Ti carbide and/or Ti carbonitride included therein" be present in each mm^2 of a cross-sectional observation face in the direction of rolling.

[0075] On the other hand, when the expression (b) is not satisfied, even if the chemical composition is within the range specified in the invention in the expressed application, good machinability cannot be obtained.

[0076] In a steel in which the forms of the inclusions satisfy the expressions (a) and (b), as a result of the addition of Ti, MnS exists in a very fine form. Thus, the number of MnS inclusions is very large. These fine MnS inclusions serve as stress concentration points in chips formed during machining and promote crack propagation in the chips, whereby the chip disposability is improved.

[0077] In summary, when not less than five "substantial MnS with Ti carbide and/or Ti carbonitride included therein" exist stably in each mm^2 of a sectional observation face in the direction of rolling in steel, and the sum of the total areas of "substantial MnS with Ti carbide and/or Ti carbonitride included therein" and "substantial MnS with neither Ti carbide nor Ti carbonitride included therein" in each mm^2 of a sectional observation face in the direction of rolling is not less than 80% of the total area of all inclusions, it is possible to obtain such tool life, finished surface roughness characteristics, and chip disposability, that are comparable or superior to those of the leaded free cutting steels and composite free cutting steels. For realizing such morphology of inclusions more stably and producing steels having good machinability at a low cost by continuous casting or a like method, it is necessary to take the balance among the contents of Mn, Ti, S and N into consideration. More specifically, the following conditions should be met.

$$\text{Ti (\%)/S (\%)} \geqq 0.25 \qquad \text{(a)}$$

[0078] If Ti is added in a large amount relative to the amount of S, namely if the Ti/S ratio exceeds 0.25, Ti sulfide and Ti carbosulfide will exist in large amounts. As a result, the expression (a) is not satisfied, and the pseudo lubricating effect of MnS will be reduced. On such occasion, the cutting force tends to increase and the built-up edge formation on the edge of cutting tool easily tends to occur resulting in deterioration in surface roughness characteristics in the finish machining and in working precision.

[0079] Conversely, when a slight amount of Ti is added relative to the amount of S, that is, when the Ti/S ratio is not higher than 0.25, Ti forms Ti carbide or Ti carbonitride while "substantial Ti sulfide and/or Ti carbosulfide" in the form of independent inclusions are almost absent.

[0080] While Ti carbide and Ti carbonitride precipitate in various forms, they exist in a form included in MnS in some instances. And, a steel containing "substantial MnS with Ti carbide and/or Ti carbonitride included therein" is machined in high-speed range using a carbide tool, a satisfactory tool life can be obtained. Thus, the Ti (%)/S (%) ratio should be adjusted to 0.25 or below so that the formation of singly existing inclusions consisting of "substantial Ti sulfide and/or Ti carbosulfide" may be prevented.

$$\text{Atomic ratio between Mn and S: [Mn]/[S]} \geqq 1 \qquad \text{(b)}$$

[0081] S is an element which causes cracking in a step of hot working. However, when an appropriate composition is maintained to meet the condition that the atomic ratio between the amount of Mn and S, namely the ratio in the number of atoms (number of moles) between Mn and S, should be not lower than 1, i.e. $[Mn]/[S] \geqq 1$, Mn crystallizes as MnS and there arises no hot workability problem even if Ti (%)/S (%)$\geqq$0.25. Supposing that the steel is produced by continuous casting, for instance, no hot workability problem arises within the above range and, therefore, it is possible to add S in large amounts to thereby increase the amount of MnS, which is effective in the machinability improvement; even at high S content levels, the morphology of inclusions as specified by the expressions (a) and (b) are not impaired.

[0082] When [Mn]/[S]<1, sulfides resulting from abundant dissolution of FeS in the MnS and the TiS are mainly formed and the hot workability cannot be further improved unless more Ti is added in an amount exceeding the amount of S. Even when [Mn]/[S]<1, the addition of Ti in a range exceeding the amount of S can improve the hot workability. In that case, however, the main sulfide product is not MnS but mainly Ti sulfide and/or Ti carbosulfide, which are harder than MnS, because Ti has a stronger tendency toward sulfide formation than Mn. In that case, the soft sulfide-due pseudo lubricating effect between the tool and work material during machining cannot be obtained, but the cutting force increases, resulting in deterioration in surface roughness level, as mentioned above. Thus, it is a desirable condition for producing the machinability improving effect of MnS and simultaneously obtaining good hot ductility so that the atomic ratio between the amounts of Mn and S should be not less than 1, namely [Mn]/[S]≧1.

$$\text{Ti }(\%)/\text{N }(\%) \geqq 1.35 \quad \text{(c)}$$

[0083] It is an outstanding feature of the free cutting steel of the present invention that it contains "substantial MnS with Ti carbide and/or Ti carbonitride included therein". In cases where Ti (%)/N (%)<1.35, this "substantial MnS with Ti carbide and/or Ti carbonitride included therein" cannot be obtained in a sufficient amount. In such cases, it is presumed that most of Ti added crystallizes as TiN in the early stage of solidification, hence a sufficient amount of Ti to form "substantial MnS with Ti carbide and/or Ti carbonitride included therein" cannot be secured. Therefore, the ratio Ti (%)/N (%) is desirably not less than 1.35 and, in order to stably obtain "substantial MnS with Ti carbide and/or Ti carbonitride included therein", the ratio Ti (%)/N (%) is more preferably not less than 1.5.

[0084] 4. Grounds for Restriction of the Chemical Composition

[0085] In the following, the grounds for restriction of the chemical composition in accordance with the present invention will be explained, together with the effects of the respective components.

[0086] C: 0.05 to under 0.20%

[0087] C is an important element exerting a great influence on the machinability. C content of 0.20% or above increases the strength of the steel but deteriorates its machinability, thus rendering the steel inappropriate to use where the machinability is regarded as important. At a C content level under 0.05%, however, the steel becomes excessively soft, allowing the occurrence of plucking during machining, and the wear on the tool is promoted and the finished surface roughness increases. Therefore, an adequate content of C is 0.05 to under 0.20%. A more adequate C content for obtaining better machinability is within the range of 0.07-0.18%.

[0088] Mn: 0.4-2.0%

[0089] Mn is an important element which forms sulfide inclusions with S and thus exerts a great influence on the machinability. At a Mn content level less than 0.4%, the absolute quantity of the sulfide is insufficient, therefore a satisfactory level of machinability cannot be obtained. Since Mn is an element increasing the hardenability of steels, the content of Mn may be increased when it is desired to obtain good carburizing characteristics. However, it is necessary for the steel of the present invention, which contains a large amount of S, to contain a large amount of Mn so that the Mn may form MnS with S. The addition of Mn for improving the carburizing characteristics means a further addition to the Mn content and therefore is undesirable from a production cost viewpoint. Therefore, the upper limit of the Mn content is set to 2.0%. At a Mn content level exceeding 2.0%, the strength of the steel increases and, accordingly, the cutting force increases, so that the tool life is shortened. In order to further reduce the cutting force and improve the tool life, chip disposability, finished surface roughness characteristics and hot workability, the relationship with the content of S is important. Therefore in order to ensure those performance characteristics, the Mn content is preferably within the range of 0.6-1.8%.

[0090] S: 0.21-1.0%

[0091] S is an element capable of forming sulfide inclusions with Mn and thus effective in machinability improvement. The machinability improving effect of MnS increases with the increase in the amount of S and, therefore, the selection of the S content level is important. At a S content level below 0.21%, it is impossible to obtain a sufficient amount of sulfide inclusions, hence no satisfactory machinability can be expected. On the other hand, generally, S contents exceeding 0.35% deteriorate the hot workability and promote the segregation of S in the center of the steel ingot and induce cracking in a step of forging. By maintaining an appropriate composition, however, it is possible to increase the upper limit to 1.0%. For machinability improvement by MnS, it is preferable to add a further amount of S, more preferably to a level of not lower than 0.35%. An addition level exceeding 0.40% is still more preferred for further machinability improvement. However, an excessive addition level results in an increase in production cost due to a decrease in yield. Therefore, a preferred upper limit to the S content is 0.70%.

[0092] Ti: 0.002-0.10%

[0093] Ti is an indispensable and important element for forming Ti carbide and/or Ti carbonitride with N and/or C, causing the MnS, which includes them, to exist in the steel. When "substantial MnS with Ti carbide and/or Ti carbonitride included therein" exists in the steel, the tool life of the high-speed machining using a carbide tool is markedly improved, as described above. For causing such MnS to exist in the steel, a Ti content not lower than 0.002% is required. In order to stably disperse it in the steel and obtaining a satisfactory tool life without deterioration in the finished surface roughness level, it is necessary to take the balance between the Ti content and the contents of S and N into consideration. At a Ti content level exceeding 0.10%, "substantial Ti sulfide and/or Ti carbosulfide" exists in the steel and deteriorates the finished surface roughness level in finish machining. Therefore, the upper limit of the Ti content is set to 0.10%. For obtaining good finished surface roughness levels more stably, the Ti content is preferably not higher than 0.08%, more preferably less than 0.03%.

[0094] On the other hand, when the Ti content is less than 0.002%, it is impossible to form "substantial MnS with Ti carbide and/or Ti carbonitride included therein" in a sufficient amount for improving the tool life. For forming such MnS more reliably and thereby improving the carbide tool life, a Ti content exceeding 0.01% is desired.

[0095] P: 0.001-0.30%

[0096] P increases the hardenability of the steel and at the same time increases the strength. For producing such effects, the content of P should be not lower than 0.001%. At a P content level not higher than 0.30%, the hardenability and strength can be secured without deteriorating the machinability. At a P content level exceeding 0.30%, the strength becomes excessively high and the machinability is somewhat deteriorated and, in addition, the hot workability is deteriorated through promoted segregation in the steel ingot. Therefore, the content of P should be 0.001-0.30%. A more preferred content of P for stably maintaining good machinability and strength levels is 0.005-0.13%.

[0097] Al: not more than 0.2% (may not be added)

[0098] Al is used as a potent deoxidizing element and may be contained up to a level of 0.2%. However, the oxide formed upon deoxidation is hard and, when the content of Al exceeds 0.2%, the hard oxide is formed in large amounts, deteriorating the machinability. Therefore, content of not more than 0.1% is more preferred. In cases where a sufficient deoxidation is possible by the addition of C and Mn, Al may not be added and the content of Al may have an impurity level not higher than 0.002%.

[0099] O (oxygen): 0.001-0.03%

[0100] When an appropriate amount of oxygen is contained in the steel, it is dissolved in the MnS and this prevents the elongation of MnS upon rolling and thus reduces the anisotropy in mechanical properties, although the effects of the oxygen in the steel of the present invention are not affected by the state of the deoxidation. Further, oxygen is also effective in improving the machinability and hot workability and also prevents the segregation of S. However, at an O content level exceeding 0.03%, it causes problems; for example, it causes deterioration of and damage to the refractory material in the melting stage. Therefore, the oxygen content should be within the range of 0.001-0.03%. A preferred range for properly obtaining the above effects is 0.0015-0.01%.

[0101] N: 0.0005-0.02%

[0102] N easily forms hard nitrides with Al and/or Ti. These nitrides are effective in making grains finer. However, when present in large amounts, these nitrides tend to promote the wear of the tool and deteriorate the machinability. Since Ti is added, as an essential component, to the steel of the present invention, the content of N should preferably be as low as possible. However, for obtaining the above effect, N is allowable to be contained at a level of not lower than 0.0005%. When, on the other hand, the content of N becomes excessive, coarse TiN may be formed, possibly impairing the machinability, hence the upper limit of the N content is set to 0.02%. For securing better machinability, the upper limit of the N content is preferably set to 0.015%. Since the present invention aims at improving the machinability by the occurrence of "substantial MnS with Ti carbide and/or Ti carbonitride included therein", it is desirable that the contents of Ti and N satisfy the condition of Ti (%)/N (%)$\geqq$1.35 so that such MnS may exist stably in the steel. This is because when Ti (%)/N (%)$<$1.35, most of Ti added forms TiN in the early stage of solidification and, as a result, "substantial MnS with Ti carbide and/or Ti carbonitride included therein" cannot be stably obtained, as described hereinabove.

[0103] Owing to the chemical composition comprising the elements whose contents are respectively adjusted as mentioned above and the morphology of inclusions as specified by the expressions (a) and (b), a low-carbon free cutting steel excellent in machinability, hot workability and finished surface characteristics can be obtained.

[0104] The low-carbon free cutting steel of the present invention may further contain one or more elements selected from at least one group among the first to third groups mentioned hereinabove (refer to page 9).

[0105] (1) Elements of the First Group

[0106] The elements of the first group are elements capable of further improving the machinability of the steel without impairing the effects obtained by the above-mentioned main composition according to the present invention. Therefore, for obtaining further improved machinability, one or more of them may be contained in the steel.

[0107] Se: 0.0005-0.10% and Te: 0.0005-0.10%

[0108] Se and Te form Mn(S, Se) and Mn(S, Te) with Mn. These play the same role as that of MnS in producing the pseudo lubricating effect during machining and, therefore, Se and Te are elements which are effective in machinability improvement and, for further machinability improvement, they may be contained in the steel within the above respective ranges. When their content levels are below 0.0005%, their effects are insignificant. On the other hand, at levels exceeding 0.10%, not only the effect of each of the Se and Te reaches a point of saturation but also due to the addition it becomes uneconomical, and also the hot workability deteriorates. For simultaneously obtaining good hot workability and more stable machinability, the additional level of each element is preferably 0.0010-0.05%.

[0109] Bi: 0.01-0.3% and Sn: 0.01-0.3%

[0110] Bi and Sn are effective in improving the machinability of the steel. This is presumably because they produce a lubricating effect during the machining as low-melting metal inclusions, similar to Pb. In order to attain that effect, the content of each is preferably set to not lower than 0.01%. When the addition level of each of them exceeds 0.30%, however, not only the effect of each of them reaches a point of saturation but also the hot workability deteriorates. For simultaneously obtaining good hot workability and more stable machinability, the additional level of each element is preferably 0.03-0.1%.

[0111] Ca: 0.0001-0.01%

[0112] Ca has a high affinity for S and O (oxygen) and forms the corresponding sulfide and oxide in the steel. Further, Ca is dissolved in MnS to form (Mn, Ca) S but the amount of Ca soluble therein is slight, hence the effects of MnS are not impaired. The oxide formed by Ca is a low-melting oxide and, thus, Ca is an additive element effective in further improving the machinability of the steel of the present invention. In order to improve the machinability produced by the addition of Ca, the lower limit of the Ca content is preferably set to 0.0001%. Since, however, the yield of the additional Ca is low, the addition of large amounts of Ca is required and, this is unfavorable from the production cost viewpoint. Therefore, the upper limit to the Ca content is set to 0.01%. A more preferred upper limit is 0.005%.

[0113] Mg: 0.0001-0.005%

[0114] Mg also has a high affinity for S and O (oxygen) in the steel and forms the corresponding sulfide and oxide. The Mg-containing sulfide and oxide function as nucleating agents in the crystallization of MnS and are effective in preventing the elongation of MnS. When such effects are desired, Mg may be added. In order to sufficiently produce those effects, the lower limit of the Mg content is preferably set to not lower than 0.0001%. Since, however, the oxide formed by Mg is hard, and excessively high Mg content deteriorates machinability. Therefore, the upper limit of the Mg content is set to 0.005%. A preferred upper limit for preventing the elongation of MnS and simultaneously obtaining good machinability is 0.002%.

[0115] B: 0.0002-0.02%

[0116] B binds to O (oxygen) or N to form the oxide or nitride and is effective in the improvement of machinability, hence may be added according to need. In order to obtain that effect, the B content of not lower than 0.0002% is required and in order to be more effective, a level of not lower than 0.0010% is desirable. At a B content level exceeding 0.02%, that effect reaches a point of saturation and, in addition, the hot workability is somewhat deteriorated.

[0117] Rare earth elements: 0.0005-0.02%

[0118] Rare earth elements constitute a group of elements classified as lanthanoids. When they are added, a misch metal or the like containing them as main components is generally used. The content of rare earth elements, so referred to herein, is expressed in terms of the total content of one or more elements among the rare earth elements. The rare earth elements form oxides with oxygen and also bind to S to form sulfides, and thereby improve the machinability. In order to be effective, their content should be not less than 0.0005%. However, at content levels exceeding 0.02%, the effect reaches a point of saturation. Further, the yield of the addition of rare earth elements is low, hence the addition of rare earth elements in large amounts is uneconomical.

[0119] (2) Elements of the Second Group

[0120] The elements of the second group all increase the strength of steel. The steel may contain one or more of these elements according to need.

[0121] Cu: 0.01-1.0%

[0122] Cu is effective in improving the strength of the steel through precipitation hardening. In order to obtain this effect, a Cu content of not less than 0.01% is required and an addition level of not lower than 0.1% is desirable. However, at a Cu content level exceeding 1.0%, the hot workability deteriorates. And moreover the above effect reaches a point of saturation due to the coarsening of the Cu precipitates. In addition, this brings about a decrease in machinability.

[0123] Ni: 0.01-2.0%

[0124] Ni is effective in improving the strength of the steel through solid-solution strengthening. In order to be effective, its content is preferably not lower than 0.01%. At a Ni content level exceeding 2.0%, however, the machinability deteriorates and, at the same time, the hot workability also deteriorates.

[0125] Mo: 0.01-0.5%

[0126] Mo is an element capable of improving hardenability, but when Mo is added in an amount sufficient to produce the carburizing characteristics equivalent to that obtainable by the addition of Si and/or Cr, the production cost disadvantageously increases since Mo is more expensive than Si or Cr. However, Mo is also effective in rendering the microstructure finer and improving the toughness, therefore when it is desired that these effects be produced, Mo may be added. In order to obtain the effects, a content of Mo of not less than 0.01% is desirable, however, at levels exceeding 0.5%, the effects reaches a point of saturation and, in addition, the steel production cost increases.

[0127] V: 0.005-0.5%

[0128] V precipitates as fine nitrides or carbonitrides and improves the strength of the steel. This effect can be obtained if the V content is not less than 0.005% but a V content of not less than 0.01% is preferred. At a V content level exceeding 0.5%, however, the above effect reaches a point of saturation and, in addition, the excessively formed nitride and/or carbide bring out a decrease in machinability.

[0129] Nb: 0.005-0.5%

[0130] Nb precipitates as fine nitrides or carbonitrides and improves the strength of the steel. This effect can be obtained if the Nb content is not less than 0.005% but a Nb content of not less than 0.01% is preferred. At a Nb content level exceeding 0.5%, however, the above effect reaches a point of saturation and, in addition, the excessively formed nitride and/or carbide bring out a decrease in machinability and the Nb addition at such level is also uneconomical.

[0131] (3) Elements of the Third Group

[0132] The elements of the third group are elements either one or both of which may be contained in the steel when the carburizing characteristics thereof need improvement.

[0133] Si: 0.1-2.0%

[0134] In the free cutting steel of the present invention, as set forth in any of Claims **1** to **4**, no positive addition of Si is made. This is due to Si being one of the impurities and the content of Si is less than 0.1%. In the case of the free cutting steel of the present invention, as set forth in any of Claims **1** to **4**, Si is added in some instances as a deoxidizing element for adjusting the oxygen content in the steel to an appropriate level. Even in those cases, it is not necessary to positively allow Si to remain; the Si remains in the steel is an impurity and its content is less than 0.1%.

[0135] Through its dissolution in ferrite, Si is effective in improving the strength of the steel and it is also effective in improving the hardenability of the steel. By increasing the hardenability of the steel, it becomes possible to also improve the carburizing characteristics which are desired in manufacturing automotive parts. In this only case, Si can be added at a level of not lower than 0.1% and in order to further improve the carburizing characteristics more reliably, a content level exceeding 0.6% is desirable. However, at a Si content level exceeding 2.0%, the machinability is adversely affected, for example the hot workability deteriorates and the cutting force increases, because of solid solution hardening of the ferrite phase. Even when the Si content is at an impurity level of lower than 0.1%, the oxygen content in the steel can be adjusted to an appropriate level by properly adding C, Mn and/or Al.

[0136] Cr: 0.03-1.0%

[0137] Cr is an element capable of improving the carburizing characteristics thereby increasing the hardenability of the steel through additional small amounts. When it contains Cr, the steel shows improved carburizing characteristics; the carburized layer hardness, after carburizing treatment, is high, and the effective hardening depth can be increased. In order to obtain such effects, the Cr content should be set to not less than 0.03% and when more reliable improvements in carburizing characteristics are desired, content exceeding 0.05% is desirable. However, at a Cr content level exceeding 1.0%, the machinability deteriorates and the production cost also increases.

[0138] When the above Si and/or Cr are contained, it becomes possible to obtain a steel having good machinability and hot workability and, further, good carburizing characteristics.

EXAMPLES

[0139] 1. Preparation of Test Specimens

[0140] Using a high frequency induction furnace, 150-kg steel ingots (diameter: about 220 mm), having various respective compositions shown in Tables 1 and 2 were prepared. The steels according to the present invention are shown in Table 1, and the conventional steels and comparative steels are shown in Table 2.

[0141] For the stable formation of "substantial MnS with Ti carbide and/or Ti carbonitride included therein", these steel ingots were heated to a temperature as high as 1,250° C. and kept for 2 hours or a longer period at that temperature. After that, in order to simulate the rolling process, forging was performed at a finishing temperature of not lower than 1,000° C. and, then, the forgings were air-cooled to produce round bars having a diameter of 65 mm. These forged bars were normalized by heating to 950° C. and maintaining that temperature for 1 hour, followed by air cooling.

[0142] The comparative steels Nos. 51 to 53 were poor in hot workability and cracking occurred during the forging, making it impossible to produce any forged bars; hence subsequent investigations were not performed with them.

TABLE 1

Steel	Chemical Composition (mass %; bal.: Fe and impurities)											[Mn]/[S] (Atomic	Ti/S (mass %	Ti/N (mass %	(A + B)/	
No.	C	Si	Mn	P	S	Al	Ti	Cr	N	O	Others	Ratio)	Ratio)	Ratio)	C	$N_A \geqq 5$
1	0.05	<0.01	0.89	0.015	0.42	<0.001	0.092	—	0.0012	0.0096	—	1.11	0.22	17.00	0.95	○
2	0.06	<0.01	1.13	0.019	0.41	<0.001	0.060	—	0.0085	0.0089	—	1.61	0.15	7.02	0.96	○
3	0.09	0.06	0.97	0.032	0.44	0.002	0.009	—	0.0028	0.0018	—	1.28	0.02	3.21	0.99	○
4	0.10	0.04	1.49	0.029	0.55	0.001	0.061	—	0.0047	0.0033	—	1.58	0.11	12.98	0.98	○
5	0.10	0.05	1.58	0.032	0.49	<0.001	0.018	—	0.0047	0.0027	—	1.88	0.04	3.83	0.97	○
6	0.10	<0.01	0.96	0.016	0.36	<0.001	0.087	—	0.0063	0.0046	—	1.56	0.24	13.79	0.88	○
7	0.10	<0.01	0.85	0.018	0.35	<0.001	0.080	—	0.0085	0.0079	—	1.42	0.23	9.41	0.94	○
8	0.12	0.04	1.10	0.030	0.38	<0.001	0.026	—	0.0125	0.0018	—	1.69	0.07	2.08	0.96	○
9	0.13	<0.01	1.59	0.032	0.48	<0.001	0.024	—	0.0050	0.0043	—	1.95	0.05	4.80	0.98	○
10	0.15	0.07	1.49	0.030	0.49	0.025	0.014	—	0.0047	0.0020	—	1.77	0.03	2.98	0.99	○
11	0.18	0.03	1.52	0.058	0.47	0.002	0.021	—	0.0130	0.0036	—	1.89	0.04	1.62	0.96	○
12	0.09	0.02	1.17	0.022	0.40	0.005	0.053	0.20	0.0054	0.0035	—	1.71	0.13	9.81	0.95	○
13	0.11	0.46	1.60	0.020	0.60	<0.001	0.014	—	0.0101	0.0026	—	1.56	0.02	1.39	0.98	○
14	0.12	1.28	1.46	0.015	0.44	0.002	0.024	—	0.0058	0.0027	—	1.93	0.05	4.14	0.98	○
15	0.15	0.04	1.12	0.026	0.40	<0.001	0.027	0.50	0.0125	0.0038	—	1.63	0.07	2.16	0.96	○
16	0.18	0.85	1.36	0.040	0.39	<0.001	0.021	—	0.0134	0.0031	—	2.04	0.05	1.57	0.97	○
17	0.18	0.01	1.46	0.028	0.46	0.002	0.025	0.15	0.0048	0.0064	—	1.85	0.05	5.21	0.98	○
18	0.14	0.06	1.65	0.028	0.45	0.002	0.018	—	0.0049	0.0024	Se: 0.010	2.14	0.04	3.67	0.99	○
19	0.08	0.13	1.60	0.030	0.42	<0.001	0.014	—	0.0095	0.0028	Te: 0.015	2.22	0.03	1.47	0.98	○
20	0.12	0.03	1.50	0.031	0.45	0.002	0.022	—	0.0120	0.0032	Bi: 0.05	1.95	0.05	1.83	0.98	○
21	0.16	0.01	1.35	0.025	0.42	0.002	0.028	—	0.0059	0.0055	Sn: 0.04	1.88	0.07	4.75	0.98	○
22	0.06	0.01	0.88	0.017	0.49	0.001	0.082	—	0.0062	0.0073	Ca: 0.0029	1.05	0.17	13.27	0.99	○
23	0.10	0.05	1.02	0.020	0.46	0.004	0.025	—	0.0037	0.0026	Mg: 0.0015	1.29	0.05	6.76	0.97	○
24	0.10	0.01	1.48	0.027	0.47	0.002	0.021	—	0.0095	0.0048	B: 0.0025	1.84	0.04	2.21	0.97	○
25	0.11	0.01	1.22	0.029	0.37	0.002	0.022	—	0.0124	0.0025	Cu: 0.10	1.92	0.06	1.77	0.98	○
26	0.15	0.02	1.38	0.035	0.43	0.002	0.025	—	0.0045	0.0056	V: 0.05	1.87	0.06	5.56	0.98	○
27	0.12	<0.01	1.55	0.030	0.46	<0.001	0.026	—	0.0047	0.0050	Nb: 0.12	1.97	0.06	5.53	0.98	○
28	0.16	0.07	1.00	0.025	0.25	0.002	0.060	—	0.0101	0.0092	Ni: 0.10	2.33	0.24	5.93	0.89	○
29	0.10	0.03	1.40	0.038	0.41	0.002	0.029	—	0.0052	0.0064	Mo: 0.10	1.99	0.07	5.58	0.97	○
30	0.11	0.01	1.25	0.035	0.46	<0.001	0.025	—	0.0130	0.0048	Ca: 0.0015, Mg: 0.0018	1.59	0.05	1.92	0.97	○
31	0.09	0.05	1.44	0.027	0.43	0.003	0.022	—	0.0112	0.0030	Bi: 0.07, Nb: 0.10	1.95	0.05	1.96	0.98	○
32	0.10	0.02	1.46	0.026	0.42	0.003	0.022	—	0.0132	0.0024	Sn: 0.07, V: 0.10	2.03	0.05	1.67	0.98	○
33	0.12	0.05	0.99	0.031	0.40	0.001	0.029	—	0.0085	0.0030	Ca: 0.001, Mo: 0.12	1.44	0.07	3.41	0.97	○
34	0.10	0.03	1.52	0.032	0.45	<0.001	0.019	—	0.0090	0.0035	Te: 0.012,	1.97	0.04	2.11	0.98	○

[0143]

TABLE 2

Steel No.	Chemical Composition (mass %; bal.: Fe and impurities) C	Si	Mn	P	S	Al	Ti	Cr	N	O	Others	[Mn]/[S] (Atomic Ratio)	Ti/S (mass % Ratio)	Ti/N (mass % Ratio)	(A + B)/C	$N_A \geqq 5$
35	0.07	<0.01	1.02	0.070	0.32	0.002	—	—	0.0052	0.0160	*Pb: 0.31	1.86	—	—	—	—
36	0.08	0.01	1.12	0.060	0.31	0.002	—	—	0.0084	0.0145	*Pb: 0.18	2.11	—	—	—	—
37	0.08	0.01	1.02	0.067	0.33	0.002	—	—	0.0066	0.0150	—	1.80	—	—	—	—
38	0.06	0.06	0.86	0.020	0.42	0.001	*0.280	—	0.0050	0.0068	—	1.20	*0.67	56.0	*0.75	○
39	0.08	0.02	1.15	0.033	0.35	0.001	*0.250	—	0.0079	0.0052	—	1.92	*0.71	31.6	*0.70	○
40	0.10	0.01	1.12	0.028	0.36	<0.001	*0.330	—	0.0085	0.0053	—	1.82	*0.92	38.8	*0.65	○
41	0.18	0.03	0.47	0.016	0.29	0.003	*0.420	—	0.0059	0.0019	—	*0.95	*1.45	71.2	*0.20	○
42	0.10	0.01	1.05	0.013	0.39	0.001	0.006	—	0.0099	0.0035	—	1.57	0.02	*0.6	0.99	x*
43	0.09	0.35	1.21	0.025	0.30	0.001	0.009	—	0.0138	0.0084	—	2.35	0.03	*0.7	0.98	x*
44	*0.52	0.17	0.52	0.016	0.21	<0.001	0.050	—	0.0079	0.0180	—	1.45	0.24	6.4	0.96	○
45	*0.45	<0.01	0.85	0.019	0.32	0.002	0.078	—	0.0046	0.0058	—	1.55	0.24	17.0	0.95	○
46	*0.01	<0.01	0.98	0.016	0.33	0.002	0.067	—	0.0048	0.0048	—	1.73	0.20	14.0	0.96	○
47	0.10	0.02	1.45	0.016	0.49	*0.35	0.028	—	0.0057	0.0017	—	1.73	0.06	4.9	0.97	○
48	0.07	0.01	0.92	0.015	0.47	<0.001	0.056	*2.50	0.0075	0.0036	—	1.14	0.12	7.5	0.99	○
49	0.09	*2.55	1.56	0.020	0.45	0.001	0.065	—	0.0058	0.0024	—	2.02	0.14	11.2	0.98	○
50	0.05	<0.01	0.48	0.015	*0.15	<0.001	0.022	—	0.0095	0.0193	—	1.87	0.15	2.3	0.92	○
51	0.09	0.01	1.85	0.018	*1.14	0.001	0.102	—	0.0078	0.0128	—	*0.95	0.09	13.1	—	—
52	0.06	<0.01	*0.21	0.016	0.33	0.001	0.074	—	0.0073	0.0078	—	*0.37	0.22	10.1	—	—
53	0.08	<0.01	1.25	0.025	0.44	0.002	0.072	—	0.0050	0.0049	*Te: 0.12	1.66	0.16	14.4	—	—
54	0.06	<0.01	1.03	0.016	0.46	<0.001	0.045	—	0.0059	0.0085	*V: 2.0	1.31	0.10	7.6	0.99	○
55	0.15	<0.01	1.11	0.015	0.46	0.002	0.080	—	0.0078	0.0063	*Mo: 1.50	1.41	0.17	10.3	0.98	○

The mark "*" indicates that the value is outside the relevant range specified by the present invention.

[0144] 2. Investigation of the Morphology of Inclusions

[0145] Many of the inclusions observed in a cross section parallel to the direction of rolling show a form which is elongated in the direction of the rolling or an unspecific form. In investigating the number of inclusions and the area occupied thereby, test specimens for microscopic observation were taken from each of the forged bars at a site corresponding to Df/4 (Df: diameter of the forged bar) in the longitudinal sectional direction, and embedded in a resin and, after mirror-like polishing, photographed under an optical microscope magnified 400 times.

[0146] Each photograph was observed by image processing and the number of inclusions and the area occupied by them were determined. Those inclusions, which were not smaller than 1 μm in circle-equivalent diameter upon conversion of the area of each inclusion into a circle, having the same area, were employed as the targets. The reason the targets were restricted to those having a circle-equivalent diameter of not smaller than 1 μm, is that those inclusions smaller than 1 μm have no substantial effect on the machinability, as described hereinabove.

[0147] The composition of each of these inclusions was confirmed in the following manner. Namely, as mentioned above, each test specimen was prepared for microscopic observation by cutting out from the forged bar at a site corresponding to Df/4 (Df is the diameter of each forged bar) in a longitudinal sectional direction, embedded in a resin, mirror-like polished and then was subjected to area analysis and quantitative analysis using an EPMA (electron probe microanalyzer), an EDX (energy dispersive X-ray spectroscope), etc. The magnification for observation had a range not exceeding 10,000 times and, at the selected observation magnification, an inclusion in which MnS and Ti carbide and/or Ti carbonitride were observed in distinctly separated phases, and in which the area percentage of MnS was not lower than 50%, corresponds to "substantial MnS with Ti carbide and/or Ti carbonitride included therein".

[0148] Based on the results of such observation, the areas of "substantial MnS with Ti carbide and/or Ti carbonitride included therein" and "substantial MnS with neither Ti carbide nor Ti carbonitride included therein" were determined for individual inclusions having a circle-equivalent diameter of not smaller than 1 μm. Then, the sums of the areas of these inclusions per mm^2 in the section in the direction of rolling were calculated and, the sum of the areas occupied by these inclusions per mm^2 in the section in the direction of rolling was calculated, and then (A+B)/C was calculated.

[0149] From the results obtained in the above manner, the number of inclusions consisting of "substantial MnS with Ti carbide and/or Ti carbonitride included therein" was determined. When the average number per mm^2 of the section in the direction of rolling was 5 or more, the relevant steel was evaluated as "○". Conversely, when the number of inclusions consisting of "substantial MnS with Ti carbide and/or Ti carbonitride included therein" was less than 5, the relevant steel was evaluated as "×". The comparative steels Nos. 35 to 37 given in Table 2 are Ti-free leaded or resulfurized free cutting steels. They are substantially free of "substantial MnS with Ti carbide and/or Ti carbonitride included therein", hence such calculations were not carried out.

[0150] 3. Machinability Testing

[0151] In the machinability testing, each forged bar was externally machined into a round bar with a diameter of 60 mm and was subjected to tests for tool life and finished surface roughness. The tool life test was carried out using an uncoated JIS P20 carbide tool under the following dry turning conditions;

[0152] Cutting speed: 150 m/min,

[0153] Feed: 0.10 mm/rev, and

[0154] Depth of cut: 2.0 mm.

[0155] Thirty minutes after the start of turning under the above conditions, the mean flank wear (VB) was measured. For those test specimens showing a mean flank wear of not less than 200 μm within 30 minutes, the time required for arriving at such wear and the mean flank wear (VB) at that time were measured for each of the specimens.

[0156] The tool life evaluation was carried out using, as a measure, the time. required for the mean flank wear (VB) to arrive at 100 μm. When the test specimen became short during testing due to its superiority in suppressing the tool wear and extremely slow wear rate of the tool, the time required for the mean flank wear to arrive at 100 μm was calculated from the turning time-tool wear curve by the regression method. The chip disposability was evaluated by collecting 200 representative chips among the chips discharged from test specimen, measuring their mass, and calculating the number of chips per unit mass.

[0157] Since the finished surface roughness is evaluated in terms of the surface roughness after machining, the surface of each machined material after machining, under the following conditions, was evaluated using a versatile instrument for the evaluation of surface texture. The test for the evaluation of the finished surface roughness was carried out using a TiAlN multilayer-coated JIS K type carbide tool. The cutting was carried out in the manner of wet turning using a lubricating oil of the aqueous emulsion type under the following condition;

[0158] Cutting speed: 100 m/min,

[0159] Feed: 0.05 mm/rev, and

[0160] Depth of cut: 0.5 mm.

[0161] Each tested steel was machined under these conditions for 1 minute, and the test specimen result was evaluated for finished surface roughness by measuring the mean finished surface roughness (Ra), while moving the stylus of the versatile instrument for the evaluation of surface texture in an axial direction.

[0162] 4. Hot Workability Testing

[0163] The hot workability was evaluated in the following manner. In order to simulate the production conditions in a continuous casting plant, a test specimen, 10 mm in diameter and 130 mm in height for high-temperature tensile test was taken from each 150-kg steel ingot. The steel ingot was produced in the same manner as mentioned above. The test specimen was taken in the direction of the steel ingot height so that the specimen center might be close to the surface of the steel ingot, namely at a site of Di/8 (Di: the diameter of the steel ingot). The specimen was heated to 1,250° C. for 5 minutes by a direct charge of an electric current at a fixation distance of 110 mm, and cooled to 1,100° C. at a cooling rate of 10° C./sec. After 10 seconds of maintaining the temperature at 1,100° C., the tensile test was carried out at a strain rate of 10^{-3}/sec. In the tensile test, the reduction of area at the site of breakage was determined and the hot workability was evaluated based thereon.

[0164] 5. Carburizing Test

[0165] The carburizing test was carried out in the following manner. A cylindrical steel material, 24 mm in diameter and 50 mm in length, was used as the test specimen. This was taken from each of the above-mentioned normalized materials, 65 mm in diameter, at a site of R/2 (R: the radius of the normalized material). This test specimen was heated to 900° C. for the carburizing treatment and then to 850° C. for the diffusion treatment. In the above-mentioned carburizing step, the carbon potential (C.P.) value was 0.8% and the treatment time was 75 minutes. The C.P. value during diffusion treatment was 0.7% and the treatment time was 20 minutes. The test specimen after carburizing treatment was cooled in an oil bath at 80° C. for quenching treatment. Finally, the test specimen was heated to 190° C. and maintained at that temperature for 60 minutes for the tempering treatment. The method of evaluation for carburizing characteristics was as follows.

[0166] The test specimen, after carburizing quenching and tempering, was measured for Vickers hardness distribution from the surface to the inside in the cross section at a site of 25 mm distant from the end of the test specimen (namely the center in the longitudinal direction). The effective case depth after carburizing corresponding to Hv 400 was determined, and a judgment was made as to whether the value was greater or smaller than the value obtained with a conventional leaded composite free cutting steel. The conventional leaded composite free cutting steel was the steel No. 25 shown in Table 2, and the effective case depth after carburizing thereof was 0.25 mm.

[0167] In the evaluation for carburizing characteristics, the steel showing an effective case depth after carburizing±0.05 mm relative to the steel No. 35, namely 0.20-0.30 mm, was evaluated as equivalent, the steel showing a value smaller than 0.20 mm as inferior, and the steel showing a value greater than 0.30 mm as superior. The results obtained are shown in Table 3 and Table 4 in terms of ○, × or ◎; the case of equivalency is represented by "○", the case of inferiority by "×", and the case of superiority by "◎".

[0168] The results obtained in the above tests are summarized in Table 3 and Table 4. Further, the relationship between (A+B)/C in relation (a) and finished surface roughness is shown in **FIG. 2**, the relationship between finished surface roughness and tool life in **FIG. 3**, and the relationship between chip disposability and tool life in **FIG. 4**.

TABLE 3

Steel No.	Reduction of Area (%)	Tool Wear after 30 min. (μm)	Time for Arriving VB of 100 μm (min.)	Chip Disposability (number/g)	Mean Finished Surface Roughness (μm)	Evaluation for Carburizing Characteristics
1	61.8	45	90	18	0.7	○
2	64.3	39	98	14	0.6	○
3	64.5	48	85	12	0.2	○
4	80.2	32	125	18	0.5	○
5	76.8	43	96	21	0.3	○
6	63.6	44	91	14	0.7	○
7	67.2	38	96	16	0.7	○
8	65.2	42	98	17	0.3	○
9	81.4	36	121	20	0.4	○
10	76.8	45	93	19	0.4	○
11	73.4	40	103	16	0.4	○
12	71.8	42	100	14	0.5	◎
13	64.7	45	93	18	0.2	◎
14	82.9	46	90	18	0.2	◎
15	65.2	42	98	17	0.4	◎
16	72.8	44	95	18	0.4	◎
17	80.1	42	95	12	0.4	◎
18	71.0	38	110	18	0.3	○
19	69.5	40	98	19	0.3	○
20	62.9	45	92	24	0.3	○
21	64.8	46	93	13	0.2	○
22	60.8	29	120	19	0.5	○
23	62.8	43	95	22	0.6	○
24	81.2	38	105	16	0.5	○
25	75.9	41	101	20	0.4	○
26	78.7	43	97	16	0.3	○
27	75.4	40	105	22	0.3	○
28	80.5	42	93	14	0.8	○
29	78.8	36	115	18	0.3	○
30	64.2	37	105	24	0.4	○
31	60.9	46	91	20	0.3	○
32	61.3	44	90	18	0.3	○
33	64.3	24	126	19	0.5	○
34	67.2	41	99	17	0.3	○

[0169]

TABLE 4

Steel No.	Reduction of Area (%)	Tool Wear after 30 min. (μm)	Time for Arriving VB of 100 μm (min.)	Chip Disposability (number/g)	Mean Finished Surface Roughness (μm)	Evaluation for Carburizing Characteristics
35	49.8	98	36	9	0.4	○
36	49.6	99	30	8	0.7	○
37	55.4	165	17	6	0.7	○
38	74.3	35	113	15	1.3	X
39	73.0	40	98	17	1.4	X
40	68.2	45	92	18	1.5	X
41	64.2	71	68	16	1.7	X
42	67.5	89	38	15	0.5	○
43	79.0	85	42	13	0.6	◎
44	52.8	93	36	12	1.3	◎
45	66.9	88	39	15	1.0	◎
46	57.5	103	29	8	1.6	X
47	78.7	101	30	16	0.3	○
48	56.0	232	12	12	1.8	◎
49	59.8	206	16	14	1.9	◎
50	65.3	129	20	9	1.3	○
51	6.4	—	—	—	—	—
52	4.3	—	—	—	—	—

TABLE 4-continued

Steel No.	Reduction of Area (%)	Tool Wear after 30 min. (μm)	Time for Arriving VB of 100 μm (min.)	Chip Disposability (number/g)	Mean Finished Surface Roughness (μm)	Evaluation for Carburizing Characteristics
53	3.4	—	—	—	—	—
54	59.5	198	17	15	1.8	○
55	58.5	264	10	10	1.9	◎

[0170] In Table 2, the steels Nos. 35 and 36 are composite free cutting steels, and the steel No. 37 is a resulfurized free cutting steel. At this time, these steels are regarded as highest in machinability. As is evident from Table 3, Table 4, **FIG. 2** and **FIG. 3**, the steels of the present invention are superior in tool life and finished surface roughness level. Furthermore, the steels Nos. 1-34 according to the present invention have good hot workability, and are at least comparable to the composite free cutting steels and resulfurized steels, as shown in Table 3 in terms of the reduction of area in the high-temperature tensile test simulating the practical production in a continuous casting plant or the like, and thus are free of problems from the practical viewpoint.

[0171] The steels Nos. 12-17 according to the present invention shown in Table 1, contains at least one including Si and Cr within the specified content range in order to improve the carburizing characteristics. It is evident that these steels show good carburizing characteristics, in particular, among the steels of the present invention.

[0172] On the other hand, as the steels 35-55 in Table 2, it is evident that those steels which fail to satisfy one or more requirements concerning the morphology of inclusions and chemical composition, as specified herein in accordance with the present invention, are inferior at least one of the following: tool life, finished surface roughness level, chip disposability and hot workability to the steels of the present invention.

[0173] Although only some exemplary embodiments of the present invention have been described in detail above, those skilled in the art will readily appreciated that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of the present invention. Accordingly, all such modifications are intended to be included within the scope of the present invention.

Industrial Applicability

[0174] In spite of its Non-leadea composition, the free cutting steel of the present invention is comparable or superior in machinability to the conventional leaded free cutting steels and composite free cutting steels and, further, are excellent from the finished surface characteristics viewpoint. When the free cutting steel of the present invention contains Si and/or Cr, it shows good carburizing characteristics. Furthermore, this steel is excellent in hot workability and can be produced at a low cost by continuous casting. It produces no environmental problems since it does not contain Pb. Therefore, it is very well suited for use as a raw material of various machine parts.

What is claimed is:

1. A low-carbon free cutting steel which comprises, on the percent by mass basis, C: 0.05 to under 0.20%, Mn: 0.4-2.0%, S: 0.21-1.0%, Ti: 0.002-0.10%, P: 0.001-0.30%, Al: not higher than 0.2%, O (oxygen): 0.001-0.03% and N: 0.0005-0.02%, with the balance being Fe and impurities, and which satisfies the relations (a) and (b) given below concerning the inclusions contained in the steel:

$$(A+B)/C \geqq 0.8 \quad \text{(a)},$$

$$N_A \geqq 5 \quad \text{(b)},$$

wherein, in the relations (a) and (b), A, B, C and NA denote as follows:

A: the total area occupied by substantial MnS with Ti carbide and/or Ti carbonitride included therein among the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling;

B: the total area occupied by substantial MnS with neither Ti carbide nor Ti carbonitride included therein among the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling;

C: the total area occupied by all the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling;

N_A: the number of substantial MnS inclusions with Ti carbide and/or Ti carbonitride included therein among the inclusions not smaller than 1 μm in circle-equivalent diameter per mm^2 of a cross section parallel to the direction of rolling.

2. A low-carbon free cutting steel according to claim 1, which further contains at least one element selected from among Se: 0.0005-0.10%, Te: 0.0005-0.10%, Bi: 0.01-0.3%, Sn: 0.01-0.3%, Ca: 0.0001-0.01%, Mg: 0.0001-0.005%, B: 0.0002-0.02% and rare earth elements: 0.0005-0.02% in lieu of part of Fe.

3. A low-carbon free cutting steel according to claim 1, which further contains at least one element selected from among Cu: 0.01-1.0%, Ni: 0.01-2.0%, Mo: 0.01-0.5%, V: 0.005-0.5% and Nb: 0.005-0.5% in lieu of part of Fe.

4. A low-carbon free cutting steel according to claim 1, which further contains at least one element selected from among Se: 0.0005-0.10%, Te: 0.0005-0.10%, Bi: 0.01-0.3%, Sn: 0.01-0.3%, Ca: 0.0001-0.01%, Mg: 0.0001-0.005%, B: 0.0002-0.02% and rare earth elements: 0.0005-0.02% and at least one element selected from among Cu: 0.01-1.0%, Ni:

0.01-2.0%, Mo: 0.01-0.5%, V: 0.005-0.5%, and Nb: 0.005-0.5% in lieu of part of Fe.

5. A low-carbon free cutting steel according to claim 1, which further contains either one or both of Si: 0.1-2.0% and Cr: 0.03-1.0% in lieu of part of Fe.

6. A low-carbon free cutting steel according to claim 2, which further contains either one or both of Si: 0.1-2.0% and Cr: 0.03-1.0% in lieu of part of Fe.

7. A low-carbon free cutting steel according to claim 3, which further contains either one or both of Si: 0.1-2.0% and Cr: 0.03-1.0% in lieu of part of Fe.

8. A low-carbon free cutting steel according to claim 4, which further contains either one or both of Si: 0.1-2.0% and Cr: 0.03-1.0% in lieu of part of Fe.

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