(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 0 919 636 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
02.06.1999 Bulletin 1999/22

(51) Int. Cl.^{6}: **C22C 38/60**

(21) Application number: **98203028.0**

(22) Date of filing: **10.09.1998**

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE
Designated Extension States:
AL LT LV MK RO SI

(30) Priority: **01.12.1997 IT MI972661**

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(54) Free-cutting steel with improved machinability

(57) Non-alloy free-cutting steel with sulphur contents in the range from 0.1% to 0.4% in weight (limiting values included), the sulphur being in the form of spheroidal sulphides with values of the spheroidisation index and shape factor within defined limits.
An addition of from 0.05% to 0.30% in weight (limiting values included) of bismuth, as an element and/or an alloy and/or as a mixture with one or more elements insoluble in liquid steel or having spheroidizing effects on sulphides, to a free-cutting steel containing spheroidal sulphides with well-defined characteristics, as described above, improves machinability substantially with respect to the present state of the art. In quantitative terms this improvement in machinability increases cutting tool life up to 30% for the same cutting parameters and conditions.

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Description

[0001] The present invention concerns non-alloy free-cutting steels with improved machinability. It is known that elements such as lead and bismuth; as elements and/or as a mixture with tellurium and selenium, behave as embrittling liquid metals when they are dispersed as inclusions in a metallic matrix and heated above their respective melting temperatures.

[0002] A liquid-metal embrittling agent is a metal, either element or alloy, with a relatively low melting temperature such that it is liquid at the temperature prevailing at the root of a microcrack, in the steel matrix, formed either at an inclusion in the steel or propagated within the steel from a starting point at the point of contact between the steel matrix and the cutting-edge of a machine tool.

[0003] To function at its best, a liquid-metal embrittling agent must also have a value of surface free energy (surface tension) which is relatively low in the liquid state in order to give the agent the necessary ability to "wet" a relatively large area along the grain boundaries or at the limits of the various phases present.

[0004] In general, once the elements or alloys have been added to the liquid metal bath in an appropriate manner, their lack of solubility in liquid steel causes them to be precipitated out as spheroidal particles which, after solidification of the steel, are distributed in an almost uniform manner throughout the steel matrix.

[0005] From an industrial point of view, it has been known for some time that the above-mentioned elements have the ability to embrittle a steel structure by melting and migration towards the roots of microcracks and that use has been made of this fact to improve the machinability of steels by treating them with additions of these elements.

[0006] In fact, at temperatures normally present in machining operations, these inclusions melt and create vacancies which constitute points of embrittlement and preferred crack-forming sites. At such a high temperature the liquid-metal embrittling agent passes almost immediately to the roots of the microcracks created in the steel matrix during the machining operations; in this manner the formation and propopagation of the microcracks are thus favoured and chip formation is directly affected. Furthermore, being liquid, these elements also act as lubricants at the tool-chip interface, thus reducing the cutting force due to frictional resistance which is inevitably created.

[0007] The combined action of the above effects results in a considerable reduction of the cutting forces in machining operations as well as reduced wear of the cutting tool edge for the same machining times and cutting parameters. In fact cutting force and tool wear are generally used to evaluate the degree of machinability of a steel.

[0008] Up to now, on account of the best relation between costs and benefits, in terms of the quantity of steel produced, lead has been the liquid metal most frequently used to embrittle steels in order to give them better machinability. In the literature it is reported that for the same chemical composition and thermal history, steels which contain various lead contents, generally between 0.15 % and 0.35 % in weight have substantially better degrees of machinability, the costs of lead addition being more than offset by the benefits to the machining operations.

[0009] Because of its high price, tellurium is generally used in combination with lead and bismuth. In steels with controlled sulphur contents and/or resulphurised steels, from the data in the literature it can be shown that a Te/S ratio of 0.2 is the most efficacious to attenuate the anistropy of mechanical properties caused by the presence of non-spheroidal sulphides. The effect of tellurium is twofold, it being a spheroidiser and it is also an embrittler for on combination with lead, and especially with bismuth, it lowers their surface free energy (or the value of surface tension) at their melting temperatures, thus enhancing their embrittling effect.

[0010] Like tellurium, selenium is only used together with lead and bismuth additions to produce effects similar to those indicated above, but its very high price excludes it as a commercially viable element.

[0011] Despite that which has been said previously, use of steels containing lead, or lead together with tellurium, has unfortunately progressively declinened over the last few years, the reason being the high toxicity of lead and tellurium which are dangerous to the health of operators involved in steelmaking and in machining operations.

[0012] National and European directives have already included a good part of the official data, published by the OSHA organisaton, which fix mandatory upper limits for concentrations in the air of lead and tellurium during steelmaking and machining operations. These limits are shown in the following table.

	Pb	Te
limit of concentration	40 $\mu g/m^3$	100 $\mu g/m^3$

[0013] Unlike lead and tellurium, there is no toxicity problem with bismuth. Because of this reason, bismuth is most interesting from an industrial point of view, for as it is known that bismuth has the ability to improve the machinability of steels, it can replace lead and tellurium in steels with improved machining characteristics.

[0014] It is known that bismuth additions in steel are present as particles which are insoluble in the metal matrix and which have dimensions normally less than 5 microns. The melting point of bismuth is relatively low (271 °C) and its surface free energy at temperatures near the melting point is also relatively low (375 erg/cm^2).

[0015] Sulphur present in the steel as sulphides therefore has a positive effect on the machinability of a steel, this effect varying according to their shape, size and orientation.

[0016] As stated above, the sulphides referred to are those of manganese and not iron sulphide which forms a eutectic phase with iron which melts at 988 °C. This eutectic phase is the cause of hot-shortness, i.e. the well-known phenomenon of brittleness during hot-rolling. For this reason in free-cutting steels the manganese content (in weight percent) of the steel must be more than three times that of sulphur in order to ensure the formation of manganese sulphides which do not form eutectic phases with iron and which have melting temperature above typical hot-rolling and hot-forging temperatures.

[0017] The effect of sulphide inclusions on machinability does not only depend on their intensity of distribution but also on the shape they take up in the metallic matrix. Sulphide inclusion morphologies can be divided into the following three main categories;

Type 1: These are spheroidal sulphides, distributed randomly within the structure, which are obtained with high oxygen contents in the liquid steel (rimming and semi-killed steels).
Type 2: These are sulphides with a dendritic structure which are formed at the boundaries of the primary grains during solidification and arranged like links of a chain. During hot-rolling these sulphides are drawn out to form stringers. Type 2 sulphides are obtained in killed steels where the low aluminium additions made are only just enough to deoxidise the steel.
Type 3: These sulphides are present as small angular irregular inclusions distributed randomly in the steel. These sulphides are formed by the raising the content of aluminium, and of other elements with an high affinity for oxygen, to levels that reduce the oxygen activity in the melt to a few parts per million. These sulphides too undergo deformation during hot-rolling.

[0018] If nothing is present to affect these properties (such as would be, for example, significant percentages of elements like copper and nickel which raise the surface tension of bismuth), bismuth has a marked tendency to "wet" grain boundaries and interphase limits.

[0019] At temperatures typical of those reached in the machining of steel (of the order of 800-1000 °C at the point of contact between tool and steel in dry-machining operations) bismuth in the metallic matrix melts and therefore acts as a liquid embrittling agent. In fact it tends to be found at grain boundaries or interphase limits, thus embrittling not only the steel-tool interface zone but also those zones which, although at some distance from the cutting edge, are subjected to a rise in temperature due to the machining operation.

[0020] It is known that the machinability of a steel is strongly dependent on the manner in which the chip is formed and fractures, and, to be more specific, on the formation and propagation of microcracks in the structure.

[0021] During a machining operation, the force applied at the point of contact between steel and tool causes microcracks to be formed which generally propagate along grain boundaries and interphase limits. The lower the energy required to propagate the microcrack, the better is the machinability.

[0022] Bismuth acts as an embrittling liquid metal and lowers the energy of microcrack propagation. In fact, at typical machining temperatures it melts and immediately migrates to the roots of microcracks, thus embrittling the matrix and facilitating chip fracture.

[0023] To act as its best as a liquid embrittling agent, the dimensions of the bismuth inclusions must be very small, indicatively around 5 microns, in order to multiply the points where it is available in the steel microstructure.

[0024] Sulphur also is employed in the production of improved-machinability steels for it combines with manganese present in the steel to form manganese sulphide inclusions, all of which are potential microcrack formers during the period when the chip separates away from the matrix.

[0025] The shape of the sulphides depends essentially on the solubility of sulphur in the liquid steel. In unkilled steels with high free oxygen contents, manganese sulphides, which have a low solubility, tend to precipitate out at relatively high temperatures as multiphase particles which also contain oxides and silicates (type 1 sulphides). In weakly deoxidised steels, deoxidation is controlled by limited aluminium additions of the order of parts per million in order to obtain a low residual free oxygen level (around 40 parts per million). Sulphides are obtained which are more soluble and which precipitate out at the primary grain boundaries (type 2 sulphides) at the solidification temperature. Finally, in strongly deoxidised steels, the solubility of manganese sulphide is lower than in the previous case, and therefore it tends to precipitate out at temperatures which are higher than those for type 1 sulphides; the inclusions formed are single phase and usually more in number than type 1 and type 2 sulphides owing to the numerous nucleation sites created by aluminium oxides or by oxides of other metals used to completely deoxidise the steel. When the steel is subjected to successive plastic working and is hence deformed, the manganese sulphide inclusions are also deformed.

[0026] Spheroidal type 1 sulphides are the most suitable for improving machinability, for they are better distributed within the matrix and, after hot-rolling, also have a lenticular shape which makes them embrittlement sites and microcrack formers that diminish the cutting forces required for chip fracture.

[0027] Compared to type 2 and 3 sulphides (lamellar or stringers), the presence of lenticular sulphides is the cause of a clear-cut improvement in the value of the machinability index.

[0028] Furthermore in high-sulphur steels the spheroidisation of the sulphide inclusions significantly attenuates the worsening of mechanical properties which is normally associated with the embrittling effect of sulphur. It is known in fact that for high sulphur contents and type 2 and 3 sulphide morphologies, the fibre structure of the steel matrix, characterised by the presence of bands of mangenese sulphides in the form of lamellae and stringers aligned along the rolling direction, causes a considerable drop in energy absorbed by impact-test test-pieces made from samples taken along a direction transverse to that of rolling.

[0029] It is known that the machinability of a steel does not only depend on one single and well-defined property but on a set of metallurgical and technological properties each one of which can vary independently of the others.

[0030] On the basis of that which has just been stated, it is readily deduced that a statistical approach would be required to have a "significant" evaluation of the degree of machinability of a steel.

[0031] On the other hand, the need to determine the value of the machinability index of a given product using "industrial" methods and time-limits usually means basing this value on a limited number of tests.

[0032] The principal factors that influence steel machinability are: the properties of the steel to be worked (chemical composition, mechanical properties, hardness, structural homogeneity and type of metallographic structure), characteristics of the tool used for machining (type of material, geometric shape, tool angles, hardness, degree of sharpness of the cutting edge) and machining parameters (type of machining, cutting speed, depth of cut, feed, type of cooling medium,...).

[0033] As is easily imaginable, this leads to objective difficulties in defining the concept of machinability, and, as a consequence, to difficulties in developing tests to measure machinability. For this reason, one of the many indices deriving from the same number of types of tests used to measure the machinability of the steel can only give a relative value and not an absolute one.

[0034] Even the national and international standards which define the fundamental criteria for the quantitative measurement of the machinability index are not intended as fixed acceptance test requirements, for they leave a considerable margin of choice to the user, even though he is required to state the technical options he has adopted.

[0035] In practical terms, a reference steel is chosen to which is assigned an arbitrary value of 100 for the machining index. Other steels are compared to the reference steel in identical test conditions. To be specific, for the purposes of this patent, tool flank wear has been adopted as the variable for the measurement of the machinability index. By tool flank wear is meant the maximum depth of wear (expressed in millimetres) on the flank of the tool used for lathe-turning.

[0036] The purpose of the present invention is to realize free-cutting steels, containing sulphides having suitable lengths, shape factors and degrees of spheroidisation, which may be used by the engineering industry in general and the automotive industry in particular and which have better machinability than the steels presently known in the art.

[0037] Another purpose of the present invention is to realise a non-alloy free-cutting steel which is not harmful neither for those who produce it in the steelworks nor for those who employ it in successive working operations.

[0038] Yet another purpose of the present invention is to realise a non-alloy free-cutting steel with improved machinability characteristics in an inexpensive manner without employing complex and costly technological means.

[0039] These purposes are fulfilled by a non-alloy free-cutting steel with improved machining characteristics according to claim 1, to which reference is made for the sake of brevity.

[0040] It is known that additions of bismuth, as an element and/or as an alloy and/or as a mixture with one or more elements which are insoluble in liquid steel, to sulphur-containing free-cutting steels lead to an appreciable improvement in machinability.

[0041] Up to the present time, however, no-one has considered the effect of an addition of bismuth, as an element and/or as an alloy and/or as a mixture with one or more elements insoluble in liquid steel or having spheroidizing effects on sulphides, to free-cutting steels containing sulphides with shape factor and spheroidisation index within well-defined ranges, in order to obtain clear-cut reliable increases of the value of the machinability index.

[0042] To define the degree of spheroidisation of the sulphides use will here be made of a method based on the relation between the length of the sulphide inclusions in the steel (hereinafter denoted by "ξ") and their thickness (hereinafter denoted by "w").

The so-called "shape factor" of the sulphide inclusions hereinafter denoted by "f" is given by the following formula:

$$f = P^2/(4\pi A); \qquad (f>=1),$$

where P indicates the perimeter of the sulphide inclusions and A indicates their area.

[0043] The relation "ξ/w" is termed the "spheroidisation index" relating to the sulphides present in the steel. On the basis of an experimental study on free-cutting steels having only sulphur as an embrittling agent, it was possible to determine the values of the mean statistical spheroidisation index of the sulphides, and their mean statistical shape factor, which gave the best results in machining operations.

[0044] It is to be understood that by the term "mean statistical value" used above and hereinafter is meant the determination of the value on a number of samples which is statistically significant, i.e. at least 1 sample per 10 tonnes of steel produced with a minimum number of 3 samples.

[0045] The mean statistical value of the spheroidisation index and the shape factor are determined metallographically as follows. Each of the above samples is divided along its longitudinal axis. On one of the sections obtained in this manner, 10 fields, equidistant between the sample axis and one of the longitudinal edges, are selected for examination at a magnification of x200 with an image processor which permits the sulphide morphology to be expressed in quantitative terms.

[0046] In order to express in quantitative terms the machinability of non-alloy free-cutting steels according to the present invention; certain reference parameters relating to the morphological charateristics of the sulphides were chosen.

[0047] Firstly a range from 0.015 millimetre to 0.20 millimetre (limiting values included) was chosen as the value of the length "ξ" of the sulphide inclusions which appears in the mean statistical index "ξ/w".

It was found that that it is possible to appreciably improve the value of the machinability index if the value of the mean spheroidisation index of the sulphides is equal to or less than 5.3 and if the mean statistical shape factor "f" is less than 2.2, and if the length of the sulphides is between 0.015 millimetre and 0.20 millimetre.

[0048] In order to express in quantitative terms the machinability of non-alloy free-cutting steels with sulphur contents between 0.1% and 0.4% in weight (limiting values included), the sulphur being in the form of spheroidal sulphides having values of the spheroidisation index and shape factor lying within defined limits, such steels also containing bismuth, added as an element and/or as an alloy, in the range from 0.05% to 0.30% in weight (limiting values included), the machining index hereinafter denoted "v20" was used to measure the machinability of the steel which is the subject of the present invention.

[0049] Tests were performed at various cutting speeds within a pre-selected range. Each test lasted for 20 minutes (hence the term "v20" used to indicate this test) and the depth of tool flank wear was measured at the end of the test using appropriate optical instrumentation.

[0050] The machinability of free-cutting steels based on sulphur alone was improved by up to 30% when the spheroidisation index, shape factor and length of sulphides fell within the above-cited limits, comparison being made with free-cutting steels having values of the spheroidisation index, shape factor and sulphide length outside these limits. The addition of bismuth as an element and/or as an alloy and/or as a mixture with one or more elements insoluble in liquid steel or having spheroidizing effects on sulphides, in proportions between 0.05% and 0.30% in weight improves the value of the machinability index up to 30% for free-cutting steels which have values of the spheroidisation index, shape factor and sulphide lengths within the above-cited limits.

Test steel/test parameters and data collected	Cutting speed (m/minutes) Tool flank wear (mm)	Test duration (minutes)
ζ/w = 4.7 f = 2.2 spheroidal sulphides	180 - 0.94 (m/min - mm)	20
ζ/w = 3.4 f = 1.8 spheroidal sulphides and bismuth	180 - 0.66 (m/min - mm)	20

[0051] From that which has been stated above the advantages obtained by use of the present invention are evident.

[0052] The addition of bismuth to carbon free-cutting steels, as an element and/or as an alloy and/or as a mixture with one or more elements insoluble in liquid steel or having spheroidizing effects on sulphides, in appropriate quantities which in any case are included in the range from 0.05% to 0.30% in weight, in the liquid-steel ladle or to the tundish or to the mould of a continuous casting machine permits bismuth to be well distributed in the metallic matrix as particles the dimensions of which must be less than or equal to 5 microns, as has been stated earlier in the introductory part.

[0053] Attention is drawn above all to the fact that by the term "free-cutting steels" are meant non-alloy steels produced with sulphur additions between 0.10% and 0.40% in weight (limiting values included). The sulphides according to claim 1 improve machinability when compared to traditional techniques, while ensuring freedom from hot-shortness and also improve the toughness of the steel, especially in the direction transverse to the rolling direction.

[0054] It is evident that the non-alloy free-cutting steel of the present invention can be subjected to numerous variations and modifications without affecting its innovative nature.

[0055] It is also evident that in a practical embodiment of the present invention, the materials, shapes and dimensions of the products may be varied according to need and that they may be replaced by other equivalent ones.

Claims

1. A non-alloy free-cutting steel containing from 0.10% to 0.40% (limiting values included) of sulphur to which bismuth is added, as an element and/or as an alloy and/or as a mixture with one or more elements insoluble in liquid steel or having spheroidizing effects on sulphides, such that the steel contains from 0.05% to 0.30% (limiting values included) of metallic bismuth. This steel is characterised by the fact that, to give it a particularly high and reliable degree of machinability compared to the present state of the art, its value of the mean statistical spheroidisation index, defined as the length of the sulphide inclusions divided by their thickness, is equal to or less than 5.3 in absolute terms, and by the fact that the mean statistical shape factor, defined as the total perimeter of the sulphide inclusions divided by the product of 4 times π and the area A of the sulphide inclusions, is equal to or less than 2.2 in absolute terms.

2. A steel of claim 1 characterised by the fact that the above value of the mean statistical spheroidisation index and the above value of the mean statistical shape factor are determined on a number of samples which is statistically significant, It is to be understood that by the term "mean statistical value" used above and hereinafter is meant the determination of the value on a number of samples which is statistically significant, that is on at least 1 sample per 10 tonnes of steel produced with a minimum number of 3 samples.

   The mean statistical value of the spheroidisation index and the shape factor are determined metallographically as follows. Each of the above samples is divided along its longitudinal axis. On one of the sections obtained in this manner, 10 fields, equidistant between the sample axis and one of the longitudinal edges, are selected for examination at a magnification of x200 with an image processor which permits the sulphide morphology to be expressed in quantitative terms.

3. A steel of claim 1, characterised by the fact that the length of the sulphide inclusions is in the range from 0.015 millimetre to 0.20 millimetre (limiting values included).

4. A steel of claim 1 characterised by the fact that bismuth is added as an element and/or as an alloy and/or as a mixture with one or more elements insoluble in liquid steel or having a spheroidizing effects on sulphides, to the liquid-steel ladle or to the tundish or mould of a continuous casting machine.

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EUROPEAN SEARCH REPORT

Application Number
EP 98 20 3028

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	3 March 1999	Gregg, N

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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