HIGH-HARDNESS, HIGH-TOUGHNESS STEELS AND CRAWLER COMPONENTS, EARTH WEAR RESISTANT COMPONENTS, FASTENING BOLTS, HIGH-TOUGHNESS GEARS, HIGH-TOUGHNESS, HIGH CONTACT PRESSURE RESISTANCE GEARS, AND WEAR RESISTANT STEEL PLATES USING THE SAME

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Tempered Hardness of Various Wear-resistant Steels

In order to provide a high-hardness, high-toughness steel, Si, Al, Cr, Mo, V, W, Ni, and Co are more appropriately added so that the steel can have an HRC hardness of 50 or higher and a Charpy impact value of 5 kgf m/cm² or more by tempering at a high temperature of 600°C or higher. The steel is a martensite steel containing at least C: 0.15 to 1.2% by weight and Si: 0.05 to 1.8% by weight, wherein Si is partially replaced by 0.15 to 1.6% by weight of Al. The steel further contains Ni: 0.3 to 2.5% by weight, Cr: 0.1 to 3.5% by weight, Mo: 0.1 to 1.7% by weight, wherein the amount of Mo is not more than the upper limit determined by the relation formula: Mo(% by weight)=1.7-0.5x(Si(% by weight)+Al(% by weight)); one or both of V: 0.05 to 0.40% by weight and W: 0.1 to 1.0% by weight; at least one alloying element of Mn, Co, Cu, Ti, B, and Nb; inevitable impurities including P, S, N, and O; and the balance consisting essentially of Fe.
FIG. 1

Fe₃Si Constitution Diagram \( \gamma / (\alpha + \gamma) \)

Temperature (°C)

Carbon Content (wt%)
FIG. 5

Result of Preliminary Experiment on the Relationship Between Charpy Impact Value and Carbon Content.
Comparison Between Tempered Hardness and Calculated Values of TPNos. 1 to 9

FIG. 6

Rockwell Hardness (HRC)

Tempering Temperature (°C)

- (Calculated) 1  - - - (Calculated) 2
- (Calculated) 3  - - - (Calculated) 4
- (Calculated) 5  - - - (Calculated) 6
- (Calculated) 7  - - - (Calculated) 8
- (Calculated) 9  - - - (Calculated) 10

Found 1
Found 2
Found 3
Found 4
Found 5
Found 6
Found 7
Found 8
Found 9
FIG. 7  Comparison Between Tempered Hardness and Calculated Values of TPNos. 10 to 22

Rockwell Hardness (HRC)

Tempering Temperature (°C)
FIG. 10
Comparison Between Tempered Hardness and Calculated Values of TPNos. 34 to 38

[Graph showing the comparison between tempered hardness and calculated values for TPNos. 34 to 38. The graph includes lines and markers indicating the calculated and found values at different tempering temperatures.]
FIG. 11

Relationship Between Tempered Hardness and Charpy Impact Values of TPNos. 47 to 49

- △ Hardness (No. 47)
- △ Hardness (No. 48)
- △ Hardness (No. 49)
- ● Impact Value (No. 47)
- ○ Impact Value (No. 48)
- ○ Impact Value (No. 49)
FIG. 12

Relationship Between Tempering Temperature and Charpy Impact Values of TPNos. 47, 10, and 12
FIG. 13

Conditions of Carburizing, Quenching, and Tempering

930°C

5hr

CH₃OH: 0.2l/hr
CP²: 0.85%

850°C

1hr

CH₃OH: 0.2l/hr

50°C
Oil
Hardening
FIG. 14

Hardness Distribution after Carburizing, Quenching, and Tempering (No. 39, 40, 41)
FIG. 16

Gouging Wear Ratios of Various Wear Resistant Material
(Standard Material: S45C with Hv500)

![Graph showing wear ratios versus hardness for various materials.]

- S30C
- S45C
- SK3
- SMn34C
- SNCM23HK
- SHSC1
- SMnCrMo3
- SCM4
- SCM5
- SK4 Free-Cutting Steel
- SUJ2
- SKD1
- RH40
- SKD12
- 6Cr7Mn
- SCMnH3
- SNCM8
- S50C
- SCMnMo
- SCM3
- Sm1H
- SCM24
- SK2
- SUP9
- SCM2
- SK7
- SK4
- SKD11
- SUS57
- 10Cr3Mn
- SCM24
- SUS27
HIGH-HARDNESS, HIGH-TOUGHNESS STEELS
AND CRAWLER COMPONENTS, EARTH WEAR RESISTANT COMPONENTS, FASTENING BOLTS,
HIGH-TOUGHNESS GEARS, HIGH-TOUGHNESS,
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GEARS, AND WEAR RESISTANT STEEL PLATES
USING THE SAME

TECHNICAL FIELD

[0001] The present invention relates to a high-hardness, high-toughness, wear-resistible steel for use in an excavating edge member of a construction or earth work machine such as a hydraulic excavator, a bulldozer, a wheel loader, a motor grader, an underground piping burying machine, a soil-improvement machine, a crusher for concrete, lumber, or the like, and a tunneling machine; a crawler belt of a crawler vehicle; a reduction gear; and the like, and relates to a member using such a steel.

BACKGROUND ART

[0002] Conventionally, examples of the wear-resistible steel widely used in construction or earth work machines include SMnB, SCR, SCIB, SCM, and SNCM medium carbon steels that are processed by heat-treatment such as quenching and tempering. For example, the components of a crawler vehicle belt such as a crawler bush, a crawler shoe, a crawler link, a track roller, and a sprocket are appropriately made wear-resistant based on the idea that toughness can be established by reducing the carbon content. Excavating edge members for use in cutting or excavating rock mass (such as a ripper point, bucket tooth, and a cutting edge) are strongly needed to have high performance. Therefore, such edge members have improved in toughness so that cracking or breakage can be prevented against more impact load and improved in wear resistance by high hardening. In particular, the near-edge portion of the excavating edge member is heated to about 600°C by severe friction with rock mass. Therefore, high-hardness, high-toughness steels with improved resistance to temper softening are often used for the edge member.

[0003] The construction or earth work machine in operation frequently goes over obstructions such as rock and other structures and frequently sways to excavate the obstructions. The gears of the reduction gears in the driving and swinging mechanisms can be broken under impact load. Therefore, the gears are formed of low-carbon case hardened steel carburized, quenched, and tempered.

[0004] The crawler components of the construction or earth work machine and the excavating edge members should satisfy both 1) high-toughness for preventing cracking or breakage under impact load and 2) high hardness for providing excellent wear resistance against earth, rock, and the like. However, high toughness and high hardness generally trade off with each other. Therefore, the addition amount of carbon should be small in order to establish toughness, the steel material (wear-resistible steel) for use should contain hardenability-enhancing alloying elements each in an appropriate amount, and the steel should be quenched and tempered before used. However, such conditions can cause a problem of insufficient wear resistance.

[0005] Toughness is important for the wear resistant members for forming the crawler belt. Therefore, the carbon content of such members is set at a low level, for example, as follows: 0.25 to 0.3% by weight in the crawler shoe, 0.3 to 0.35% by weight in the track roller, 0.35 to 0.4% by weight in the crawler link, and 0.35% by weight in the sprocket. In addition, their quenched and tempered hardness is adjusted to between HRC45 and HRC52. Under such conditions, the members are often insufficient in wear resistance and have a problem of the high cost of repairing the crawler belt in the construction or earth work machine.

[0006] In terms of structure, wear resistance is important for the crawler bush for forming the crawler belt. For example, therefore, high-toughness SCM420 is carburized, quenched, and tempered to give the crawler bush. However, its cost can be high, because the carburizing process for forming a deep, very hard carburized case takes a very long time period. In addition, it is susceptible to damage, because the carburizing process can significantly reduce the toughness.

[0007] In the process of a toughness-conscious member such as a tunneling disk cutter or shank, for example, as disclosed in Japanese Patent No. 3227730, a low carbon, high Ni steel (for example, SCM420) is quenched and tempered to show HRC45 or higher and a Charpy impact value of 5 kgf m/cm² or more before used. However, its durability is insufficient in both hardness and toughness, and its cost is high.

[0008] The tooth plate of a jaw crusher for crushing rock and concrete is also toughness-conscious and often uses Hadfield steel. Such a plate also has a problem of insufficient wear resistance.

[0009] In the process of a cutter (such as a soil cutter and a pin) of a stirring machine for stirring and pulverizing earth such as a soil-improvement machine and a tilter, the carbon content is limited to 0.25 to 0.3% by weight, and the steel is quenched and tempered to have an HRC level of 48 before used. Such a cutter also has a problem of insufficient wear resistance.

[0010] When the construction or earth work machine such as the bulldozer, the wheel loader, the hydraulic excavator, and the motor grader is used to cut or excavate rock, the edge portion of the excavating edge member (such as a ripper point, bucket tooth, a cutting edge, and an end bit) or the tunneling disk cutter is heated to a temperature of 300 to 600°C by severe friction with the rock. In such a case, the initial hardness can significantly be reduced so that the wear resistance can be insufficient. The steel to be used should have not only high toughness and high hardness but also sufficient resistance to temper softening even in heating at about 600°C. However, it has been unclear how to appropriately add alloying elements (for example, how to select alloying elements and how to determine the addition amount) for improvement in the resistance to temper softening. Therefore, excessive addition of the alloying elements cannot be prevented so that the toughness can be reduced or the cost can be high.

[0011] It has been very difficult for the wear-resistible steels with various alloying elements to be free from "temper brittleness", which develops by tempering at a temperature of 350 to 550°C after quenching. Therefore, such steels cannot have sufficiently high durability.

[0012] On the other hand, carbon steels show very little "temper brittleness" even when tempered at a temperature of
350 to 550° C. but can be insufficient in hardenability. Therefore, high cleanliness steels made of high-alloy wear-resistant steels with less P or S have been produced as less "temper brittleness" steels. However, such steels can be expensive and therefore have a problem with commercial availability.

[0013] For example, Japanese Patent Publication No. 55-12177 (1980) discloses such a conventional wear-resistant steel, which contains C: 0.25 to 0.40%, Si: 1.5 to 2.5%, Mn: 1.6% or less, Cr: 3.0 to 5.0%, and Mo: 0.5 to 1.2%. In such a wear-resistant steel, however, the high content of Si, Cr, or Mo can lead to sharp reduction in tempered hardness at 550° C. or higher. Such a steel is insufficient in wear resistance and uneconomical.

[0014] Japanese Patent Laid-Open No. 54-124816 (1979) discloses a wear-resistant steel that contains C: 0.4 to 0.6%, Si: 0.8 to 1.7%, Mn: 0.4 to 0.8%, Cr: 0.6 to 2.0%, Mo: 0.1 to 0.8%, and Al: 0.2 to 1.0%. Japanese Patent Laid-Open No. 54-143715 (1979) discloses a wear-resistant steel that contains C: 0.4 to 0.6%, Si: 0.8 to 1.7%, Mn: 0.4 to 0.8%, Cr: 0.6 to 2.0%, W: 0.1 to 0.5%, and Al: 0.2 to 1.0%. However, these steels are insufficient in temper softening and toughness.

[0015] Japanese Patent Laid-Open No. 59-107066 (1984) discloses a wear-resistant steel that contains C: 0.4 to 0.6%, Si: 1.6 to 2.2%, Mn: 0.5% or less, Cr: 1.0 to 1.5%, Mo: 0.8 to 1.2%, V: 0.2 to 0.5%, and Ni: 1.0 to 2.0%. Such a wear-resistant steel is insufficient in toughness as well as resistance to temper softening because of the high content of Mo and V.

[0016] Japanese Patent Laid-Open No. 60-215743 (1985) discloses a wear-resistant steel that contains C: 0.35 to 0.45%, Si: 0.6 to 1.5%, Mn: 1.8% or less; Cr: 2.5 to 4.5%; and Mo: 0.2 to 1.0%; and/or at least one of V: 0.01 to 0.5%, Nb: 0.1 to 0.10%, and W: 0.01 to 0.5%; and Ti: 0.01 to 0.10%, and B: 0.0005 to 0.0030%. In such a wear-resistant steel, a relatively high content of C can reduce the Si-induced resistance to temper softening and always reduces the toughness.

[0017] Japanese Patent Laid-Open No. 5-78781 (1993) discloses a wear-resistant steel that contains C: 0.35 to 0.55%, Si: 0.5% or less, Mn: 0.5% or less, P: 0.015% or less, S: 0.010% or less, Cr: 1.00 to 2.5%, Mo: 1.00 to 2.00%, V: 0.05 to 0.30%, B: 0.0003 to 0.0050%, Al: 0.005 to 0.10%, and Nb: 0.01 to 0.20%. In this steel, the low Si-induced reduction in the resistance to temper softening can be recovered by high Mo and V addition, but the recovered resistance to temper softening is insufficient. In order to ensure the toughness, the content of P, S, and Mn is set low in the steel so that the grain boundary can be strengthened. However, such a steel is generally expensive and therefore has a problem with commercial availability and can be insufficient even in toughness.

[0018] In the driving and swinging mechanisms of the reduction gears of the construction or earth work machine, the gears must be prevented from fracturing due to impact load. For such a purpose, the gears are formed of high-toughness steel; low-carbon case hardening steels (with 0.1 to 0.25% by weight of Cr, carburized, quenched, and tempered. However, the toughness can sharply decrease, as the surface carburized case becomes deeper. Particularly, in such a case, the gears cannot improve in toughness, if the carburized case must be formed with a depth of 0.5 mm or more in terms of contact pressure strength and dedendum bending fatigue strength. The high-carbon case hardening steels have also been reduced in P and S contents to have strengthened grain boundary, but such steels are generally expensive and therefore have a problem with commercial availability and can be insufficient even in toughness.

[0019] The present invention has been made in order to solve the problems. It is therefore an object of the present invention to provide a high-hardness, high-toughness steel that contains Si, Al, Cr, Mo, V, W, Ni, and Co more appropriately added so as to have an HRC hardness of 50 or higher and a Charpy impact value of 5 kgf m/em or more by tempering at a high temperature of 600° C. or higher.

[0020] It is another object of the present invention to provide a steel that contains Al and Ni in combination and therefore has high toughness in spite of being formed of high-carbon, high-hardness, quenched and tempered martensitic steel.

[0021] It is another object of the present invention to provide a variety of wear resistant members, gear members, and bolt members that are each formed of the inventive steel and appropriately heat-treated to show high hardness and high toughness.

SUMMARY OF THE INVENTION

[0022] The inventor has paid attention to a commonality between the fact that the excavating edge member or the like is heated up to 600° C. by friction and the process in which quenched steels are tempered at 550° C. or higher to recover the toughness without temper brittleness. Thus, the inventor has investigated and found appropriate carbon content for providing a sufficient hardness of HRC45 or higher (preferably HRC50 or higher) even after quenching and tempering at 550° C. or higher, preferably 600° C.; appropriate type and addition amount of alloying elements (such as C, Si, Al, Cr, Mo, V, and W); and appropriate technique in consideration of the interaction between alloying elements as described below, so that unnecessary addition of the alloying elements, which would otherwise cause brittleness and deterioration, can be prevented, and economy can be achieved.

[0023] It has also been found that Al can significantly enhance the resistance to temper softening and that the combined addition of Al and Ni can provide significant toughness without the temper brittleness even through tempering at low temperature. It has also been found that the high-hardness, high-toughness tempered martensite steel having a carbon content in the range of up to 1.2% by weight and showing a Charpy impact value of 5 kgf m/em or more can be used to improve the wear resistance of the various members.

[0024] In addition, Co, which can raise the magnetic transformation temperature of quenched and tempered martensite, is added in an appropriate amount so that high toughness is produced without high temperature temper brittleness, and therefore the resistance to high temperature temper softening further increases without reduction in toughness.

[0025] In the present invention, the content (% by weight) of each alloying constituent in the steel is defined for the reasons below. As shown in Examples below, the reasons were found from the results of analysis of hardness data on various wear resistant steels that were tempered at a temperature of 200 to 700° C.
Various quenched steels different in carbon content were tempered at a low temperature of 200°C and then examined. As a result, HRC45 or higher was achieved when the lower limit of the carbon content was set at 0.15% by weight, and a Charpy impact value of 5 kgf m/cm² or more was achieved when the upper limit of the carbon content was set at about 0.60% by weight. In addition, the inventive steel that contains Al and Ni in combination requires that the upper limit of the carbon content should be 1.20% by weight, and considering that the inventive steel should be applied to the carburized gears and the like, the lower limit of the carbon content should be 0.1% by weight. In the present invention, therefore, the carbon content should be from 0.1 to 1.2% by weight.

As mentioned above, the high-hardness, high-toughness steel for use in the member for which resistance to temper softening is important contains 0.25 to 0.55% by weight of weight of carbon. On the other hand, in the steels that contain little alloying element, the carbon content has little effect on the hardness during tempering at 400 to 600°C. (a carbon content of 0.55% by weight or more provides +2.5 of ΔHRC at 500°C and +1.0 of ΔHRC at 600°C). Therefore, analysis was carried out using, as the amount of resistance to temper softening (an increase in hardness), the difference between the hardness obtained by adding alloying elements and by tempering at 400 to 600°C and the standard hardness of carbon steel. In order to obtain a hardness of HRC45 or higher by tempering at 600°C, the carbon content is preferably 0.25% by weight or more.

As mentioned below, in order to increase the resistance to temper softening, an alloying element such as Mo and V is positively added to the high-hardness, high-toughness steel. In such a case, a carbon content of 0.60% by weight or more is not preferred. This is because such an increased carbon content can reduce the solid solution amount of the alloying element which would otherwise contribute to the resistance to temper softening in the austenite phase area during heating for quenching; the reduction in the role of the alloying element contributing to the resistance to temper softening is not economical; and the carbide in the tempered martensite increases in amount and size so that the toughness is reduced.

The carbon element can significantly stabilize the austenite. As mentioned below, therefore, the inventive steel that contains a large amount of ferrite-stabilizing Si, Al, or Mo preferably contains 0.10% by weight or more of carbon so that the quenching temperature can be suppressed to 950°C or lower. For the purpose of suppressing the addition amount of the austenite-stabilizing element Mn, Ni, or Cr which can reduce the quenching temperature, the carbon content is preferably 0.10% by weight or more.

Si: 0.05 to 2.5% by Weight

Si is inevitably introduced by steel making and the Si content is generally 0.05 to 0.3% by weight. In the present invention, however, Si may be added in an amount of less than 2.5% by weight, because it can suppress the precipitation of cementite, contribute to the improvement in toughness by tempering at about 400°C or lower, and enhance the resistance to temper softening. A Si addition amount of less than 0.3% by weight cannot provide such significant effects. A Si addition amount of up to about 1.2% by weight is known to enhance the resistance to temper softening. However, the addition amount of Si should be determined in such a range that Si can stabilize the α+δe phase to raise the A3 transformation temperature and does not excessively raise the quenching temperature. Therefore, in the case that the steel with a carbon content from 0.1 to 0.35% by weight is used as a gear member after carburized, quenched and tempered, the Si addition amount is preferably suppressed to 2.5% by weight or less and is more preferably 1.8% by weight in terms of the effect of Si addition on Mo or V as described below.

In addition, it has been found that the maximum addition amount of effective Mo (YMo % by weight) is preferably controlled according to the formula YMο=1.7+0.5×Si % by weight (at 950°C) and the Mo addition amount is preferably set at the effective addition amount or less depending on the Si addition amount.

Si and V have also been found to interact with each other similarly to Si and Mo. At a Si addition amount of 1.8% by weight or more, the effective maximum addition amount of V (VV) was 0.15% by weight at 925°C, and at less than 1.8% by weight of Si, it was 0.3% by weight, and at 950°C, such maximum addition amounts were 0.2% by weight and 0.4% by weight, respectively. According to the present invention, the steel also contains Al, which can stabilize the ferrite phase of the steel similarly to Si. Therefore, the total addition amount of Al and Si should be 1.8% by weight or less (Al+Si≤1.8% by weight) so that an excessive raise in the quenching temperature can be avoided.

The addition of Si can provide resistance to temper softening at 400°C or higher, but such resistance is significantly reduced (to about half at 600°C) when 3.5% by weight or more of Cr coexists. This suggests that the combined addition of Si and 3.5% by weight or more of Cr should not be effective. This is owing to the reduction in the cementic precipitation-suppressing effect of Si by the increase in the Cr amount.

The coexisting Cr at a content of 3.5% by weight or more also reduces the upper limit of the Mo addition amount to about half, otherwise such Mo would be effective at enhancing the resistance to temper softening. Therefore, it is apparent that Mo in the effective addition amount or more can reduce the toughness.

Al: 0.15 to 1.6% by Weight

Al has a very strong deoxidizing action. It is known that Al reacts with nitrogen in the steel to form AlN and make the crystal grains fine. Killed case hardened steels generally contain 0.005 to 0.05% by weight of Al. The solid Al dissolved in the steel has a strong tendency to segregate at the grain boundary and functions to strongly exclude, from the grain boundary, the impurity element such as P and S, which can reduce the grain boundary strength, and to strongly attract Ni, which can improve the grain boundary toughness. According to the present invention, therefore, Al and Ni are positively added at the same time so that the carbon content can be high and the tempered martensite structure steel with a high hardness of HRC45 or higher can drastically improve in toughness. The positive addition of Al and Ni at the same time can also prevent temper brittleness, which would otherwise be caused by tempering at 350°C or higher. It is well known that the drastic improvement in the toughness of the high-hardness tempered martensite structure steel can lead to not only resistance to impact load but also drastic prevention of intergranular fracture. As described below, therefore, this performance can be used to drastically improve the resistance to delayed fracture, for
example, in high-tensile bolts such as a crawler shoe bolt, or a crawler bush or link of a crawler link assembly used after press-fitting the crawler bush and pin.

[0039] It has been found that Mo and V as described below can enhance the resistance to temper softening at a higher temperature of 400°C or higher, and in contrast, Al and Si are effective at enhancing the resistance to temper softening both at a lower temperature of 400°C or lower and at a higher temperature of 400°C or higher. Therefore, Al may be added as needed with the relationship Al+Si<1.8% by weight maintained. At an Al addition amount of 0.15% by weight or less, improvement in toughness can be insufficient. At an Al addition amount of 1.6% by weight or more, the A3 temperature can excessively be raised, and the toughness improvement effect can be saturated. Therefore, the Al addition amount should be from 0.15 to 1.6% by weight. Similarly to the above, in the case that the steel is applied to the low carbon gear member, the Al addition amount is preferably 1.2% by weight or less so that the eutectoid phase can be prevented from coexisting at a quenching temperature of 900°C.

[0040] Al coexistent with Ni is preferred in terms of wear resistance, because in such a case, the development of the age hardening can further enhance the resistance to temper softening (Al-1Ni can produce 44 of AHRC at 600°C) as described below.

[0041] Ni: 0.3 to 2.5% by Weight

[0042] Ni can enhance hardenability and improve the toughness of the tempered martensite phase. For example, SNCM case hardened steel and AISI4340 high tension steel each contain 3.5% by weight or less of Ni. Some quenched and tempered materials containing 2.5 to 4.0% by weight of Ni has been used as a shank steel product for tunneling (Japanese Patent No. 3227730).

[0043] In the present invention, the combined addition of 0.3 to 2.0% by weight of Al and Ni is essential for more effective contribution to toughness improvement, and therefore the lower limit of the Ni addition amount should be 0.3% by weight. The upper limit of the Ni addition amount is preferably 2.5% by weight, because the combined addition of Ni and Al can enhance the resistance to temper softening by the precipitation of NiAl intermetallic compounds and improve the wear resistance, but excessive addition can reduce the toughness and be economically disadvantageous.

[0044] Al and Si strongly stabilize ferrite and these elements at a high content can disadvantageously make the Ac3 temperature higher so that a higher quenching temperature can be required. For example, FIG. 1 shows that based on the effect of various alloying elements on the Ac3 temperature line of Fe-3 wt % Si—C alloy, alloyed steels with a lower carbon content (from 0.10% by weight) can preferably be reduced in the heat treatment cost by the quenching temperature-lowering effect of the Mn, Ni, or Cr addition, and even at a C content of about 0.4% by weight, Mn or Ni may preferably be added in an amount of about 1% by weight.

[0045] Mn: 0.3 to 3.0% by Weight

[0046] Mn has a significant desulfurizing action. Mn is effective at improving the hardenability of steels. Similarly to Ni, Mn can strongly stabilize the austenite phase of steel so that the A3 transformation temperature can be lowered and the quenching temperature can effectively be reduced. The Mn element is also effective at suppressing the raise in the A3 transformation temperature by the addition of the ferrite-stabilizing element Al or Si. In the present invention, therefore, the Si addition amount should be 3.0% by weight or less, considering the effect of Mn, Ni, Si, and Al on the eutectoid temperature and the approximate relation: (Si+2×Al)+(Ni+Mn). In such a addition amount range, the quenching temperature is preferably suppressed not to be 950°C or higher, and the old austenite crystal grain is preferably suppressed in growth not to have an ASTM grain size number of greater than 8, in terms of heat treatment cost.

[0047] Cr: 0.1 to 3.5% by Weight

[0048] Cr can improve the hardenability of steels and enhance the resistance to temper softening. Its hardening effect is, however, smaller than that of Mo, V, W, or the like. If its addition amount is more than about 7.5 times as much as the coexisting carbon content, the resistance to temper softening per Cr addition amount (% by weight) at higher temperature can be reduced and the Si or Al-induced resistance to temper softening at higher temperature can also be reduced. Therefore, if the steel should benefit from the Si or Al-induced resistance to temper softening, the maximum of the Cr addition amount should be at most 7.5 times as much as the carbon content. More specifically, the Cr addition amount should be 3.5 wt % for 0.55 wt % of C, 2.9 wt % for 0.45 wt % of C, 2.3 wt % for 0.35 wt % of C, and 1.6 wt % for 0.25 wt % of C. If the Cr addition amount should be more, the effective addition amount of Mo should be reduced to about half in designing the alloy as described below.

[0049] At a Cr addition amount of 5.5% by weight or more, the Cr-induced resistance to temper softening can be reduced to about half. Therefore, the following two methods can be used in designing the alloy.

[0050] 1) A method in which the Cr addition amount is limited to 3.5% by weight or less and Si, Al, Mo, V, and W are controlled; and

[0051] 2) A method in which the Cr addition amount is set in the range of 3.5 to 5.5% by weight, and then the Si addition amount is set at 0.5% by weight or less, and Mo is set in the effective addition amount range (up to 1.0% by weight), and Al, V, and W are controlled (a Mo addition amount of 1.0% by weight or more cannot effectively contribute to the enhancement of the resistance to temper softening).

[0052] In method 1), the maximum Cr addition amount is preferably less than 3.5% by weight in terms of cost, and the minimum Cr addition amount is preferably 0.1% by weight or more, because the Cr-induced resistance to temper softening is not so high and the Cr addition can enhance the hardenability of the steel. However, Cr can significantly accelerate the cementite precipitation and significantly increase the temper brittleness, which can generate in tempering at about 350°C or higher. Therefore, the Cr addition amount is preferably limited to less than 1% by weight, in terms of toughness.

[0053] In method 2), for the steel to which Cr is added in an amount of 3.5% by weight or more, Si is preferably added in a small amount, and Mo is preferably added in an amount of the effective addition amount or less, and V or W is preferably added to enhance the resistance to temper softening. For example, in order to make the 600°C tempered hardness comaparable to that of hot work tool steel SKD6 (C: 0.32 to 0.42%, Si: 0.8 to 1.2%, Mn: 0.5% or less, Cr: 4.5 to 5.5%, Mo: 1.0 to 1.5%, and V: 0.3 to 0.5%), the elements are
preferably added as follows: Si: 0.5% by weight or less, Cr: 3.5 to 5.5% by weight, Mo: 0.3 to 1.0% by weight, V: 0.2 to 0.4% by weight, and W: 0.1 to 0.5% by weight, and optionally Al: 0.15 to 0.6% by weight and Ni: 0.3 to 1.5% by weight.

[0054] Mo: 0.1 to 1.9% by Weight

[0055] Mo can improve the hardenability. Mo can also enhance the toughness of the low-temperature tempered martensite steel and the resistance to temper softening as mentioned above. Therefore, the lower limit should be 0.1% by weight for the development of an effective resistance to temper softening, and the upper limit should be the maximum addition amount (YMo % by weight) up to which Mo can be effective for the resistance to quench softening at quenching temperature. Based on the relation to the solubility limit of Mo carbide, the maximum addition amount should be as follows: YMo=1.6 wt % (at 900°C) in the absence of Si and Al, and YMo=1.6 wt % (Si 1.0% +Al 1.0%) in the presence of both Si and Al. However, the constant 1.6 wt % can be altered depending on the quenching temperature. The constant is approximately 1.6 at 900°C, 1.9 at 950°C, and 2.3 at 1000°C. In terms of quenching equipment and the productivity thereof and coarse crystal grain grown by heating, the quenching temperature is preferably 950°C or lower, more preferably 900°C or lower.

[0056] Concerning the contribution to the resistance to temper softening at 600°C, Si or Al can provide HRC=55.8 per 1% by weight, while Mo can provide HRC=41.1. According to the above relation, therefore, if Si or Al is effectively used as much as possible, the Mo addition amount can apparently be reduced without considerable reduction in the resistance to temper softening. In the present invention, therefore, the maximum addition amount of Mo is preferably less than 1% by weight in terms of economy.

[0057] As mentioned above, if Co coexists at a content of 3.5% by weight or more, the effective maximum addition amount (YMo % by weight) is further reduced to about half. In the steel with a Cr content of 3.5 to 5.5% by weight, therefore, the content of Mo is preferably 1% by weight or less.

[0058] V: 0.05 to 0.4% by Weight

[0059] In contrast to Cr and Mo, V can significantly enhance the resistance to temper softening in the tempering temperature range of 600°C or higher and be effective at improving wear resistance. In the present invention, therefore, either V or W (W has a V-like action as described below) is an essential component. However, the solid solubility of V carbide is low, and the V carbide can precipitate into the austenite phase during heating at quenching temperature so that the toughness can be reduced. Therefore, the upper limit of the V addition amount is preferably 0.3% by weight. As described above, the upper limit can appropriately be changed into 0.4% by weight at a quenching temperature of 950°C and 0.5% by weight at 1000°C.

[0060] Where V coexists with Si and Al and (Si+Al) is 1.8% by weight or more, the upper limit of the V addition amount should be reduced to half, that is, 0.15, 0.2, or 0.25 wt % at each quenching temperature. The quenching temperature is preferably 950°C or lower in terms of quenching equipment and the productivity thereof and coarse crystal grain grown by heating. Therefore, the upper limit of the addition amount should be 0.4% by weight. More preferably, the quenching temperature is 900°C or lower, and therefore the upper limit of the addition amount is 0.3% by weight. If Si coexists, a V addition amount of 1.0% by weight or more can reduce the Si-induced resistance to temper softening, and therefore the maximum addition amount is preferably 0.4% by weight or less.

[0061] W: 0.1 to 1.0% by Weight

[0062] W does not produce resistance to temper softening as much as Mo or V does. However, the resistance to temper softening produced by W can be maximum at a temperature of 600 to 700°C, and the upper limit of the addition amount up to which W is effective (YWM) can be high. Therefore, either W or V is an essential component. W can be effective in an addition amount of 0.1% by weight or more. Similarly, to V and Mo, the effective upper limit depends on temperature and should be 0.8% by weight at 900°C, 1.7% by weight at 950°C, and 2.5% by weight at 1000°C. If W is added in an amount of 1% by weight or more, the Mo-induced resistance to temper softening can significantly be reduced. W is more expensive than Mo. Therefore, the maximum addition amount is preferably 1.0% by weight or less.

[0063] Co: 1 to 20% by Weight

[0064] It is well known that Co itself does not produce resistance to temper softening. In the present invention, the addition of Co can sharply raise the magnetic transformation temperature and suppress the diffusion of other alloying elements. For example, Co can be effective at raising the reaction temperature in the formation of Si, Al, Cr, Mo, V, or W carbide which can produce the resistance to temper softening. Co can exert age hardening together with Si and Al, and coexisting Al can effectively change the magnetic transformation temperature. In an appropriate addition amount of Co, the magnetic transformation temperature increased by 18°C per 1% by weight, and such an effect was obtained up to 10% by weight. In an amount of more than 10 to 20% by weight, an increase of 10°C was obtained per 1% by weight. In an amount of more than 20% by weight, the effect will be saturated, and the cost can be too high. More efficiently, the usage of Co is preferably 10% by weight or less.

[0065] B: 0.0005 to 0.0030% by Weight

[0066] B can significantly improve hardenability. In many cases, the addition of B can be economically advantageous, because the usage of the hardenability-enhancing alloying element such as Mn, Cr, and Mo can be reduced. The addition amount of Cr, which tends to cause high-temperature temper brittleness, can be reduced. In the present invention, therefore, positive use of B is preferred. The addition amount of B is appropriately from 0.0005 to 0.0030% by weight, because it cannot be effective in an amount of less than 0.0005% by weight, and an amount of more than 0.0030% by weight is known to produce BN precipitation that can reduce the toughness.

[0067] B tends to segregate at the crystal grain boundary more strongly than P or S. B tends to strongly allow S to segregate and particularly, can strongly eliminate S from the grain boundary to improve the grain boundary strength. Therefore, positive use of B is preferred.

[0068] Zr, Nb, Ti: 0.005 to 0.20% by Weight

[0069] Zr, Nb, and Ti are known to make crystal grains fine and added in a conventional amount range. However, an amount of more than 0.2% by weight is known to increase the amount of carbide and nitride precipitations and to be disadvantageous for toughness.
P, S: 0.03% by Weight

P and S are contained as inevitable impurities but important because they are involved in the temper brittleness at a temperature of 350 to 550°C. The content of these elements in high cleanliness steels is reduced as low as possible. In the present invention, the maximum content of P or S may be more than 0.03% by weight, because high temperature tempering at 600°C or higher can be used and/or the addition of Al and Ni can prevent the temper brittleness. However, 0.03% by weight or less is preferred in terms of stabilization of higher toughness, and 0.015% by weight or less is more preferred, because such an amount presents no cost problem with the conventional steel making technique.

The present invention is based on the above discussion and results. In a first aspect of the present invention, the high-hardness, high-toughness steel contains Mo, V, and W in such an appropriate addition amount that they can produce strong resistance to temper softening while efficiently using Si-induced resistance to temper softening. Such a steel is economical and highly tough and wear-resistant.

According to the present invention, such a steel contains at least C: 0.15 to 0.60% by weight, Si: 0.05 to 1.8% by weight, and Cr: 0.1 to 3.5% by weight and is characterized by comprising Mo in an amount of 0.1 to 1.7% by weight, wherein the addition amount of Mo is not more than the upper limit determined by the relation formula: the upper limit Mo(% by weight) = 1.7 - 0.5x(Si(% by weight)) or one of both of V: 0.10 to 0.40% by weight and W: 0.1 to 1.0% by weight; at least one alloying element of Mn, Ni, Co, Cu, Al, Ti, Nb, Zr, Ta, Hf, and Ca; and inevitable impurities including P, S, N, and O; and the balance consisting essentially of Fe, wherein the steel is a tempered martensite steel.

In the present invention, in order to improve the toughness of the higher-hardness steel tempered at 150°C or higher, preferably, the Cr addition amount is limited to less than 1% by weight, the amounts are limited as follows: Si: 0.8-1.6% by weight, Cr: 0.1-1.0% by weight, and Mo: 0.5-1.3% by weight, and B is added in an amount of 0.0005 to 0.005% by weight.

Preferably, the addition amount of each alloying element is controlled to satisfy the relation formula: the upper limit Mo(% by weight) = 1.7 - 0.5x(Si(% by weight)) + Al(% by weight) = 0.5xCr(% by weight) + 11xMo(% by weight) + 25.7xV(% by weight) + 7.5xW(% by weight) ≤ 36.2, and quenching is carried out from a temperature of 950°C or lower and then tempering process is carried out at 600°C so that an HRC hardness of 50 to 60 is provided.

In a second aspect of the present invention, the high-hardness, high-toughness steel contains at least 0.1 to 1.20% by weight of carbon and 0.05 to 1.8% by weight of Si and is characterized in that Si is partially replaced by 0.15 to 1.0% by weight of Al, Ni is added to the steel in an amount of 0.3 to 2.5% by weight, the steel contains at least one alloying element of Mn, Cr, Nb, V, W, Co, Cu, Ti, B, Nb, Zr, Ta, Hf, and Ca; and inevitable impurities including P, S, N, and O; the balance consists essentially of Fe; and the steel has a quenched and tempered martensite structure.

In the present invention, the Cr content is preferably in the range of 0.1 to 3.5% by weight.

Mo may be added in an amount of less than 1.7% by weight and up to its upper limit determined by the relation formula: the upper limit Mo(% by weight) = 1.7 - 0.5x(Si(% by weight)) + Al(% by weight) depending on the addition amount of Si and Al so that a high-toughness, wear-resistance steel having improved toughness can be provided.

One or both of 0.05 to 0.40% by weight of V and 0.1 to 1.0% by weight of W are preferably added so that the resistance to temper softening can further be enhanced.

Preferably, Al is in an amount of 0.15 to 0.75% by weight in order to prevent excessive Al addition and give an adequate increase in the A3 transformation temperature, and one or both of limiting the Ni amount to between 0.3 and 2.0% by weight and adding 0.0005 to 0.005% by weight of B for enhancement of hardenability at low cost are made.

In order to ensure that the high-toughness, wear-resistance steel with Al and Ni coexisting in the above content range has an HRC hardness of 45 to 65 after tempering at 600°C or higher, the addition amount of each alloying element is preferably controlled to satisfy the relation formula: a lower limit Mo(% by weight) + Al(% by weight) + 2.8xCr(% by weight) + 11xMo(% by weight) + 25.7xV(% by weight) + 7.5xW(% by weight) = 41.2.

In a third aspect of the present invention, the high-hardness, high-toughness steel contains at least C: 0.25 to 0.55% by weight, Si: less than 0.8% by weight, and Cr: 3.5 to 5.5% by weight and is characterized in that Mo is added to the steel in an amount of 0.3 to 1.0% by weight, one or both of V: 0.10 to 0.40% by weight and W: 0.1 to 1.0% by weight are added to the steel, the steel contains at least one alloying element of Mn, Ni, Co, Cu, Al, B, Ti, Nb, Zr, Ta, Hf, and Ca; and inevitable impurities including P, S, N, and O; the balance consists essentially of Fe; and the steel is a tempered martensite steel.

In the present invention, to the steel containing 3.5 to 5.5% by weight of Cr, preferably, Al is added in an amount of 0.15 to 1.0% by weight, Ni is added in an amount of 0.3 to 2.5% by weight, and Mo is added in an amount of 0.3 to 1.0% by weight.

Preferably, the addition amount of each alloying element is controlled to satisfy the relation formula: 21.2 ≤ 3x(Si(% by weight)) + Al(% by weight) + 2.8xCr(% by weight) + 11xMo(% by weight) + 25.7xV(% by weight) + 7.5xW(% by weight) = 41.2 in order to have an HRC hardness of 45 or higher after tempering at 600°C.

In each above aspect of the present invention, Co may be added in an amount of 1 to 20% by weight so that the magnetic transformation temperature of the tempered martensite can increase by about 200°C, the diffusion of alloys during the tempering process can significantly be slowed down, and therefore significant resistance to softening can be developed by tempering even at 600°C or higher.

In each above aspect of the present invention, at least one of Nb, Ti, Zr, Ta, and Hf is preferably added in a total amount of 0.005 to 0.2% by weight in order to produce fine crystal grains in heating at high temperature for quenching.

In each above aspect of the present invention, the high-hardness, high-toughness steel quenched and then tempered at a high temperature of 600°C or higher can have an HRC hardness of 50 or higher and a Charpy impact value of 5 kgf m/cm2 or more.

In each above aspect of the present invention, the steel quenched and then tempered at a temperature of 150°C
C. or higher can have an adjusted HRC hardness of 45 or higher and a Charpy impact value that satisfies the relation formula: \[ \log(\text{Charpy impact value (kgf/m/cm})^2) = -0.0263x \times HRC + 2.225 \] where its HRC hardness is in the range from 45 to 55, or have a HRC hardness of 55 or higher and a Charpy impact value of 6 kgf m/cm² or more where its HRC hardness is 55 or higher.

**[0089]** The high-hardness, high-toughness steel according to each above aspect of the present invention may be processed into a crawler component such as a crawler bush, a crawler link, a top or bottom tracker roller for a crawler, and a crawler shoe, characterized by having a quenched and tempered HRC hardness of 52 or higher and a Charpy impact value of 6 kgf m/cm² or more and comprising a wear-resistant portion whose wear resistance is increased to at least 1.2 times on average as much as that of a conventional crawler component. Such a component can be obtained through whole heating, quenching with a suitable cooling medium such as water, an aqueous quenching solution, and a quenching oil, and tempering at a temperature of 150°C to 400°C. However, it will be understood that the wear-resistant portion of each component may be formed through high-frequency heating for quenching and tempering.

**[0090]** The high-hardness, high-toughness steel according to each above aspect of the present invention may be processed into a crawler component such as a crawler bush, a crawler link, a top or bottom tracker roller for a crawler, and a crawler shoe, characterized by having a quenched and tempered HRC hardness of 52 or higher and a Charpy impact value of 6 kgf m/cm² or more and comprising a wear-resistant portion whose wear resistance is increased to at least 1.2 times on average as much as that of a conventional crawler component. Such a component can be obtained through whole heating, quenching with a suitable cooling medium such as water, an aqueous quenching solution, and a quenching oil, and tempering at a temperature of 150°C to 400°C. However, it will be understood that the wear-resistant portion of each component may be formed through high-frequency heating for quenching and tempering.

**[0091]** The high-hardness, high-toughness steel according to each above aspect of the present invention may be processed into a crawler component such as a tunneling shank, a tunneling disk cutter, a chisel tool, and a cutting blade for soil improvement, characterized by having a quenched and tempered HRC hardness of 50 or higher and a Charpy impact value of 8 kgf m/cm² or more, wherein the hardness and the Charpy impact value are each increased to at least 1.2 times on average as much as that of a conventional component. Such a component can be obtained through whole heating, quenching with a suitable cooling medium such as water, an aqueous quenching solution, and a quenching oil, and tempering at a temperature of 150°C to 350°C. However, it will be understood that the wear-resistant portion of each component may be formed through high-frequency heating for quenching and tempering. In terms of cost, the addition amount of Ni is preferably 1% by weight.

**[0092]** The high-hardness, high-toughness steel according to each above aspect of the present invention may be processed into a fastening bolt for use in construction equipment such as a crawler shoe bolt, a reduction gear, a swing circle fixing bolts, characterized by having a carbon content of 0.30% by weight or more, a quenched and tempered HRC hardness of 40 or higher, and a Charpy impact value that satisfies the relation formula: \[ \log(\text{Charpy impact value (kgf/m/cm}}^2) = -0.0263x \times HRC + 2.225 \] Such a component can be obtained through whole heating, quenching with a suitable cooling medium such as water, an aqueous quenching solution, and a quenching oil, and tempering at a temperature of 150°C to 500°C. However, it will be understood that the thread portion of the bolt may be induction-hardened and tempered.

**[0093]** The high-hardness, high-toughness steel according to each above aspect of the present invention may be processed into a gear shape and then carburized, quenched, and tempered to result in a gear or a high-toughness gear such as a crawler bush and a crawler shoe bolt, characterized by having a surface carbon concentration of 0.6% to 1.0% by weight, a surface carburizing depth of 0.4 mm or more, and an adjusted HRC hardness of 55 to 64, and providing a Charpy test piece with the equivalent depth and a Charpy impact value of 8 kgf m/cm² or more, preferably 5 kgf m/cm² or more.

**[0094]** The high-hardness, high-toughness steel according to each above aspect of the present invention may be processed into a gear shape and then carburized to have a surface carbon content of 0.8% to 1.3% by weight, temporarily cooled down to the AI transformation temperature or lower, and then heated again, quenched, and tempered to result in a high-toughness, high contact pressure-resistance gear, characterized by having a surface carburized case depth of 0.4 mm or more, containing cementite particles with an average particle diameter of 1 μm or less dispersed in its quench-hardened case, having an adjusted HRC hardness of 59 to 65, and providing a Charpy test piece with its equivalent depth and a Charpy impact value of 4 kgf m/cm² or more.

**[0095]** The high-hardness, high-toughness steel according to each above aspect of the present invention may be processed into a gear shape and then induction-hardened and tempered to result in a high-toughness gear, characterized by having an adjusted surface HRC hardness of 52 to 64 and providing a Charpy test piece with its equivalent hardened depth and a Charpy impact value of 5 kgf m/cm² or more. The gear can be obtained through whole heating, quenching with a suitable cooling medium such as water, an aqueous quenching solution, and a quenching oil, and tempering at a temperature of 150°C to 350°C. However, it will be understood that the gear tooth portion may be induction-hardened and tempered to have a Charpy impact value of 5 kgf m/cm² or more.

**[0096]** The high-hardness, high-toughness steel according to each above aspect of the present invention may quenched and tempered to result in a wear-resistant steel plate, characterized by having a high tension of 50 kgf/mm² or higher and/or an adjusted HRC hardness of 50 or higher and being weldable to a bucket, a bulldozer blade, or the like for use. The wear-resistant steel plate can improve in low-temperature cracking susceptibility in welding to a bucket, a blade or the like of a construction or earth work machine or improve in cracking susceptibility in re-heating.
The steel according to each above aspect of the present invention is applicable to excavating edge members that set importance on the resistance to temper softening under frictional heating. Therefore, the present invention is also directed to an earth wear-resistant component for use in earth excavation such as a ripper point, an end bit, bucket tooth, an edge, and a tunneling disk cutter, characterized by comprising the high-hardness, high-toughness steel which contains less than 3.5% by weight of Cr and alloying elements each in a controlled addition amount that satisfies the relation formula: 26.2±5.8x(Si(% by weight)+Al(% by weight))+2.8xCr(% by weight)+11xMo(% by weight)+25.7xV(% by weight)+7.5xW(% by weight)±41.2 so that the steel can have an HRC hardness of 50 or higher by tempering at 600°C.

**FIG. 12** is a graph showing the relationship between the tempering temperature and the Charpy impact value on products Nos. 10, 12, and 47;

**FIG. 13** is a graph showing conditions of carburizing and quenching;

**FIG. 14** is a diagram showing hardness distribution in carburized, quenched, and tempered Charpy test pieces;

**FIGS. 15(a) and 15(b)** are micrographs each showing a surface quench-hardened layer structure formed through the steps of carburizing at 1000°C for 2 hours to provide a surface carbon concentration of 1.1% by weight or 1.3% by weight, cooling to room temperature, and reheating at 850°C for 1 hour for quenching and tempering; and

**FIG. 16** is a graph showing the relationship between hardness and wear ratio on various steels where the gouging wear amount of the quenched and tempered S45C steel (Hv 500) is normalized as 1.

**DESCRIPTION OF THE PREFERRED EMBODIMENTS**

**Referring to the drawings,** examples of the high-hardness, high-toughness steel according to the present invention are described in the following.

**EXAMPLE 1**

**Preliminary Research and Experiment**

In Example 1, the handbook “Hagane no Netsu-Shori” (in Japanese) (Heat-Treatment of Steels), revised 5th edition, edited by The Iron and Steel Institute of Japan, published by MARUZEN CO., LTD, 1985 was referred to, and the relations between tempering temperature and Rockwell hardness on various tough steels (martensite steels) described therein were organized so that target values for improvement of wear-resistant steels were investigated in making the present invention.

As a result, as shown in **FIG. 2,** it has been found that SCr, SCM, SNCM, and high-Si tough steels each containing 0.6% by weight or less of carbon cannot have more than HRC45 by tempering at 600°C and that target values can be achieved by using SKD6 (0.4C-5Cr-1.3Mo-0.3V).

**FIGS. 3 and 4** shows the relationship between the 150 to 700°C tempered hardness and the Charpy impact value on steels including SUJ2 and SKH9. These graphs show that the Charpy impact value can be 5 kgf/m² or more where the HRC hardness has an upper limit of about 56. **FIG. 5** shows the result of preliminary experiments in which steels each having the composition as shown in Table 1 were quenched and then tempered at 200°C for 2 hours, and the relationship between the Charpy impact value and the carbon content was examined. The result shows that there is almost no possibility that a carbon content of 0.55% or more provides a Charpy impact value of 5 kgf/m² or more.
TABLE 1

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<th>P</th>
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<td>0.05</td>
<td>0.9</td>
<td>0.01</td>
<td>15</td>
<td>0.28</td>
<td>1.84</td>
<td>0.72</td>
</tr>
<tr>
<td>15</td>
<td>0.28</td>
<td>1.84</td>
<td>0.72</td>
<td>0.028</td>
<td>0.031</td>
<td>0.13</td>
<td>2.11</td>
<td>0.4</td>
<td>16</td>
<td>0.26</td>
<td>0.29</td>
<td>0.76</td>
</tr>
<tr>
<td>16</td>
<td>0.26</td>
<td>0.29</td>
<td>0.76</td>
<td>0.011</td>
<td>0.014</td>
<td>0.47</td>
<td>0.44</td>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EXAMPLE 2

[0119] Preparation of Wear-Resistant Test Steels

[0120] Table 2 shows the compositions of the steels used. The addition amount of each element was in the following range: C: 0.14 to 0.73% by weight, Si: at most 2.5% by weight, Mn: at most 1.3% by weight, Cr: 0.3 to 8% weight, Mo: at most 4% by weight, V: at most 1% by weight, W: at 2% by weight, Al: at most 2% by weight, and Ni: at most 2% by weight. Other elements such as Nb, B, and Ti were added in a very small amount, and each level was selected concerning the control of P and S and the like. The steels were used in investigating the effect of each alloying element on the resistance to temper softening (and the Charpy impact value). Each ingot steel about 25 kg in weight was prepared using a high-frequency smelter, formed into a round bar shape 32 mm in diameter by hot forging, machined into a round bar 25 mm in diameter, cut to have a suitable length, heat-treated in a certain manner, and subjected to the experiments as shown below.
EXAMPLE 3

[0121] Check Test for Resistance to Temper Softening (Effect of Alloying Elements on Tempered Hardness)

[0122] In this example, each test piece 25 mm in diameter with the composition as shown in Table 2 was heated at a temperature of 870°C to 980°C for 1 hour in N₂ gas atmosphere, then water-quenched, tempered at a temperature of 200 to 700°C for 2 hours, rapidly cooled in water, and measured for hardness. The purpose of the test was to investigate and analyze the effect of each alloying element on the resistance to temper softening and to establish the way to design alloys that can have a tempered HRC hardness of 45 or higher by tempering at 600°C.

[0123] As a result of the check test, it has been found that the effect of alloying elements on the hardness of the martensite steel tempered at 600°C after quenched from 900°C, for example, can be calculated according to the following formula:

\[ \Delta HRC = 5.7x(YMo( wt \%) + 0.7x(Al( wt \%)) + 2.8x(Cr( wt \%) + 11x(Mo( wt \%) + 25.7x(W( wt \%)) + 7.5x(W( wt \%)) \]

[0124] As described above, Mo, V, and W are accompanied by the maximum addition amounts YMo, YV, and YW, respectively. If any of these elements is added in an amount of more than the maximum addition amount, the hardness of the alloyed steel is calculated by using the maximum addition amount in place of the actual amount in the formula.

[0125] FIGS. 6 to 10 each show the result of the measurement of tempered hardness of different steel products (indicated by “Found”) shown in FIG. 2 and the result of the calculation of tempered hardness based on the process in which the effect of each alloying element on the tempered hardness is analyzed and quantified (indicated by “Calculated”). These graphs show that there is very good agreement between the calculated and found values of the tempered hardness of each alloyed steel and that the effect of each alloying element can almost reasonably be quantified.

[0126] FIG. 6 shows the found values (at a quenching temperature of 870°C) and the calculated values of the tempered hardness of products Nos. 1 to 9 for comparison. In the drawing, Nos. 1 to 3 show the effect of Mo or V addition on low Cr-high Si steels, Nos. 4 to 6 show the effect of V, Ni, and W, and Nos. 7 to 9 show the effect of the combined addition of Al and Ni. The drawing shows that Si, Mo, V, W, and Al each develop significant resistance to temper softening even at low Cr content and that particularly, the Al-induced resistance to temper softening is very well calculated at the same degree of influence as Si, and Al develops the resistance to temper softening by substantially the same mechanism as Si.

[0127] From the comparison between the calculations based on the analysis and the actual measurements, hardening caused by the aging effect of NiAl based intermetallic compounds has been demonstrated in the case that Al coexists with Ni (ΔHRC=44 by 1Al+1Ni). However, at a quenching temperature of 870°C, Mo in No. 2, Mo and V in No. 4, V in No. 5, and V and W in No. 6 are each slightly in excess of the above-mentioned effective addition amount. In such cases, for example, the resistance to temper softening is found to be more effectively developed where the steel is tempered after quenched from 950°C (for example, in the effective Mo amount: YMo=1.3-0.5x(Si+Al)).

[0128] FIG. 7 shows the found values (at a quenching temperature of 870°C) and the calculated values of the tempered hardness of products Nos. 10 to 22 for comparison. In the drawing, product No. 16 undergoes the process in which quenching is performed at a higher temperature of 980°C, and then tempering is performed, and it shows that the process of dissolving 0.5% by weight of V into the alloy and then tempering effectively contributes to the resistance to temper softening.

[0129] FIG. 8 shows the found values (at a quenching temperature of 900°C) and the calculated values of the tempered hardness of products Nos. 23 to 29 for comparison. This shows the results of the investigation of the relationship between high content of Cr and Mo and V addition and demonstrates that Mo and V forms the above-described relationship even in the case that Cr coexists in an amount of about 3% by weight. In No. 28, Mo is added in large amount, but the effective Mo amount should be about 1.0% by weight in consideration of the amount of coexisting Si and the high carbon content (amount of the precipitated Mo carbide into the austenite) (ΔYM0=0.15). Therefore, it has been found that the product is highly hardened to have HRC55, which is equivalent to or higher than the 600°C tempered hardness of hot work tool steel SKD6, for example. In contrast to SKD6 which is practically used after the process of quenching at 1000 to 1050°C and tempering at 550 to 600°C for adjusting HRC to 53 or lower, products Nos. 23 to 29 according to the present invention is apparently useful as a hot work tool steel. These products have Cr and Mo contents reduced to less than 3% and less than 1% by weight, respectively, and are quenched at a reduced temperature of 900°C and therefore more economical. The carbon content of these steels is limited to at most 0.55% by weight. However, it will be understood that the carbon content is more preferably 0.45% by weight or less in terms of the content range of SKD6.

[0130] FIG. 9 shows the found values (at a quenching temperature of 950°C) and the calculated values of the tempered hardness of products Nos. 30 to 33 for comparison. The drawing shows the effect of higher Cr content than those in FIG. 8. For example, as shown by the comparison between Nos. 31 and 33, the result of analysis shows that the effect of Cr on the resistance to temper softening drastically decreases as the Cr content becomes about 3.5% by weight or more and that the steel with a Cr content of more than 3.5% by weight is drastically reduced in the Si-induced resistance to temper softening. Therefore, it is apparent that the Cr usage is preferably limited to 3.5% by weight or less so that Cr can be effective at developing the resistance to temper softening.

[0131] If Cr is added in large amount as in Nos. 29 to 33, the mechanism of the Cr-induced resistance to temper softening becomes more significant as the carbon content becomes smaller compared with the Cr addition amount. From the result of the analysis, it has been found that as described above, the addition of Cr in an amount of more than about 7.5 times as much as the carbon content reduces the resistance per Cr addition amount.

[0132] FIG. 10 shows the found values (at a quenching temperature of 900°C) and the calculated values of the tempered hardness of products Nos. 34 to 38 for comparison. The drawing shows the effect of Mo, W, and Si in a high
Cr content range. It has been found, from the result, that the maximum effective addition amount of W is about 1.0% by weight at 900°C and that the addition of W in an amount of more than 1% by weight drastically reduces the maximum effective addition amount of Mo, and therefore the addition amount of W is desirably not more than 1% by weight. It has also been found that 6% by weight or more of Cr further drastically reduces the Cr-induced resistance to temper softening (see No. 38).

[0133] It is apparent, from the above, that in developing the high-toughness, wear-resistance steels, the addition of the alloying element in an amount of more than the maximum addition amount as described above is not only uneconomical but also makes almost no contribution to wear resistance and can reduce the toughness. It is also apparent that the contribution of the alloying element such as Si, Al, and Cr to the resistance to temper softening depends on the addition amount range, and therefore such an element is preferably added so as to be more effective in consideration of economy.

[0134] In order to provide the martensite steel with an HRC hardness of 45 or higher by tempering at 600°C, the alloying elements should be used in such a combination that the following formula is satisfied.

\[
21.1 \leq 5.7 \times (S/\text{wt} \% + Al/\text{wt} \% + 2.8 \times Cr/\text{wt} \% + 11 \times Mo/\text{wt} \% + 25.7 \times V/\text{wt} \% + 7.5 \times W/\text{wt} \%)
\]

**EXAMPLE 4**

**[0136]** Results of Impact Test

**[0137]** Table 2 also shows the results of the 2U Charpy impact test (using JIS (Japanese Industrial Standards) No. 3 test piece) in which the steels tempered at 200°C or 600°C for 2 hours were examined. Table 3 also shows the results on additional materials according to the present invention and comparative materials. It has been found, from the results, that among the materials tempered at 200°C or 600°C for 2 hours,

- [0138] 1) the materials each with about 1% by weight or less of Cr and with Mo positively added;
- [0139] 2) the materials with 0.81% by weight or less of W added; and
- [0140] 3) the materials with Al and Ni added in combination have high-toughness. It has also been found that thanks to the combined addition of Al and Ni, the upper limit of the carbon content can be about 1.2% by weight in the tempered martensite structure steel showing such toughness as a Charpy impact value of 3 kgf m cm² or more.

<table>
<thead>
<tr>
<th>TABLE 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPNo.</td>
</tr>
<tr>
<td>No. C</td>
</tr>
<tr>
<td>39</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>41</td>
</tr>
<tr>
<td>42</td>
</tr>
<tr>
<td>43</td>
</tr>
<tr>
<td>44</td>
</tr>
<tr>
<td>45</td>
</tr>
<tr>
<td>46</td>
</tr>
<tr>
<td>47</td>
</tr>
<tr>
<td>48</td>
</tr>
<tr>
<td>49</td>
</tr>
</tbody>
</table>

**[0135]** In order to produce high-toughness, wear-resistance steels, limitations are preferably placed on the upper limit of the hardness obtained by tempering at 600°C, and, for example, such hardness is preferably set at HRC55 or lower in the case that SKD6 or the like is referred to as a conventional standard. However, the combined addition of Al and Ni can increase such an upper limit of the hardness to HRC65, and therefore the addition amount range of the alloying element is preferably in accordance with the following formula:

\[
21.2 \leq 5.8 \times (S/\text{wt} \% + Al/\text{wt} \% + 2.8 \times Cr/\text{wt} \% + 11 \times Mo/\text{wt} \% + 25.7 \times V/\text{wt} \% + 7.5 \times W/\text{wt} \%)
\]

**EXAMPLE 4**

**[0141]** FIG. 11 shows the relationship between the hardness and the Charpy impact value on products Nos. 47, 48, and 49 each quenched from the temperature as shown in the table and tempered at each temperature of 200 to 500°C for 3 hours. No temper brittleness-induced decrease in the impact value was observed between low-temperature tem-
pered HRC60 and 500° C. tempered HRC47, and particularly, the toughness was rapidly recovered by tempering at 200° C.

[0142] FIG. 12 shows the relationship between each tempering temperature and the Charpy impact value on product No. 47 in Table 3 and products Nos. 10 and 12 in Table 2. It is apparent, from the drawing, that product No. 12 is rapidly embrittled by tempering at 200° C. or higher, but product No. 10 with a high Si content retains the toughness at 350° C. or lower and is significantly embrittled at 500° C. and recovers the toughness at 600° C. It is also apparent that product No. 47 with Al and Ni added in combination shows no temper embrittlement but very high toughness.

[0143] The example of the low-carbon Al—Ni steel (No. 40) is found to show excellent toughness even in the tempering process at a low temperature of 200° C. It is also apparent, from the comparison with the results on the steels in Table 3 (Nos. 39, 41, 45, and 46), that the Al—Ni steel has a very high toughness in a wide range of carbon content and a wide range of hardness and that a suitable carbon content is preferably from 0.15 to 1.20% by weight. Therefore, it has been found that the alloy is preferably designed in such a manner that HRC45 or higher is established by tempering at 600° C. while wear resistance is retained at HRC45 or higher.

EXAMPLE 5

[0144] Results of Impact Test on Carburized, Quenched and Tempered Steels

[0145] Steels Nos. 39, 40, and 41 in Table 3 were each normalized at 980° C. and then formed into a test piece shape for the Charpy impact test, giving test pieces for use in this example. The carburizing, quenching and tempering process was carried out as shown in FIG. 13. The carbon potential was set so as to provide 0.85% by weight of carbon at 930° C. The time period for carburization diffusion was set at 5 hours so as to provide a carburized case depth of 0.8 to 1.2 mm. The tempering was carried out at 180° C. for 3 hours.

[0146] In FIG. 14 showing the distribution of the hardness in the test pieces carburized, quenched, and tempered, the hardness of the surface carburized case is presented as a Vickers hardness from Hv750 to Hv800 (corresponding to HRC62 to HRC64), and the Charpy impact values of the respective test pieces are as follows: No. 39: 1.74 k gf/m²; No. 40: 11.9 k gf/m²; and No. 41: 1.24 k gf/m². As a result of the observation of the structure, products Nos. 39 and 40 was found to keep the cFe phase remaining. Therefore, a high temperature of 910° C. was substituted for 850° C. in the tempering process after carburizing, and the test pieces were subjected to the Charpy impact test. As a result, drastic improvement was achieved as follows: No. 39: 2.52 k gf/m² and No. 40: 22.6 k gf/m². In particular, the impact value of product No. 40 is close to that of the low-carbon base material as shown in Table 3.

[0147] It is apparent, from the results, that they are highly preferable steels to form the gear of the reduction gear or the slewing gear in the construction or earth work machine, which tends to receive impact load. It is also apparent that they are preferable steels to form the crawler bush and the like, which is used after the process of carburizing, quenching, and tempering.

[0148] FIGS. 15(a) and 15(b) are photographs each showing the structure with a depth of 0.2 mm from the surface of the Charpy test piece, which was prepared by carburizing product No. 40 at 1000° C. so as to provide a surface carbon content of 1.1% by weight (a) or 1.3% by weight (b), temporarily cooling it to the A1 temperature or less, reheating it at 870° C. for quenching, and tempering it at 200° C. for 3 hours. In each structure, cementite particles with an average particle diameter of 1 μm or less are almost homogeneously dispersed, and the surface carburized case has an HRC hardness of 62. Conventionally, gear members having a surface carburized case structure in which lots of fine cementite particles are dispersed have been excellent in contract pressure resistance and expected to form a much compact gear for reduction gears, but have been very poor in toughness. From the results of the Charpy impact test (No. 40: 4 to 6 k gf/m² and No. 41: 0.7 to 1.0 k gf/m²), however, it has been found that the steel can improve in toughness by adding Al and Ni in combination according to the present invention and that such a steel with cementite particles dispersed can be used to form a high contact pressure-resistant gear.

EXAMPLE 6

[0149] First Example of Application of High-Hardness, High-Toughness Steels

[0150] In this example, wear resistance data of some conventional wear resistant components for construction or earth work machinery, which are potential use of the above high-hardness, high-toughness steels, are organized to show the effect and the advantage of the present invention. Table 4 shows typical components and their carbon content and their quenched and tempered hardness, and tempering parameters calculated from typical alloying constituents. Many of these components are designed to satisfy both high toughness and high hardness and therefore commonly contain 0.25 to 0.40% by weight of carbon. Such components are rarely used at a hardness of HRC52 or higher and therefore apparently insufficient in wear resistance. It is apparent that the bucket tooth, the ripper point, the end bit, and the cutting edges, which are frequently used in excavating rock and therefore need resistance to temper softening, can be insufficient in wear resistance, because the constituents are controlled to provide the tempering parameter between 10 and 22, and the hardness after tempering at 600° C. is as low as between HRC33 and HRC46.
TABLE 4

<table>
<thead>
<tr>
<th>Components</th>
<th>Manufacturer</th>
<th>600°C C. Carbon Content Weight % by Hardness HRC</th>
<th>Heat Treatment</th>
<th>Ingredients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bucket Tooth</td>
<td>A</td>
<td>13.8 0.33C 48-52</td>
<td>Through-hard</td>
<td>1.75S60.6Cr1.1MoB</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>4.0 0.33C 48-52</td>
<td></td>
<td>1.1Mo1CrB</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>12.0 0.35C 48-52</td>
<td></td>
<td>1.8Sl1.3Mn0.8Cr0.04Mo0.15V</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>15.7 0.3C 48-52</td>
<td></td>
<td>1.78Sl1.2Mn1.35Cr0.2Mo</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>12.5 0.26C 48-52</td>
<td></td>
<td>1.28Sl1.2Cr0.25Mo</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>7.7 0.25C 48-52</td>
<td></td>
<td>1.2Mn1.5Cr</td>
</tr>
<tr>
<td></td>
<td>F, E</td>
<td>10.1 0.26C 45-49</td>
<td></td>
<td>0.7S1.2N0.7Cr0.035Mo</td>
</tr>
<tr>
<td>Ripper Point</td>
<td>F</td>
<td>21.6 0.30 48-52</td>
<td>Trough-hard</td>
<td>1.68L2Cr0.35Mo0.1V</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>22.5 0.44C 48-52</td>
<td></td>
<td>0.4M2Cr1Mo1.15V</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>13.8 0.33C 48-52</td>
<td></td>
<td>1.75S60.6Cr1.1MoB</td>
</tr>
<tr>
<td>Cutting Edge</td>
<td>F</td>
<td>4.5 0.3C 45-49</td>
<td>Through-hard</td>
<td>1.75S60.6Cr1.1MoB</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>15.6 0.40C 45-49</td>
<td></td>
<td>2.2S80.4Mn1Cr</td>
</tr>
<tr>
<td>End Bit</td>
<td>F</td>
<td>22.9 0.3C 45-49</td>
<td>Through-hard</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>6.3 0.3C 45-49</td>
<td></td>
<td>0.6S1.2Mn0.4Cr0.15Mo</td>
</tr>
<tr>
<td>Segment</td>
<td>F</td>
<td>2.7 0.33C 45-49</td>
<td>Through-hard</td>
<td>1.3Mn1.2Cr</td>
</tr>
<tr>
<td>Teeth</td>
<td>A</td>
<td>2.5 0.35C 48-52</td>
<td></td>
<td>1.2Mn0.5Cr</td>
</tr>
<tr>
<td>Bottom</td>
<td>F, E</td>
<td>3.7 0.35C 48-52</td>
<td>Through-hard</td>
<td>1.2Mn0.5Cr0.1MoB</td>
</tr>
<tr>
<td>Trucker Roller</td>
<td>F, E</td>
<td>4.1 0.35C 48-52</td>
<td>Through-hard</td>
<td>1.2Mn0.5Cr0.1MoB</td>
</tr>
<tr>
<td>Crawler Link</td>
<td>F, E</td>
<td>3.5 0.35C 50-52</td>
<td>Induction</td>
<td>1.2Mn1.5Cr</td>
</tr>
<tr>
<td>Crawler Shoe</td>
<td>F, A</td>
<td>9.8 0.4C 50-54</td>
<td></td>
<td>0.4Mn1Cr0.5MnB</td>
</tr>
<tr>
<td>Crawler Shoe Bolt</td>
<td>A, F</td>
<td>7.3 0.25C 49-47</td>
<td>Through-hard</td>
<td>1.0Mn0.5Cr</td>
</tr>
<tr>
<td>Crawler Shoe Bolt</td>
<td>A, F</td>
<td>7.7 0.3C 46-52</td>
<td></td>
<td>0.78S0.6Mn1Cr2B</td>
</tr>
<tr>
<td>Disc Cutter</td>
<td>A</td>
<td>5.8 0.4C 50-54</td>
<td>Through-hard</td>
<td>1.8S0.8Cr0.2Mo</td>
</tr>
<tr>
<td>Tool Bit</td>
<td>A</td>
<td>5.0 0.4C 45-50</td>
<td>Through-hard</td>
<td>3Ni0.5Cr0.25Mo</td>
</tr>
<tr>
<td>Shank</td>
<td>A</td>
<td>14.0 0.3C 45</td>
<td></td>
<td>3NiCr1.5Mo</td>
</tr>
<tr>
<td>Soil Cutter</td>
<td>A, F</td>
<td>3.9 0.27C 48-50</td>
<td>Through-hard</td>
<td>1.4Mn0.5Cr0.55MoB</td>
</tr>
<tr>
<td>Bucket</td>
<td>A, F</td>
<td>3.9 0.27C 48-50</td>
<td>Through-hard</td>
<td>1.4Mn0.5Cr0.55MoB</td>
</tr>
</tbody>
</table>

*Tempering Parameter = 5.8 × (Si(% by weight) + Al(% by weight)) + 2.8 × Cr(% by weight) + 11 × Mo(% by weight) + 25.7 × (V(% by weight) + 7.5 × W(% by weight))
**600°C C. Tempered Hardness (HRC) = 23.6 + Tempering Parameter

[0151] Such steels include no case where Al and Ni are added in combination in order to provide high hardness and high toughness. Considering the results of the Charpy impact values in the above examples, such steels still have problems of cracking, chipping, and fracturing due to insufficient toughness.

[0152] The applicant has data concerning the relationship between the hardness of various steels and the gouging wear resistance, wherein the wear resistance (W: wear amount) of the quenched and tempered steel with a Vickers hardness of Hv500 is normalized as 1, and reduction in hardness by friction heating is not significant. Such wear resistance is approximately calculated according to the formula: Wv(Hv) = 250000 (see FIG. 16). It is apparent, from this result, that if the components with the toughness unchanged can have the average hardness increased from HRC50 (Hv513) to HRC55 (Hv600), their wear resistance would significantly increase by about 20% or more. Therefore, it is apparent that for example, the high-hardness, high-toughness steel with Al and Ni added in combination can be used and appropriately heat-treated to form a significantly improved-wear resistance crawler link, crawler shoe, crawler bush, bucket tooth, cutting edge, end bit, segment teeth, bottom tracker roller, tunneling tool bit, shank, disk cutter, chisel tool, or soil cutter for earth stirring in a soil-improvement machine, each having a hardness of HRC55 or higher and a Charpy impact value of 5 kgf cm² or more.

[0153] It is also apparent that the bucket tooth, ripper point, end bit, and cutting edges, which are frequently used in excavating rock and need resistance to temper softening, can be prevented from cracking, chipping, or fracturing by using the above tempering parameters, appropriately adding the alloying elements so as to provide a hardness of HRC45 or higher, preferably HRC50 or higher by tempering at 600°C, and enhancing the toughness by the combined addition of Al and Ni.

[0154] The results of the impact test in Examples 4 and 5 suggest that the improvement in toughness by the combined addition of Al and Ni should lead to reinforcement of the grain boundary (old austenite grain boundary) and be very effective at improving the crawler shoe bolt, which would otherwise have a problem with resistance to delayed fracture. It is known that the delayed fracture frequently occurs in the bolts using quenched and tempered steels with a hardness of HRC40 or higher. The delayed fracture also tends to occur in steels that are significant in temper brittleness. Therefore, conventional bolts are often made of boron steels (corresponding to S35C in Table 4) which contain alloying elements in a small amount and B so as to have enhanced hardenability. However, such steels have a Charpy impact value of about 7 to 11 kgf cm² at HRC45. Such a value is not satisfying in comparison with the improved Charpy impact value of the steel with Al and Ni added in combination according to the present invention. Therefore, it is apparent that a higher tension bolt can be produced by
using the steel that is reduced in temper brittleness and significantly improves in the grain boundary strength to satisfy HRC 41 or more and the relation formula: log-
(Charmy impact value (kgf m/cm²))² = -0.0263xHRC+2.225
garding to the present invention.

[0155] Example 4 and FIG. 11 show that product No. 40 in Table 3 ensures a high Charmy impact value at a hardness of HRC60. Product No. 40 has a very high toughness (see Example 5) in contrast to the carburized, quenched and
tempered SCM420H product, which is supposed to form
gears. Therefore, it is apparent that the inventive steel with
Al and Ni added in combination and 0.45 to 1.2% by weight
of carbon can be used and worked into a gear shape and then
induction-quenched and tempered or subjected to known
appropriate quenching and tempering to form a gear with a
surface hardness of HRC55 or higher at lower cost than that
for conventional carburized, quenched and tempered gears.

[0156] The results of the impact test in Examples 4 and 5
show that the quenched and tempered steel and the carbur-
zied, quenched and tempered steel each with a high carbon
content of up to 1.2% by weight have a Charmy impact value
of 5 kgf m/cm² or more. It is therefore apparent that such
steels are also applicable to a tap, a press die, a chisel,
shilering shear blade, a saw blade, a cutter, and the like.

EXAMPLE 7

[0157] Second Example of Application of High-Hardness,
High-Toughness Steels

[0158] This example focuses on the fact that low tempera-
ture cracking or re-heating cracking of high tension steel
plates or wear resistant steel plates in the construction or
earth work machine, which are potential use of the above
high-hardness, high-toughness steels, is attributed to the
welding heat-induced embrittlement of old austenite grain
boundary in the base metal. This example shows that the
inventive high-hardness, high-toughness steels are effective
at preventing such weld cracking.

[0159] When higher tension welding steel plates or wear
resistant welding plates are developed, it is important to
show the way to prevent the low temperature cracking in the
base metal after welding, and therefore specifications of
such steel plates are provided based on their chemical
constituents. In manufacturing high tension steels with a
tension of 50 kgf/mm² or higher and manufacturing wear
resistant welding steels using the same, the applicant con-
trols the steel constituents to set the Nippon Steel Corpora-
tion’s specification PH at 1 or less. PH is calculated from the
content (% by weight) of the respective elements according
to the following formula:

\[ \text{PH} = 0.015 \times (\text{C}) + 0.035 \times (\text{Cr}) + 0.06 \times (\text{Si}) + 0.01 \times (\text{Ni}) + 0.001 \times (\text{Mn}) \]

[0160] From this relation formula, the amount of P is
limited to 0.01% by weight or less because P can significa-
cantly cause grain boundary embrittlement and signifi-
cantly facilitate the weld cracking, the amount of B is carefully
controlled in order to ensure the hardenability of the steels,
and the carbon content is limited to between 0.1 and 0.3% by
weight.

[0161] For example, the bucket wear-resistible steel plate
in Table 4, which is to be fillet-welded to the bottom of the
bucket, has a limited carbon content of 0.3% by weight or
less and comprises controlled constituents according to the
above to be free from weld cracking. Therefore, such a steel
can be insufficient in wear resistance. In this example, two
types of quenched and tempered steel plates: Fe-0.45C-
0.21Si-1.2Mn-0.5Ni-0.15Cr-0.018P-0.001B (PH=1.411)
and this plus 0.26% by weight of Al (PH=1.48) (each about
HRC54 in hardness, 15 mm in thickness, 70 mm in width,
and 600 mm in length) each were fillet-welded to the bucket
bottom at two corners in the longitudinal direction at room
temperature under CO₂, and weld cracking was examined.
As a result, two out of five Al-free steel plates generated
cracks, but 20 Al-added steel plates had no crack.

[0162] After each welded bucket was heated at 500°C for
30 minutes for the purpose of removing the residual stress,
it was air-cooled to room temperature and examined for
 cracking at the weld. As a result, the remaining three Al-free
steel plates all generated cracks, but the Al-added steel plates
had no crack. Therefore, it has been found that the high
tension steel plate with 0.15% by weight or more of Al and
0.3% by weight or more of Ni added in combination will
have a PH upper limit of 1.4 to 1.48 and that in the case that the
P content is limited to 0.02% by weight or less, the
addition amount of carbon will be up to about 0.6% by
weight and therefore the carbon content will appropriately
be from 0.1 to 0.6% by weight.

What is claimed is:
1. A high-hardness, high-toughness steel containing
   at least C: 0.15 to 0.60% by weight, Si: 0.05 to 1.8% by weight,
   and Cr: 0.1 to 3.5% by weight, which comprises: Mo in an
   amount of 0.1 to 1.7% by weight, wherein the amount of Mo
   is not more than the upper limit determined by the relation
   formula: Mo(%) by weight=1.7-0.5×Si(%) by weight; one
   or both of V: 0.10 to 0.40% by weight and W: 0.1 to 1.0% by
   weight; at least one alloying element of Mn, Ni, Co, Cu,
   Al, Ti, B, Nb, Zr, Ta, Hf, and Ca; inevitable impurities
   including P, S, N, and O; and the balance consisting essen-
tially of Fe, wherein the steel is a quenched and tempered
martensite steel.
2. The steel according to claim 1, wherein Si is in an
   amount of 0.8 to 1.60% by weight, Cr is in an amount of
   at least 0.1% by weight and less than 1.0% by weight, and Mo is
   in an amount of 0.5 to 1.3% by weight, and B is added in an
   amount of 0.0005 to 0.005% by weight.
3. The steel according to claim 1, wherein the amount of
each alloying element is adjusted to satisfy the relation
   formula: 26.2 ≤ 5.8×Si(%) by weight)+Al(%) by weight)+
   2.8×Cr(%) by weight)+11×Mo(%) by weight)+25.7×V(%) by
   weight)+7.5×W(%) by weight) ≤ 36.2.
4. The steel according to claim 1, wherein Co is added in
   an amount of 1 to 20% by weight.
5. The steel according to claim 1, wherein the steel
   contains at least one of Nb, Ti, Zr, Ta, and Hf in a total
   amount of 0.005 to 0.2% by weight.
6. The steel according to claim 1, wherein the steel
   provides an HRC hardness of 50 to 60 and a Charmy impact
   value of at least 5 kgf m/cm² after quenching and following
   tempering at a high temperature of at least 600°C.
7. The steel according to claim 1, wherein the steel is a
tempered martensite steel quenched and then tempered and
has an HRC hardness of at least 45 and a Charmy impact
value that satisfies the relation formula: log(Charpy impact value (kgf m/cm³)) = -0.0263xHRC + 2.225 where its HRC hardness is in the range from 45 to 55, or has an HRC hardness of at least 55 and a Charpy impact value of at least 6 kgf m/cm².

8. A high-hardness, high-toughness steel containing at least C: 0.10 to 1.20% by weight and Si: 0.05 to 1.8% by weight, which comprises: 0.15 to 1.6% by weight of Al partially replacing Si; 0.3 to 2.5% by weight of Ni; at least one alloying element of Mn, Cr, Mo, V, W, Co, Cu, Ti, B, Nb, Zr, Ta, Hf, and Ca; inevitable impurities including P, S, and O; and the balance consisting essentially of Fe, wherein the steel is a quenched and tempered martensite structure steel.

9. The steel according to claim 8, wherein the steel contains Cr in an amount ranging from 0.1 to 3.5% by weight.

10. The steel according to claim 8, wherein Mo is added in an amount of less than 1.7% by weight and the amount of Mo is not more than the upper limit determined by the relation formula: Mo(% by weight)=1.7-0.5x(Si(% by weight)+Al(% by weight)) depending on the amount of Si and Al.

11. The steel according to claim 8, wherein one or both of V: 0.05 to 0.40% by weight and W: 0.1 to 1.0% by weight are added to the steel.

12. The steel according to claim 8, wherein the steel satisfies one or both of limitation (1): Al is in an amount of 0.15 to 0.75% by weight and Ni is in an amount of 0.3 to 2.0% by weight and limitation (2): B is added in an amount of 0.0005 to 0.005% by weight.

13. The steel according to claim 8, wherein the amount of each alloying element is adjusted to satisfy the relation formula: 21.2xSi(% by weight)+4Al(% by weight)+2.8xCr(% by weight)+11xMo(% by weight)+25.7xV(% by weight)+7.5xW(% by weight) = ±41.2.

14. The steel according to claim 8, wherein Co is added in an amount of 1 to 20% by weight.

15. The steel according to claim 8, wherein the steel contains at least one of Nb, Ti, Zr, Ta, and Hf in a total amount of 0.005 to 0.2% by weight.

16. The steel according to claim 8, wherein the steel provides an HRC hardness of 50 to 60 and a Charpy impact value of at least 5 kgf m/cm² after quenching and following tempering at a high temperature of at least 600°C.

17. The steel according to claim 8, wherein the steel is a tempered martensite steel quenched and then tempered and has an HRC hardness of at least 45 and a Charpy impact value that satisfies the relation formula: log(Charpy impact value (kgf m/cm³)) = -0.0263xHRC + 2.225 where its HRC hardness is in the range from 45 to 55, or has an HRC hardness of at least 55 and a Charpy impact value of at least 6 kgf m/cm².

18. A high-hardness, high-toughness steel containing at least C: 0.25 to 0.55% by weight, Si: less than 0.8% by weight, and Cr: 3.5 to 5.5% by weight, which comprises: Mo in an amount of 0.3 to 1.0% by weight; one or both of V: 0.10 to 0.40% by weight and W: 0.1 to 1.0% by weight; at least one alloying element of Mn, Ni, Co, Cu, Al, B, Ti, Nb, Zr, Ta, Hf, and Ca; inevitable impurities including P, S, and O; and the balance consisting essentially of Fe, wherein the steel has a quenched and tempered martensite structure.

19. The steel according to claim 18, wherein the steel contains Al in an amount of 0.15 to 1.0% by weight and Ni in an amount of 0.3 to 2.5% by weight so that it has an improved resistance to temper softening and an improved toughness.

20. The steel according to claim 19, wherein the amount of each alloying element is adjusted to satisfy the relation formula: 21.2xSi(% by weight)+4Al(% by weight)+2.8xCr(% by weight)+11xMo(% by weight)+25.7xV(% by weight)+7.5xW(% by weight) = ±41.2.

21. The steel according to claim 18, wherein Co is added in an amount of 1 to 20% by weight.

22. The steel according to claim 18, wherein the steel contains at least one of Nb, Ti, Zr, Ta, and Hf in a total amount of 0.005 to 0.2% by weight.

23. The steel according to claim 18, wherein the steel provides an HRC hardness of 50 to 60 and a Charpy impact value of at least 5 kgf m/cm² after quenching and following tempering at a high temperature of at least 600°C.

24. The steel according to claim 18, wherein the steel is a tempered martensite steel quenched and then tempered and has an HRC hardness of at least 45 and a Charpy impact value that satisfies the relation formula: log(Charpy impact value (kgf m/cm³)) = -0.0263xHRC + 2.225 where its HRC hardness is in the range from 45 to 55, or has an HRC hardness of at least 55 and a Charpy impact value of at least 6 kgf m/cm².

25. A crawler component including a crawler bush, a crawler link, a top or bottom track roller for a crawler, and a crawler shoe for a crawler vehicle, which comprises the high-hardness, high-toughness steel according to any one of claims 1 to 24, wherein the steel is a quenched and tempered martensite steel having an HRC hardness of at least 52 and a Charpy impact value of at least 6 kgf m/cm².

26. An earth wear-resistant component including a tunneling shank, a tunneling disk cutter, a chisel tool, and a stirring blade for soil improvement, which comprises the high-hardness, high-toughness steel according to any one of claims 1 to 24, wherein the steel is a quenched and tempered martensite steel having an HRC hardness of at least 50 and a Charpy impact value of at least 8 kgf m/cm².

27. A fastening bolt for use in a construction machine, which comprises the high-hardness, high-toughness steel according to any one of claims 1 to 24, wherein the steel is a quenched and tempered martensite steel having an HRC hardness of at least 40 and a Charpy impact value that satisfies the relation formula: log(Charpy impact value (kgf m/cm³)) = -0.0263xHRC + 2.225.

28. A high-toughness gear, which comprises the high-hardness, high-toughness steel according to any one of claims 1 to 24, wherein the steel is formed into a gear shape and then carburized and quenched, and tempered to have a surface carbon concentration of 0.6 to 1.0% by weight, a surface carburizing depth of at least 0.4 mm, and an adjusted HRC hardness of 55 to 64 and to provide a Charpy test piece with an equivalent depth and a Charpy impact value of at least 8 kgf m/cm².

29. A high-toughness, high contact pressure-resistance gear, which comprises the high-hardness, high-toughness steel according to any one of claims 1 to 24, wherein the steel is formed into a gear shape and then carburized to have a surface carbon content of 0.8 to 1.3% by weight, temporarily cooled to the Al transformation temperature or lower, and then heated again, quenched, and tempered to have a surface carburized case depth of at least 0.4 mm, to contain cementite particles with an average particle diameter of at
most 1 μm dispersed in its quench-hardened case, to have an adjusted HRC hardness of 59 to 65, and to provide a Charpy test piece with its equivalent depth and a Charpy impact value of at least 4 kgf/m².

30. A high-toughness gear, which comprises the high-hardness, high-toughness steel according to any one of claims 1 to 24, wherein the steel is formed into a gear shape and then induction-hardened and tempered to have an adjusted surface HRC hardness of 52 to 64 and to provide a Charpy test piece having a hardened depth equivalent to that of the steel and a Charpy impact value of at least 5 kgf/m².

31. A wear-resistant steel plate, which comprises the high-hardness, high-toughness steel according to any one of claims 1 to 24, wherein the steel is quenched and tempered to have a high tension of at least 50 kgf/mm² and/or an adjusted HRC hardness of at least 50, and weldable use of the steel plate includes a bucket and a bulldozer blade.

32. An earth wear-resistant component for use in earth excavation including a ripper point, an end bit, bucket tooth, an edge, and a tunneling disk cutter, which comprises the high-hardness, high-toughness steel according to any one of claims 1 to 24, wherein the steel contains less than 3.5% by weight of Cr and alloying elements each in a controlled amount that satisfies the relation formula: 26.2≤5.8×(S(%) by weight)+Al(%) by weight))×11×Mo(%) by weight)+7.5×W(%) by weight)≤41.2 so that the steel can have an HRC hardness of at least 50 by tempering at 600°C.

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