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(54) High strength large steel forging

Grosse Stahlschmieden mit hoher festigkeit

Acier de Forgeage de grande dimension et de grande tenue

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Description

FIELD OF THE INVENTION

[0001] The present invention relates to a high strength large steel forging.

BACKGROUND OF THE INVENTION

[0002] High strength is required for large size crankshafts and intermediate shafts used for ships or power generators. Generally, these shafts are produced by steel forgings. Nowadays, in addition to further improvement of strength, excellent toughness, which usually has a trade-off relationship with strength, is also required for these large steel forgings.

[0003] In order to improve strength and toughness of steel forgings, (1) high strength steel for a large steel forging in which component compositions are limited (refer to Japanese Unexamined Patent Application Publication No. 2005-344149); (2) steel for forging that is made by limiting component compositions and specifying a structure mainly including bainite and martensite (refer to Japanese Patent No. 3896365); (3) a crankshaft that is made by limiting component compositions and limiting a grain size of prior austenite (refer to Japanese Unexamined Patent Application Publication No. 2010-248540); (4) nickel-based thermal refining steel that is made by specifying an amount of aluminum on grain boundaries (refer to Japanese Unexamined Patent Application Publication No. 2000-212705); (5) steel for forging that is made by specifying concentrations of magnesium and aluminum (refer to Japanese Unexamined Patent Application Publication No. 2008-25021 and Japanese Unexamined Patent Application Publication No. 2009-173961); and (6) a forging that is made by specifying a rate of content of sulfur, conditions of hot forging, and the like (refer to Japanese Unexamined Patent Application Publication No. 2003-147436) have been developed.

[0004] However, even the steels (1) to (3) described above cannot demonstrate sufficient strength because a block size and a grain size of the formed structure may be not adequate, and therefore, toughness and fatigue strength cannot be improved in a balanced manner. In addition, the aluminum content in the steel (4) described above is high, and thus, nonmetallic inclusions and intermetallic compounds may be generated to deteriorate toughness and fatigue strength. The steel (5) is said to improve strength. However, the steel (5) is not intended to improve toughness. The steel forging (6) is said to have high strength and high toughness. However, existence of the predetermined amount of sulfur generates nonmetallic inclusions such as MnS, and, as a result, fatigue strength deteriorates. As described above, none of the conventional steel forgings have improved strength, toughness and fatigue strength in a balanced manner.

SUMMARY OF THE INVENTION

[0005] The present invention is achieved in view of the above-described problems and the object of the present invention is to provide a high strength large steel forging having highly balanced strength and toughness and having high fatigue strength.

[0006] The invention for solving the problem described above is a high strength large steel forging including:

compositions including
basic compositions including:

- C: 0.31% by mass or more and 0.5% by mass or less,
- Si: 0.02% by mass or more and 0.2% by mass or less,
- Mn: 0.1% by mass or more and 0.6% by mass or less,
- Ni: 2.6% by mass or more and 3.4% by mass or less,
- Cr: 0.8% by mass or more and 1.9% by mass or less,
- Mo: 0.25% by mass or more and 0.8% by mass or less,
- V: 0.05% by mass or more and 0.2% by mass or less, and
- Al: 0.005% by mass or more and 0.1% by mass or less, and
- a remainder including Fe and unavoidable impurities;
- wherein a content S as the unavoidable impurity is 0.008% by mass or less; and
- wherein the high strength large steel forging consists of a martensitic structure or a mixed structure of martensite and bainite;
- a grain size of prior austenite is 19 μm or more and 70 μm or less; and
- a maximum block size of martensite is 15 μm and a minimum block size of martensite is 0.5 μm or less.

[0007] The high strength large steel forging has excellent strength and toughness in a balanced manner and, in addition, provides high fatigue strength by limiting the above-described compositions and structure as described above and setting the prior austenite grain size and the block size within the range described above.

[0008] Here, "large" in the high strength large steel forging means a steel forging having a spherical part or a cylindrical part whose diameter is 150 mm or more, a steel forging having a plate-like part whose thickness is 150 mm or more, and a steel forging having a similar size or larger size.

[0009] As described above, the high strength large steel forging of the present invention has excellent strength and toughness in a balanced manner and, in addition, has high fatigue strength. For this reason, the high strength large steel forging can preferably be used for large size crankshafts, intermediate shafts, and the like used for ships, power generators, or the like.

BRIEF DESCRIPTION OF DRWAINGS

[0010]

Fig.1 is a graph illustrating a relationship between a ratio x of a depth and a distance from a surface to a center part of a high strength large steel forging and a fraction of a martensitic structure $f_m(x)$ (%);

Fig. 2 is a graph illustrating a relationship between a maximum size of a martensitic block and Charpy absorbed energy measured by using specimens of Examples and Comparative Examples;

Fig. 3 is a graph illustrating a relationship between tensile strength and the Charpy absorbed energy measured by using the specimens of Examples and Comparative Examples;

Fig. 4 is a graph illustrating a relationship between the tensile strength and fatigue strength measured by using the specimens of Examples and Comparative Examples;

Fig. 5 is an inverse pole figure map of the specimen of Example 4;

Fig. 6 is an inverse pole figure map of the specimen of Example 11;

Fig. 7 is an inverse pole figure map of the specimen of Comparative Example 3;

Fig. 8 is an inverse pole figure map of the specimen of Comparative Example 7;

Fig. 9 is an inverse pole figure map of the specimen of Comparative Example 9;

Fig. 10 is a TTT diagram used as analysis conditions in an analysis example;

Figs. 11 are graphs illustrating temperature dependence of each physical property used as the analysis conditions in the analysis example;

Figs. 12 are graphs illustrating plastic behavior in each phase used as the analysis conditions in the analysis example;

Fig. 13A is a graph illustrating analysis conditions A and B in the analysis example and Fig. 13B is a graph illustrating the analysis results; and

Fig. 14A is a graph illustrating a relationship between a depth of a high strength large steel forging and Brinell hardness in Reference Example and Fig. 14B is a graph illustrating a relationship between the depth and a fraction of martensitic structure in Reference Example.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0011] Hereinafter, embodiments of the high strength large steel forging of the present invention will be described in detail.

<Composition>

[0012] The high strength large steel forging is constituted by basic components including: C: 0.31% by mass or more and 0.5% by mass or less, Si: 0.02% by mass or more and 0.2% by mass or less, Mn: 0.1% by mass or more and 0.6% by mass or less, Ni: 2.6% by mass or more and 3.4% by mass or less, Cr: 0.8% by mass or more and 1.9% by mass or less, Mo: 0.25% by mass or more and 0.8% by mass or less, V: 0.05% by mass or more and 0.2% by mass or less, and Al: 0.005% by mass or more and 0.1% by mass or less, and a remainder including Fe and unavoidable impurities. Reason of limitation of each component will be described below.

(C: 0.31% by mass or more and 0.5% by mass or less)

[0013] The lower limit of the carbon (C) content is 0.31% by mass and the lower content is preferably 0.33% by mass. On the other hand, the upper limit of the carbon (C) content is 0.5% by mass and the upper content is preferably 0.4% by mass. Carbon (C) contributes to improving hardenability and strength. A carbon content being less than the lower limit described above causes difficulty in obtaining sufficient hardenability and strength. Conversely, a carbon content being more than the upper limit described above causes extreme deterioration in toughness and promotes generation of "A" segregation in a large ingot.

(Si: 0.02% by mass or more and 0.2% by mass or less)

[0014] The lower limit of the silicon (Si) content is 0.02% by mass and the lower content is preferably 0.06% by mass. On the other hand, the upper limit of the silicon (Si) content is 0.2% by mass and the upper content is preferably 0.16% by mass. Silicon (Si) contributes to deoxidation and improvement of strength. A silicon content being less than the lower limit described above cannot provide sufficient demonstration of this effect. Conversely, a silicon content being more than the upper limit described above causes significant "A" segregation, and thus, a pure ingot is difficult to be obtained.

(Mn: 0.1% by mass or more and 0.6% by mass or less)

[0015] The lower limit of the manganese (Mn) content is 0.1% by mass and the lower content is preferably 0.3% by mass. On the other hand, the upper limit of the manganese (Mn) content is 0.6% by mass and the upper content is preferably 0.45% by mass. Manganese (Mn) improves hardenability and strength. A manganese content being less than the lower limit described above causes difficulty in demonstration of the effect described above. Conversely, a manganese content being more than the upper limit described above promotes temper embrittlement.

(Ni: 2.6% by mass or more and 3.4% by mass or less)

[0016] The lower limit of the nickel (Ni) content is 2.6% by mass and the lower content is preferably 2.8% by mass. On the other hand, the upper limit of the nickel (Ni) content is 3.4% by mass. Nickel (Ni) improves hardenability, strength, and toughness. A nickel content being less than the lower limit described above cannot provide sufficient demonstration of this effect. A nickel content being more than the upper limit causes difficulty in obtaining adequate size of prior austenite grains. In addition, an amount of used Ni, which is high price, can be reduced, and production cost can be reduced by setting the nickel content less than the upper limit described above.

(Cr: 0.8% by mass or more and 1.9% by mass or less)

[0017] The lower limit of the chromium (Cr) content is 0.8% by mass and the lower content is preferably 1.4% by mass. On the other hand, the upper limit of the chromium (Cr) content is 1.9% by mass and the upper content is preferably 1.65% by mass. Chromium (Cr) improves hardenability and toughness. A chromium content being less than the lower limit described above cannot provide sufficient demonstration of the effect described above. Conversely, a chromium content being more than the upper limit described above promotes "A" segregation.

(Mo: 0.25% by mass or more and 0.8% by mass or less)

[0018] The lower limit of the molybdenum (Mo) content is 0.25% by mass and the lower content is preferably 0.4% by mass. On the other hand, the upper limit of the molybdenum (Mo) content is 0.8% by mass and the upper content is preferably 0.6% by mass. Molybdenum (Mo) improves hardenability, strength and toughness. A molybdenum content being less than the lower limit described above cannot provide sufficient demonstration of the effect described above and promotes "A" segregation. Conversely, a molybdenum content being more than the upper limit described above promotes micro-segregation and tends to generate gravity segregation.

(V: 0.05% by mass or more and 0.2% by mass or less)

[0019] The lower limit of the vanadium (V) content is 0.05% by mass and the lower content is preferably 0.07% by mass. On the other hand, the upper limit of the vanadium (V) content is 0.2% by mass and the upper content is preferably 0.13% by mass. Addition of a small amount of vanadium (V) extremely improves hardenability and strength. However, vanadium has a small equilibrium distribution coefficient, and thus, tends to generate micro-segregation. A vanadium content being less than the lower limit described above cannot ensure sufficient strength. Conversely, a vanadium content being more than the upper limit described above promotes generation of micro-segregation.

(Al: 0.005% by mass or more and 0.1% by mass or less)

[0020] The lower limit of the aluminum (Al) content is 0.005% by mass and the lower content is preferably 0.008% by mass. On the other hand, the upper limit of the aluminum (Al) content is 0.1% by mass and the upper content is preferably 0.03% by mass. Aluminum (Al) is used as a deoxidation agent. In addition, aluminum generates fine compounds such as AlN, and this AlN terminates growth of grains and can form fine grains. An aluminum content being less than the lower limit described above cannot provide sufficient demonstration of this effect. Conversely, an aluminum content being more than the upper limit described above may generate oxides and intermetallic compounds and may deteriorate toughness and fatigue strength because aluminum forms bonds to other elements such as oxygen.

[0021] The basic components of the high strength large steel forging are described above. The remainder components are substantially iron (Fe). However, trace amounts of unavoidable impurities (for example, S, O, P, Cu, Sn, N, and the like) may be included. Further, other elements may be positively included in a range as long as the elements do not provide adverse effect to the operation and effect of the high strength large steel forging. Examples of these other elements may include Ti, Ca, and Mg. From the viewpoint of reduction in generation of coarse inclusions, a total amount of the unavoidable impurities is preferably controlled to 0.5% by mass or less.

(S: 0.008% by mass or less)

[0022] The sulfur (S) content is 0.008% by mass or less and preferably 0.003% by mass or less. Sulfur (S), which forms MnS in the steel forging, deteriorates fatigue strength when the content exceeds the upper limit described above. However, industrially, the content never becomes 0% by mass.

[0023] Contents of the other unavoidable impurities are preferably as follows.

(O: 0.0025% by mass or less)

[0024] The oxygen (O) content is preferably 0.0025% by mass or less and more preferably 0.002% by mass or less. Oxygen (O) bonds with various elements to form nonmetallic inclusions, and as a result, deteriorates fatigue strength. Consequently, the oxygen content is preferably the upper limit described above or less. However, industrially, the content never becomes 0% by mass.

(P: 0.02% by mass or less)

[0025] The upper limit of the phosphorus (P) content is preferably 0.02% by mass or less and more preferably 0.01% by mass or less. A phosphorus (P) content being more than the upper limit described above causes deterioration in hot ductility and tends to generate cracks and other defects during forging.

(Cu: 0.1% by mass or less)

[0026] The upper limit of the copper (Cu) content is preferably 0.1% by mass or less and more preferably 0.05% by mass or less. A copper (Cu) content being more than the upper limit described above tends to generate cracks and other defects during forging.

(Sn: 0.03% by mass or less)

[0027] The upper limit of the tin (Sn) content is preferably 0.03% by mass or less and more preferably 0.01% by mass or less. A tin (Sn) content being more than the upper limit described above may causes deterioration in toughness.

(N: 0.02% by mass or less)

[0028] The upper limit of a nitrogen (N) content is preferably 0.02% by mass or less and more preferably 0.01% by mass or less. A nitrogen (N) content being more than the upper limit described above causes deterioration in hot ductility and tends to generate cracks and other defects during forging.

<Structure>

[0029] Subsequently, the structure of the high strength large steel forging will be described.

[0030] The high strength large steel forging consists of a martensitic structure or a mixed structure of martensite and bainite. Both strength and toughness can be simultaneously satisfied in a balanced manner by forming the high strength large steel forging consisting of only those two types of structures. Existence of other structures such as ferrite and perlite in the high strength large steel forging cannot simultaneously satisfy both strength and toughness.

[0031] A grain size of prior austenite in the high strength large steel forging (an average size) is 19 μm or more and 70 μm or less. The grain size of prior austenite affects a block size. A coarse grain size of prior austenite enlarges the block size and does not provide sufficient toughness. As a result, the upper limit of the grain size of prior austenite is determined to be 70 μm. Conversely, too fine grain size being less than 19 μm causes deterioration in hardenability and causes contamination with proeutectoid ferrite, and thus, balance between strength and toughness deteriorates.

The grain size of prior austenite can be measured by a method described in Examples.

[0032] In a martensitic block size, which is a substructure of the martensitic structure forming the high strength large steel forging, a maximum block size thereof is 15 μm or less and a minimum block size thereof is 0.5 μm or more. The martensitic block size being determined to be the range described above allows the steel forging to improve strength, toughness, and fatiguing strength in a balanced manner. Particularly, reduction in this maximum block size to 15 μm or less allows the steel forging to demonstrate stable toughness. On the other hand, too much reduction in the block size increases grain boundary density and increases in a crack growth rate. Consequently, the minimum block size is determined to be 0.5 μm or more.

[0033] In the high strength large steel forging, it is preferable that a fraction of a martensitic structure $f_m(x)$ (%) where a ratio of a depth to a distance from a surface to a center part is defined as x ($0 \leq x \leq 1$) is

$fm(x) = 100$, where $0 \leq x \leq 0.1$;
$104-40x \leq f_m(x) \leq 100$, where $0.1 < x \leq 0.15$,
$122-160x \leq fm(x) \leq 100$, where $0.15 < x \leq 0.2$;
$230-700x \leq f_m(x) \leq 100$, where $0.2 < x \leq 0.3$;
$110-300x \leq f_m(x) \leq 112-40x$, where $0.3 < x \leq 0.35$;
$(22-20x)/3 \leq f_m(x) \leq 105-20x$, where $0.35 < x \leq 50.5$;
$(32-40x)/3 \leq f_m(x) \leq 95$, where $0.5 < x \leq 0.8$; and
$0 \leq f_m(x) \leq 95$, where $0.8 < x \leq 1$ (the range (a) illustrated in Fig. 1).

[0034] Here, a remainder structure is a bainitic structure. This fraction of the martensitic structure can be measured by using a method described in Examples, that is, a rule of mixtures derived from measurement results of hardness.

[0035] The "center part" of the high strength large steel forging means the deepest position from each position of the surface. For example, when the high strength large steel forging has a spherical part, the center part means the center point of the spherical part; when the forging has a cylindrical part, the center part means the center axis of the cylindrical part; and when the forging has a plate-like part, the center part means the center plane that is located at the equal distance from both surfaces. A "distance from the surface to the center part" means a vertical distance from each part of the surface to the center part. For example, when the forging has a spherical part or a cylindrical part, the distance from the surface to the center part means a radius of the spherical part or the cylindrical part, and when the forging has a plate-like part, the distance from the surface to the center part means a half of the plate thickness.

[0036] Control of the fraction of martensitic structure $f_m(x)$ in the high strength large steel forging as described above enables to reduce generation of whole internal stress from the surface to the center. As a result, the balance between strength, toughness, and fatigue strength can be further improved.

[0037] When the high strength large steel forging includes a depth region in which a fraction of the martensitic structure is less than the range described above, tensile stress may remain in a region close to the surface, particularly close to around x = 0.2. This residual tensile stress causes reduction in fatigue strength. The high strength large steel forging is preferably used for a crankshaft and the like. Bending stress is repeatedly applied to a fillet part of a crankshaft, and thus, high fatigue strength is particularly required for the surface of the fillet part. The crankshaft is finished by machine processing after heat treatment, so that the surface layer is ground. Reduction in the residual tensile stress in the range of a certain depth from the surface (around $0 \leq x \leq 0.3$) can provide higher fatigue strength when the high strength large steel forging is used for the crankshaft and the like. On the other hand, a fraction of the martensitic structure including a depth region exceeding the range described above may cause increase in internal transformation stress caused by quenching, and thus quenching cracks may tend to be generated.

[0038] In the high strength large steel forging, it is preferable that the fraction of the martensitic structure $f_m(x)$ (%) is

$f_m(x) = 100$, where $0 \leq x \leq 0.1$;
$104-40x5 \leq f_m(x) \leq 100$, where $0.1 < x \leq 0.15$;
$122-160x \leq f_m(x) \leq 100$, where $0.15 < x \leq 0.2$;
$150-300x \leq f_m(x) \leq 100$, where $0.2 < x \leq 0.3$;
$105-150x \leq f_m(x) \leq 112-40x$, where $0.3 < x \leq 0.35$;
$105-150x \leq f_m(x) \leq 105-20x$, where $0.35 < x \leq 0.5$;
$80-100x \leq f_m(x) \leq 170-150x$, where $0.5 < x \leq 0.8$; and
$0 \leq fm(x) \leq 130-100x$, where $0.8 < x \leq 1$,

in order to further reduce generation in whole internal stress from the surface to the center (the range (b) illustrated in Fig. 1).

[0039] Setting the fraction of the martensitic structure to the lower limit value described above or more can further reduce generation of tensile stress close to the surface. On the other hand, setting the fraction of martensitic structure to the upper limit value described above or less can reduce internal tensile stress, and thus, risk of quenching crack can be further reduced.

[0040] In order to further improve the operation and effect described above (reduction in generation of whole internal stress from the surface to the center), it is preferable that $d(f_m(x))/dx \leq 0$, where $0 \leq x \leq 1$.

<Performance, application, and the like>

[0041] The high strength large steel forging, which has the compositions and the structure described above, has both excellent strength and toughness and has high fatigue strength. This strength (tensile strength) is preferably 1,050 MPa or more, and more preferably 1,080 MPa or more. The tensile strength means a value measured in accordance with JIS-Z2241 (1998).

[0042] The high strength large steel forging has excellent strength, toughness, and fatigue strength as described above, and therefore, can be preferably used for large size crankshafts and intermediate shafts used for ships or power generators. Particularly, in order to achieve improvement of output power and formation of smaller engines of diesel engines for ships or diesel engines for land-based power generation, for example, further fatigue strength and tensile strength (for example, a tensile strength of 950 MPa or more) are required for large size crankshafts. The high strength large steel forging can sufficiently satisfy these requirements.

<Manufacturing method>

[0043] A method for manufacturing the high strength large steel forging is not particularly limited. The high strength large steel forging can be obtained by forging and thermally treating the steel adjusted in the compositions described above. Hereinafter, one example of the method for manufacturing the high strength large steel forging that is a solid type crankshaft having a diameter of 150 mm or more will be described.

[0044] First, steel in which predetermined component compositions described above are adjusted is melted by using an electric furnace, a high frequency induction furnace, a steel converter, and the like. Thereafter, impurities (sulfur, oxygen, and the like) are removed (reduced) by vacuum refining and the like. After the impurities are removed, an ingot is formed from this steel by casting. As a method for casting, ingot casting is mainly used. A continuous casting may also be used when relatively small steel forging is formed.

[0045] Subsequently, a round-bar material before forming a crankshaft is forged. In order to forge the steel within the range of excellent deformation property of the steel, a temperature in this operation is preferably 1,150°C or more, and more preferably 1,200°C or more. Lower heating temperature causes increase in flow stress and reduction in manufacturing efficiency. A heating period is preferably 3 hours or more. This heating period is essential for equalizing the temperatures between the surface and the inside of the ingot. Generally, this heating period is proportional to square of a diameter of a processed object. For example, the heating period is determined to be 3 hours or more at the time of manufacturing the large size crankshaft described above.

[0046] After the round-bar material is made by forging, the round-bar material is forged in a shape of the solid type crankshaft. This forging is preferably performed by a Continuous Grain Flow (CGF) forging method. The CGF forging method is a method in which an ingot is forged and processed so that an axle center of the ingot becomes a center of axle part of the solid type crankshaft and the ingot is forged in an integrated manner and processed so that a part that tends to deteriorate properties by centerline segregation is included in the whole of an axle center part of the solid type crankshaft. Examples of the CGF forging method described above may include an RR forging method and a TR forging method. These methods are preferable because high purity parts occupy the surface side of the solid type crankshaft, and therefore, the solid type crankshaft having excellent strength and fatigue property tends to be obtained.

[0047] Hereinafter, the method of forging will be described using the RR forging method as an example.

[0048] In the RR forging, the obtained forged material is heated at 1,150°C or more for 3 hours or more to hot-form each crank throw. As a specific procedure, first, the round-bar material obtained by the procedure described above is processed by a machine to form a material for RR forging. Thereafter, pin shafts, a pair of block parts, and journal shafts, which are corresponding to forming one cylinder, are partially heated and vertical force of a press is converted into force in the lateral direction by a wedge mechanism, and thereby one cylinder is forged by simultaneously applying compression force in the lateral direction and eccentric force to the RR material. By repeating this operation in the number of required cylinders, a single crankshaft is formed. In order to forge the steel within the range of excellent deformation property of the steel, a temperature in this operation is preferably 1,150°C or more, and more preferably 1,200°C or more. Lower heating temperature causes increase in flow stress and reduction in manufacturing efficiency. This heating period is essential for equalizing the temperatures between the surface and the inside of the ingot. The heating period is determined to be 3 hours or more at the time of manufacturing the large size crankshaft described above.

[0049] After the RR forging, retained austenite (γ) contained in the forging may be decomposed before thermal refining treatment (quenching and tempering treatment) is performed. In order to form a finer structure, phase transformation during the thermal refining treatment is used. At this time, the retained γ continues to exist during heating in the thermal refining treatment until a temperature exceeds the Ac1 transformation point, when the retained γ existing after forging is stable. This retained γ is γ that remains during the forging and the heat treatment and originally has the same orientation in the prior austenite after forging. Consequently, an interface between the retained γ does not form grain boundary, when γ transformation proceeds and retained γ are brought in contact with each other. As a result, a grain size of γ after completion of γ transformation is a coarse grain size that is similar to the original grain size of γ. Consequently, treatment of decomposing the retained γ is performed.

[0050] An example of the method for decomposing the retained austenite includes a method for aging treatment in which the forging is maintained under heating at the Ac1 transformation point or less (600°C to 680°C). In this treatment, the maintained heating time is 5 hours or more and preferably 20 hours or more. By such aging treatment, the retained austenite is decomposed and can be reduced to 1% by volume or less. For another example of the method for decomposing retained austenite, sub-zero treatment can be used.

[0051] Subsequently, the thermal refining treatment (quenching and tempering treatment) is performed. First, the forging is slowly heated (a heating rate of 30°C/hour to 70°C/hour) to the Ac3 transformation point or more (840°C to 940°C) and maintained for a certain period (3 hours to 9 hours) before quenching. From the viewpoint of reduction in formation of coarse prior austenite grain, the quenching is preferably preformed at relatively low temperature (840°C to 940°C) that is the Ac3 transformation point or more as described above. A large product, which generates temperature difference between an outer part and an inner part of the material during heating, is slowly heated to a heating temperature before quenching and maintained for a certain period in order to equalize the temperature between the surface and the inner part of the steel. Required maintaining time depends on a diameter of a steel product. The larger the product, the longer the maintaining time becomes. Consequently, the following quenching is performed after sufficient maintaining time is taken and the temperature is equalized to the inner part of the steel product.

[0052] The quenching is performed using a cooling agent such as oil and polymer solution and the martensitic structure or the structure made of martensite and bainite is obtained. In order to obtain such a structure, the quenching is performed in an average cooling rate of 3°C/minute or more. This cooling rate is more preferably 5°C/minute or more and 100°C/minute or less, and further preferably 10°C/minute or more and 60°C/minute or less.

[0053] In a large steel forging, water quenching has a risk of generating cracks, and thus, oil quenching and polymer quenching are commonly used for quenching of a large size crankshaft. The cooling rate at the time of quenching depends on a size of a steel forging. An average cooling rate between 800°C and 500°C of a crankshaft having a diameter of about 500 mm is about 20°C/minute in oil quenching and about 50°C/minute in polymer quenching. A crankshaft having a larger diameter (for example, 1,000 mm) requires much slower cooling rate.

[0054] In order to satisfy both strength and toughness of the high strength large steel forging, control of the martensitic structure or the mixed structure of martensite and bainite is required. As a result of study for conditions to realize such a structure even when a quenching cooling rate for applying to a large size crankshaft having a diameter of 150 mm or more is about 20°C/minute (in the case of oil quenching), the inventors of the present invention have accomplished to determine the chemical component compositions as described above.

[0055] In quenching, the steel forging is cooled to 200°C or less. By cooling to 200°C or less as described above, the transformation can be fully completed. Insufficient cooling causes non-transformed retained austenite to remain, and this causes fluctuation in properties. After quenching, the steel forging is preferably tempered.

[0056] In annealing, the steel forging is slowly heated (a heating rate 30°C/hour to 70°C/hour) to the predetermined temperature (550°C to 620°C) and maintained for a certain period (5 hours to 20 hours). In order to adjust the balance between strength and toughness and to remove internal stress (residual stress) during quenching, this annealing is performed at 550°C or more. However, too high temperature of the annealing results in softening caused by formation of coarse carbides and recovery of dislocation structures, and thereby sufficient strength cannot be ensured. Consequently, the annealing temperature is determined to be 620°C or less.

[0057] The high strength large steel forging can be obtained from the forging treated with thermal refining as described above by further performing finish machine processing including grinding of at least a part of the surface, if necessary. The method for manufacturing the high strength large steel forging of the present invention is not limited to the method for manufacturing described above. The high strength large steel forging can also be manufactured by, for example, free forging. The high strength large steel forging other than large size crankshafts can be obtained by a similar method for manufacturing.

[Examples]

[0058] Hereinafter, the present invention will be described in further detail with reference to Examples. However the present invention is not limited to these Examples.

[Measurement methods]

[0059] Each measurement in Examples is performed by the following methods.

1. Grain size (μm) of prior austenite (γ)

[0060] In accordance with ASTM (E112-96), the grain size number was determined by the comparative method with the following procedure, and thereafter, a grain size (a nominal grain size) of a prior austenite grain was calculated.

(1) A corresponding grain size number N is determined by comparing a photograph of 100 magnifications in the observation under an optical microscope and the standard chart.
(2) The grain size number N is determined in accordance with the number of grains n in 25 mm square (625 mm^2: microscopic field) in the observation under an optical microscope of 100 magnifications, and the following formula (1) can be established.

$$N = \frac{\log n}{0.301} + 1 \quad \cdots (1)$$

(3) A grain size d (μm) can be calculated by the following formula (2) because n grains possibly exist in 62,500 μm^2.

$$d(\mu m) = \sqrt{\frac{62500(\mu m^2)}{n}} \quad \cdots (2)$$

[0061] Here, the grain size of the prior austenite was measured in 10 places (10 microscopic fields), and each average grain size was calculated.

2. Martensitic block size (μm)

[0062] A group of laths, which is a substructure of martensite, having almost the same orientation is referred to as a block (a martensitic block). A misorientation between blocks is 15° or more (high angle grain boundary). Consequently, by the following method, a martensitic block size (μm) was calculated from an inverse pole figure map obtained by the FESEM-EBSP method.

(1) An inverse pole figure map is obtained by EBSP measurement at intervals of 0.3 μm in a microscopic fields of 120 μm × 120 μm.
(2) Regions that are surrounded in a misorientation between adjacent crystals of 15° or more are specified from the inverse pole figure map, and each area thereof is determined.
(3) A block size is determined by calculating square roots of each area (√(area)) described above.

[0063] The block size of martensite was measured in 10 places (10 microscopic fields), and a maximum size and a minimum size were determined in each microscopic field, and then each average size (an average of maximum size and an average of minimum size) was determined.

3. Tensile property (0.2% yield strength: YS (MPa), Tensile strength: TS (MPa), Elongation: (%), and Reduction in area: RA (%))

[0064] These properties were measured in accordance with JIS-Z2241 (1998). A shape of the specimen was the shape of No. 14 specimen illustrated in JIS-Z2201 (1998), and its demission was set to ϕ6 × G.L. 30 mm.

4. Charpy absorbed energy: vE (J)

[0065] Charpy absorbed energy was measured in accordance with JIS-Z2242 (2005). A shape of the specimen was the shape having 2 mm V-notch illustrated in JIS-Z2242 (2005). Three specimens were tested in each sample and the average value was determined as the absorbed energy.

5. Rotating bending fatigue strength FS (MPa) and Endurance limit

[0066] A rotating bending fatigue strength test was performed in accordance with the following test method, and the fatigue strength was evaluated.

Specimen: ϕ10 mm × G.L. 30 mm smooth specimens (5 pieces)
Test method: Rotating bending (Stress ratio = -1, Rotational speed = 3,000 to 3,600 rpm)
Evaluation method: Step method (Step increment 20 MPa)
Fatigue strength [FS] = Braking stress (MPa) - Step increment (MPa)
Endurance limit = Fatigue strength [FS]/Tensile strength [TS]

[Examples 1 to 13 and Comparative Examples 1 to 14]

[0067] Steel types a to q having compositions shown in Table 1 were produced through melting. Here, "-" in Table 1 represents below measurable limits. A seventy-ton ingot of the steel type a was casted by melting in an electric furnace and refining in a ladle. Forty-kilogram ingots of each of the steel types b to q were casted by melting in a high frequency induction furnace.

[Table 1]

Steel type	Composition (% by mass)													
	C	Si	Mn	Ni	Cr	Mo	V	Al	S	O	P	Cu	Sn	N
a	0.35	0.09	0.35	3.04	1.61	0.45	0.10	0.017	0.001	0.0012	0.008	0.03	0.001	0.0049
b	0.35	0.08	0.34	2.74	1.58	0.45	0.10	0.011	0.006	-	0.007	0.01	0.006	0.0054
c	0.35	0.08	0.34	3.23	1.57	0.46	0.10	0.016	0.007	-	0.007	0.01	0.006	0.0050
d	0.32	0.14	0.47	2.78	1.62	0.45	0.10	0.012	0.007	-	0.009	0.02	0.007	0.0048
e	0.32	0.16	0.46	3.22	1.59	0.48	0.10	0.008	0.007	-	0.010	0.01	0.007	0.0055
f	0.23	0.07	0.28	3.04	1.56	0.34	0.11	0.003	0.004	0.0013	0.003	0.01	0.001	0.0040
g	0.32	0.24	0.43	3.29	1.62	0.45	0.10	0.012	0.007	-	0.010	0.02	0.006	0.0051
h	0.34	0.21	1.00	3.01	1.61	0.50	0.10	0.037	0.007	-	0.010	0.01	0.007	0.0053
i	0.345	0.05	0.32	1.61	1.51	0.50	0.15	0.044	0.005	-	0.004	0.01	0.008	0.005
j	0.32	0.07	0.32	3.72	1.66	0.38	0.10	-	0.008	-	0.007	-	-	-
k	0.35	0.25	0.95	3.04	0.21	0.50	0.11	0.025	0.006	-	0.007	0.01	0.007	0.0063
l	0.38	0.21	1.04	3.05	3.01	0.52	0.14	0.008	0.006	-	0.005	0.01	0.006	0.0072
m	0.35	0.26	1.01	2.98	1.62	0.50	<0.01	0.020	0.007	-	0.010	0.03	0.008	0.0064
n	0.35	0.19	0.28	1.61	1.61	0.51	0.15	0.027	0.005	-	0.004	0.01	0.008	0.0050
o	0.33	0.27	0.64	1.63	1.63	0.25	0.15	0.004	0.002	-	0.007	0.03	0.001	0.0058
p	0.40	0.24	0.97	0.41	1.97	0.27	0.08	0.003	0.003	0.0009	0.006	0.03	0.007	0.0054
q	0.33	0.30	0.43	0.17	3.01	0.47	0.078	0.028	0.0005	-	0.007	0.03	0.001	0.0064

[0068] The ingot (70 ton) of the steel type a was hot forged to form round-bar-shaped forgings having a diameter of 500 mm. Steel types b to q were forged to a size of 90 mm × 90 mm × 600 mm, and thereafter cooled in the atmosphere. Each forging of the steel types a to q was cooled to room temperature, and thereafter a small piece having a size of 20 mm × 20 mm × 180 mm was cut out from each forging. Each small piece was thermally treated in the conditions shown in Table 2 that simulated a forging process of a crankshaft, and each of the treated small pieces was cooled in the furnace to prepare specimens.

[0069] Thereafter, thermal refining treatment (quenching and tempering treatment) was performed for each specimen in order to ensure strength of the crankshaft. The quenching treatment was performed in quenching conditions that simulated a heating and cooling rate of a crankshaft having a diameter of 500 mm. Specifically, the quenching treatment was performed in a manner that, using a small simulating furnace, the temperature was raised to 870°C to 940°C in a heating rate of 40°C/hour and this temperature was maintained for 3 hours to 8 hours, and thereafter the specimens were cooled so that an average cooling rate in a temperature range of 870°C to 500°C was 20°C/minute to 50°C/minute. In the tempering treatment, the specimens were maintained at a temperature of 560°C to 610°C for 13 hours and cooled in the furnace (treatment conditions for each specimen are shown in Table 2). The specimens (steel forgings) of Examples 1 to 13 and Comparative Examples 1 to 14 were obtained by the methods as described above.

[Table 2]

	Steel type	Heating conditions for forging		Heat treatment conditions				
				Quenching conditions			Annealing conditions	
		Temperature (°C)	Maintained time (Hr)	Temperature (°C)	Maintained time (Hr)	Cooling rate (°C/min)	Temperature (°C)	Maintained time (Hr)
Example 1	a	1280	9	870	3	20	560	13
Exarnple 2	a	1280	9	870	3	20	580	13
Example 3	a	1280	3	870	8	50	590	13
Example 4	a	1310	3	870	8	50	580	13
Example 5	a	1280	9	870	3	50	580	13
Example 6	a	1280	9	870	3	50	600	13
Example 7	a	1280	9	870	3	50	610	13
Example 8	a	1280	9	920	3	50	590	13
Example 9	a	1280	9	940	3	50	580	13
Example 10	b	1280	3	870	3	20	580	13
Example 11	c	1280	3	870	3	20	580	13
Example 12	d	1280	3	870	3	20	580	13
Example 13	e	1280	3	870	3	20	580	13
Comparative Example 1	f	1230	3	870	3	20	590	13
Comparative Example 2	g	1230	3	870	3	20	580	13
Comparative Example 3	h	1280	3	870	3	20	580	13
Comparative Example 4	i	1280	3	870	3	20	580	13
Comparative Example 5	J	1280	3	870	3	20	580	13

(continued)

	Steel type	Heating conditions for forging		Heat treatment conditions				
				Quenching conditions			Annealing conditions	
		Temperature (°C)	Maintained time (Hr)	Temperature (°C)	Maintained time (Hr)	Cooling rate (°C/min)	Temperature (°C)	Maintained time (Hr)
Comparative Example 6	k	1280	3	870	3	20	580	13
Comparative Example 7	l	1280	3	870	3	20	580	13
Comparative Example 8	m	1280	3	870	3	20	580	13
Comparative Example 9	n	1280	3	870	3	50	600	13
Comparative Example 10	o	1200	1	870	3	20	580	13
Comparative Exampie 11	o	1200	1	870	3	20	610	13
Comparative Example 12	p	1200	1	870	3	20	580	13
Comparative Example 13	p	1200	1	870	3	20	610	13
Comparative Example 14	q	1200	1	870	3	20	590	13
Comparative Example 15	a	1280	9	960	3	20	610	13
Comparative Example 16	a	1280	9	1050	3	20	612	13
Comparative Example 17	b	1230	3	960	3	20	580	13

[0070] Each state of the micro-structures (martensitic structures (M) or bainitic structures (B)) of the specimens in Example 1 to 13 and Comparative Example 1 to 14 was observed. In addition, the prior austenite grain size, the martensitic block size, the tensile properties, the Charpy absorbed energy, and the fatigue properties (the fatigue strength FS and the endurance limit) were evaluated by the measurement method described above. The measurement result is shown in Table 3.

[0071] Here, "-" in Table 3 represents that the property was not measured.

[Table 3]

	Structure							Property									Comprehensive evaluation	
	Microstructure e	Prior γ grain size		Minimum block size (μm)	Maximum block size (μm)	Related figure	Structure evaluation	Tensile					Charpy		Fatigue			
		Minimum (μm)	Maximum (μm)					YS (MPa)	TS (MPa)	EL (%)	RA (%)	Evaluation	vE (J)	vE evaluation	FS (MPa)	Endurance limit		
Example 1	M	26	53	-	-	-	○	1084	1202	16.0	61.3	○	71	○	-	-		○
Example 2	M	26	53	-	-	-	○	1014	1130	163	61.6	○	123	○	524	0.464		○
Example 3	M	19	37	-	-	-	○	1052	1153	156	604	○	108	○	-	-		○
Example 4	M	26	53	05	105	Fig. 5	○	1103	1195	130	51.1	○	85	○	562	0470		○
Example 5	M	26	44	-	-	-	○	1097	1206	172	6369	○	102	○	-	-		○
Example 6	M	26	44	-	-		○	1047	1153	17.4	65.6	○	111	○	-	-		○
Example 7	M	26	44	-	-	-	○	946	1058	157	67.3	○	125	○	563	0.532		○
Example 8	M	37	63	-	-	-	○	1000	1102	159	584	○	126	○	-	-		○
Example 9	M	44	63	-	-	-	○	1019	1101	171	65.5	○	132	○	-	-		○
Example 10	B+M	44	63	-	-	-	○	1005	1143	163	621	○	59	○	-	-		○
Example 11	M	53	63	0.5	13.5	Fig.6	○	1073	1191	170	60.8	○	64	○		-		○
Example 12	B+M	37	62	-	-	-	○	931	1064	185	63.1	○	75	○	-	-		○
Example 13	M	53	63	-	-	-	○	938	1066	17.3	615	○	76	○	-	-		○
Comparative Example 1	B	26	53	-	-	-	○	891	1015	165	612	×	113	○	-	-	Insufficient strength	×
Comparative Example 2	M	44	125	-	-	-	×	976	1118	165	61.0	○	29	×	-	-	Insufficient toughness	×
Comparative Example 3	M	105	250	05	24.5	Fig. 7	×	943	1072	14.1	48.4	○	20	×	-	-	Insufficient toughness	×

(continued)

	Structure							Property									Comprehensive evaluation	
	Micro struc-ture e	Prior γ grain size		Mini-mum block size (μm)	Maxi-mum block size (μm)	Relat-ed fig-ure	Structure evalua-tion	Tensile					Charpy		Fatigue			
		Mini-mum (μm)	Maxi-mum (μm)					YS (MPa)	TS (MPa)	EL (%)	RA (%)	Evalua-tion	vE (J)	vE evalu-ation	FS (MPa)	Endur-ance limit		
Compara-tive Exam-ple 4	M	22	44	-	-	-	○	1047	1172	136	554	○	29	×	-	-	Insuffi-cient tough-ness	×
Compara-tive Exam-ple 5	M	44	88	-	-	-	×	Insufficient grain size										×
Compara-tive Exam-ple 6	B	26	63	-	-	-	○	939	1067	173	58.7	○	23	×	-	-	Insuffi-cient tough-ness	×
Compara-tive Exam-ple 7	M	149	250	05	20.5	Fig. 8	×	1000	1149	13.3	48.7	○	42	×	-	-	Insuffi-cient tough-ness	×
Compara-tive Exam-ple 8	M	31	74	-	-	-	×	887	1029	184	636	×	77	○	-	-	Insuffi-cient strength	×
Compara-tive	B+M	19	149	05	175	Fig. 9	×	1034	1136	16.1	59.4	○	42	×	-	-	Insuffi-cient	×
Example 9																	tough-ness	
Compara-tive Ex-ampe 10	B	26	63	-	-	-	○	966	1103	17.0	56.9	○	34	×	-	-	Insuffi-cient tough-ness	×

(continued)

	Structure							Property									Comprehensive evaluation	
	Micro struc-ture e	Prior γ grain size		Mini-mum block size (μm)	Maxi-mum block size (μm)	Relat-ed fig-ure	Structure evalua-tion	Tensile					Charpy		Fatigue			
		Mini-mum (μm)	Maxi-mum (μm)					YS (MPa)	TS (MPa)	EL (%)	RA (%)	Evalua-tion	vE (J)	vE evalu-ation	FS (MPa)	Endur-ance limit		
Compara-tive Exam-ple 11	B	26	63	-	-	-	○	833	963	182	65.1	×	56	○	458	0476	Insuffi-cient strength	×
Compara-tive Exam-ple 12	B	26	37	-	-	-	○	919	1078	16.3	603	○	19	×	-	-	Insuffi-cient tough-ness	×
Compara-tive Exam-ple 13	B	26	37	-	-	-	○	805	964	182	652	×	64	○	465	0.482	Insuffi-cient strength	×
Compara-tive Exam-ple 14	B	26	44	-	-	-	○	857	1012	16.1	63.5	×	45	×	-	-	Insuffi-cient strength and tough-ness	×
Compara-tive Exam-ple 15	M	63	177	-	-	-	×	980	1095	12.1	43.8	○	25	×	-	-	Insuffi-cient tough-ness	×
Compara-tive Exam-ple 16	M	88	250	-	-	-	×	987	1143	12.6	33.4	○	17	×	-	-	Insuffi-cient tough-ness	×
Compara-tive Exam-ple 17	B+M	63	105	-	-	-	×	1093	1201	152	48	○	22	×	-	-	Insuffi-cient tough-ness	×

[0072] Fig. 2 illustrates a relationship between a maximum size of the martensitic block and the Charpy absorbed energy measured by using the specimens of Examples and Comparative Examples. Fig. 3 illustrates a relationship between the tensile strength and the Charpy absorbed energy measured by using the specimens of Examples and Comparative Examples. Fig. 4 illustrates a relationship between the tensile strength and the fatigue strength measured by using the specimens of Examples and Comparative Examples.

[0073] Inverse pole figure maps of the specimens of Example 4, Example 11, Comparative Example 3, Comparative Example 7, and Comparative Example 9 are illustrated in Fig.5, Fig. 6, Fig. 7, Fig. 8, and Fig. 9, respectively.

[Discussion]

[0074] Examples 1 to 13, in which both compositions and manufacturing conditions of the steels satisfy the requirements of the present invention, provided steel forgings having desired properties. Comparative Examples 1 to 14, in which the compositions of the steels did not satisfy the requirements of the present invention, did not provide the steel forgings having desired properties. Comparative Examples 15 to 17, in which, although the compositions of the steels satisfied the requirements of the present invention, the prior austenite grain size did not satisfy the requirements of the present invention because of inadequate quenching temperature, did not provide steel forgings having desired properties.

[0075] As illustrated in Fig. 2, it is found that a maximum block size of martensite of 15μm or less provides excellent toughness (Charpy absorbed energy). As illustrated in Fig. 3, it is found that the high strength steel for the large steel forging has excellent toughness (an impact property) even when the high strength steel for the large steel forging has higher strength (a strength of 1,050 MPa or more) than the strength of conventional steel. Generally, a material having higher strength has lower toughness. However, a high strength large steel forging having excellent strength and toughness in a balanced manner (for example, a strength of 1,050 MPa or more) can be provided by optimizing chemical components and metal structures.

[0076] Fig. 4 illustrates a relationship between the tensile strength and the fatigue strength. The fatigue strength of the steel forging of the present invention increases about 10% or more compared with that of the conventional steel. The endurance limit (= fatigue strength/tensile strength) is equal to the conventional steel, and the proportional relationship between the tensile strength and the fatigue strength is maintained. In other words, increase in notch sensitivity associated with higher strength is not observed.

[Analysis example]

[0077] A heat transfer and thermal stress analysis for the transformation stress in a steel by quenching was performed using general-purpose software FORGE 2009. Specific conditions are as follows. Assuming a round-bar shape, modeling was performed by using a two-dimensional axisymmetric model. In an axis direction, the modeling was performed in only a unit length, and the upper surface and the lower surface were determined to be an adiabatic state. The heat transfer and thermal stress analysis was performed in conditions that the initial temperature was uniformly set to 870°C and the temperature was cooled to around room temperature. Each material property used in the analysis is illustrated in Figs. 10 to 12. The following analysis conditions A and B were used in the analysis.

(Analysis conditions A)

[0078] As illustrated by a dashed line in Fig. 13A, a structure fraction in the round-bar steel in which 100% of the martensitic structure exists in a ratio of a depth to a distance from the surface to the center part from 0 to 0.35 and 95% of the martensitic structure and 5% of the bainitic structure exist at the center part

(Analysis conditions B)

[0079] As illustrated by a solid line in Fig. 13A, a structure fraction in the round-bar steel in which 100% of the martensitic structure exists in a ratio of a depth to a distance from the surface to the center part from 0 to 0.1 and 100% of the bainitic structure exists at the center part

[0080] The analysis results in the analysis conditions A and B are illustrated in Fig. 13B. As illustrated in this Fig. 13B, the analysis conditions A result in larger internal transformation stress. The analysis conditions B cause residual stress at a position in a ratio of depth of about 0.2. A structure fraction between the analysis conditions A and B enables to control whole internal stress from the surface to the center in low stress.

[Reference Example 1]

[0081] A seventy-ton ingot of the steel type a having component compositions shown in Table 1 described above was casted by melting in an electric furnace and refining in a ladle. The ingot (70 ton) of the steel type a was hot forged by a free forging press to form round-bar-shaped forgings having a diameter of 500 mm (a radius of 250 mm), and thereafter, the round bar was cooled in the atmosphere. The round-bar forgings were treated with heat of 1,280°C for 3 hours, which simulated heating before RR forging. Before quenching and tempering treatment, aging treatment for the round-bar forgings was performed (maintaining at a temperature of 650°C for 20 hours), and the round-bar-shaped forgings were cooled to room temperature. The quenching conditions were as follows. The round-bar forgings were heated in a heating rate of 40°C/hour and maintained at 870°C for 8 hours, and thereafter, polymer quenching was performed. Thereafter, the round-bar forgings were maintained at 580°C for 15 hours as the tempering treatment and cooled in the furnace to 350°C, and thereafter, the round-bar forgings were air-cooled to room temperature to obtain a high strength large steel forging of Reference Example 1.

[0082] The obtained high strength large steel forging was ground so that a part of each depth in a direction from the surface to the center (25 mm, 40 mm, 70 mm, 100 mm, 130 mm, 160 mm, 190 mm, 220 mm and 250 mm) forms a surface. Brinell hardness HB, tensile strength (MPa), structure fraction (%), and prior austenite (γ) grain size (μm) at each depth were measured. The tensile strength of the high strength large steel forging in Reference Example 1 is a converted value calculated from the measured Brinell hardness HB in accordance with the hardness conversion table (SAE J 417). Methods for measuring and calculating Brinell hardness and a fraction of a martensitic structure are as follows. The measurement result is shown in Table 4 together with heating treatment conditions at the time of manufacture.

Brinell hardness

[0083] The Brinell hardness was measured in accordance with JIS-Z2243 (2008).

Fraction of martensitic structure (%)

[0084] The fraction of martensitic structure was calculated from the measurement result of the hardness (Brinell hardness: HB) using the following formula derived from the rule of mixtures. Structures other than the martensitic structure were determined as the bainitic structure, and a bainitic structure fraction (%) was also calculated.

$$HB = HB_M \times f_m(x)/100 + HB_B \times (1 - f_m(x)/100)$$

$f_m(x)$: Fraction of martensitic structure (%)
HB_M: Brinell hardness of martensite
(Actual measured value of the part of full martensite: 368)
HB_B: Brinell hardness of bainite
(Actual measured value of the part of full bainite: 352)

[Table 4]

	Steel type	Heating conditions for forging		Heat treatment conditions							Position		Properties		Structure		
				Aging treatment conditions		Quenching conditions			Annealing conditions				Brinell hardness HB	Tensile strength (Converted value) (MPa)	Fraction of structure		Prior γ grain size (μm)
		Temperature (°C)	Maintained time (Hr)	Temperature (°C)	Maintained time (Hr)	Temperature (°C)	Maintained time (Hr)	Cooling medium	Temperature (°C)	Maintained time (Hr)	Depth (mm)	Ratio (x)			martensite	bainite	
Reference Example 1	A	1,280	3	650	20	870	8	Polymer solution	580	15	25	0.10	368	1,130	100%	0%	35
											40	0.16	368	1,130	100%	0%	31
											70	0.28	367	1,127	94%	6%	35
											100	0.40	365	1,121	81%	19%	[illegible]
											130	0.52	361	1,109	56%	44%	[illegible]
											160	0.64	358	1,100	38%	62%	44
											190	0.76	356	1,094	25%	75%	41
											220	0.88	352	1,083	0%	100%	45
											250	1.00	352	1,083	0%	100%	43

[0085] A relationship between each depth and Brinell hardness of the high strength large steel forging in the reference Example 1 is illustrated in Fig. 14A and a relationship between each depth and a fraction of a martensitic structure is illustrated in Fig. 14B.

[0086] A high strength large steel forging of the present invention has both excellent strength and toughness, and has high fatigue strength. Consequently, the high strength large steel forging can preferably be used for large size crankshafts and intermediate shafts used for ships or power generators.

Claims

1. A high strength large steel forging comprising:

compositions comprising
basic compositions comprising:

C: 0.31% by mass or more and 0.5% by mass or less,
Si: 0.02% by mass or more and 0.2% by mass or less,
Mn: 0.1% by mass or more and 0.6% by mass or less,
Ni: 2.6% by mass or more and 3.4% by mass or less,
Cr: 0.8% by mass or more and 1.9% by mass or less,
Mo: 0.25% by mass or more and 0.8% by mass or less,
V: 0.05% by mass or more and 0.2% by mass or less, and
Al: 0.005% by mass or more and 0.1% by mass or less, and
a remainder comprising Fe and unavoidable impurities;
wherein a content S as the unavoidable impurity is 0.008% by mass or less; and
wherein the high strength large steel forging consists of a martensitic structure or a mixed structure of martensite and bainite;
a grain size of prior austenite is 19 μm or more and 70 μm or less; and
a maximum block size of martensite is 15 μm or less and a minimum block size of martensite is 0.5 μm or more.

2. The high strength large steel forging according to claim 1, wherein a fraction of martensitic structure $f_m(x)$ (%) where a ratio of a depth to a distance from a surface to a center is defined as x ($0 \le x \le 1$) is

$f_m(x) = 100$, where $0 \le x \le 0.1$;
$104-40x \le f_m(x) \le 100$, where $0.1 < x \le 0.15$;
$122-160x \le f_m(x) \le 100$, where $0.15 < x \le 0.2$;
$230-700x \le f_m(x) \le 100$, where $0.2 < x \le 0.3$;
$110-300x \le f_m(x) \le 112-40x$, where $0.3 < x \le 0.35$; $(22-20x)/3 \le f_m(x) \le 105-20x$, where $0.35 < x \le 0.5$;
$(32-40x)/3 \le f_m(x) \le 95$, where $0.5 < x \le 0.8$; and
$0 \le f_m(x) \le 95$, where $0.8 < x \le 1$.

Patentansprüche

1. Große Stahlschmiede mit hoher Festigkeit, umfassend:

Zusammensetzungen, umfassend Grundzusammensetzungen, umfassend:

C: 0,31 Masse-Prozent oder mehr und 0,5 Masse-Prozent oder weniger,
Si: 0,02 Masse-Prozent oder mehr und 0,2 Masse-Prozent oder weniger,
Mn: 0,1 Masse-Prozent oder mehr und 0,6 Masse-Prozent oder weniger,
Ni: 2,6 Masse-Prozent oder mehr und 3,4 Masse-Prozent oder weniger,
Cr: 0,8 Masse-Prozent oder mehr und 1,9 Masse-Prozent oder weniger,
Mo: 0,25 Masse-Prozent oder mehr und 0,8 Masse-Prozent oder weniger,
V: 0,05 Masse-Prozent oder mehr und 0,2 Masse-Prozent oder weniger, und
Al: 0,005 Masse-Prozent oder mehr und 0,1 Masse-Prozent oder weniger, und
wobei der Rest Fe und unvermeidbare Verunreinigungen umfaßt,
wobei ein Gehalt an S als die unvermeidbare Verunreinigung 0,008 Masse-Prozent oder weniger beträgt, und
wobei die großen Stahlschmiede mit hoher Festigkeit aus einer martensitischen Struktur oder einer ge-

mischten Struktur von Martensit und Bainit besteht,
eine Voraustenitkorngröße 19 μm oder mehr und 70 μm oder weniger beträgt, und
eine Maximalblockgröße an Martensit 15 μm oder weniger beträgt und eine Minimalblockgröße an Martensit 0,5 μm oder mehr beträgt.

2. Große Stahlschmiede mit hoher Festigkeit gemäß Anspruch 1, wobei eine Fraktion der martensitischen Struktur $f_m(x)$ (%), worin ein Verhältnis einer Tiefe zu einem Abstand von einer Oberfläche zu einem Zentrum als x ($0 \leq x \leq 1$) definiert ist, ist

$f_m(x) = 100$, worin $0 \leq x \leq 0{,}1$;
$104\text{-}40x \leq f_m(x) \leq 100$, worin $0{,}1 < x \leq 0{,}15$,
$122\text{-}160\ x \leq 100$, worin $0{,}15 < x \leq 0{,}2$,
$230\text{-}700\ x \leq f_m(x) \leq 100$, worin $0{,}2 < x \leq 0{,}3$;
$110\text{-}300\ x \leq f_m(x) \leq 112\text{-}40x$, worin $0{,}3 < x \leq 0{,}35$;
$(22\text{-}20x)3 \leq f_m(x) \leq 105\text{-}20x$, worin $0{,}35 < x \leq 0{,}5$;
$(32\text{-}40x)/3 \leq f_m(x) \leq 95$, worin $0{,}5 < x \leq 0{,}8$; und
$0 \leq f_m(x) \leq 95$, worin $0{,}8 < x \leq 1$.

Revendications

1. Pièce forgée de grande dimension en acier à haute résistance comprenant :

des compositions comprenant
des compositions de base comprenant :

C : entre 0,31% en masse ou plus et 0,5% en masse ou moins,
Si : entre 0,02% en masse ou plus et 0,2% en masse ou moins,
Mn : entre 0,1% en masse ou plus et 0,6% en masse ou moins,
Ni : entre 2,6% en masse ou plus et 3,4% en masse ou moins,
Cr : entre 0,8% en masse ou plus et 1,9% en masse ou moins,
Mo : entre 0,25% en masse ou plus et 0,8% en masse ou moins,
V : entre 0,05% en masse ou plus et 0,2% en masse ou moins, et
Al : entre 0,005% en masse ou plus et 0,1% en masse ou moins, et
un complément comprenant du Fe et des impuretés inévitables ;
dans laquelle une teneur en S en tant qu'impureté inévitable est inférieure ou égale à 0,008% en masse ; et
dans laquelle la pièce forgée de grande dimension en acier à haute résistance se compose d'une structure martensitique ou d'une structure mélangée à base de martensite et de bainite ;
une taille de grain de l'austénite antérieure est supérieure ou égale à 19 μm et inférieure ou égale à 70 μm ; et
une taille de bloc maximum de martensite est inférieure ou égale à 15 μm et une taille de bloc minimum de martensite est supérieure ou égale à 0,5 μm.

2. Pièce forgée de grande dimension en acier à haute résistance selon la revendication 1, dans laquelle une fraction de structure martensitique $f_m(x)$ (%), dans laquelle un rapport d'une profondeur sur une distance d'une surface à un centre est défini par x ($0 \leq x \leq 1$), est telle que :

$f_m(x) = 100$, lorsque $0 \leq x \leq 0{,}1$;
$104 - 40x \leq f_m(x) \leq 100$, lorsque $0{,}1 < x \leq 0{,}15$;
$122 - 160x \leq f_m(x) \leq 100$, lorsque $0{,}15 < x \leq 0{,}2$;
$230 - 700x \leq f_m(x) \leq 100$, lorsque $0{,}2 < x \leq 03$;
$110 - 300x \leq f_m(x) \leq 112 - 40x$, lorsque $0{,}3 < x \leq 0{,}35$;
$(22 - 20x)/3 \leq f_m(x) \leq 105 - 20x$, lorsque $0{,}35 < x \leq 0{,}5$;
$(32 - 40x)/3 \leq f_m(x) \leq 95$, lorsque $0{,}5 < x \leq 0{,}8$; et
$0 \leq f_m(x) \leq 95$, lorsque $0{,}8 < x \leq 1$.

FIG. 1

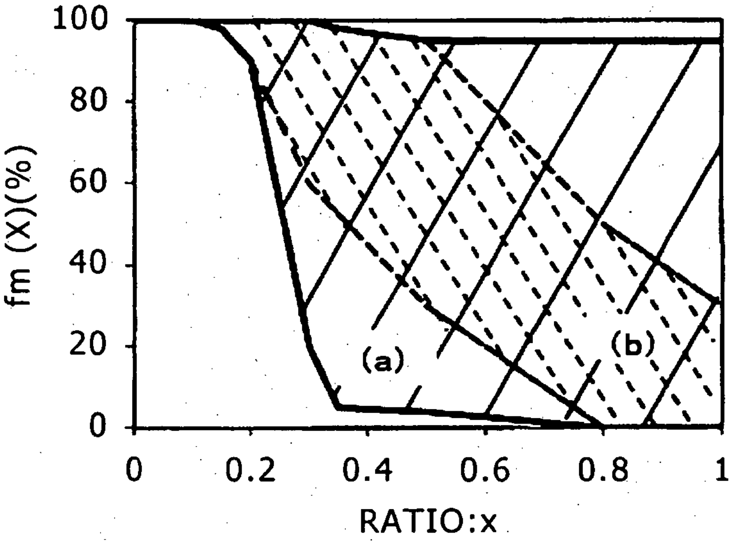


FIG. 2

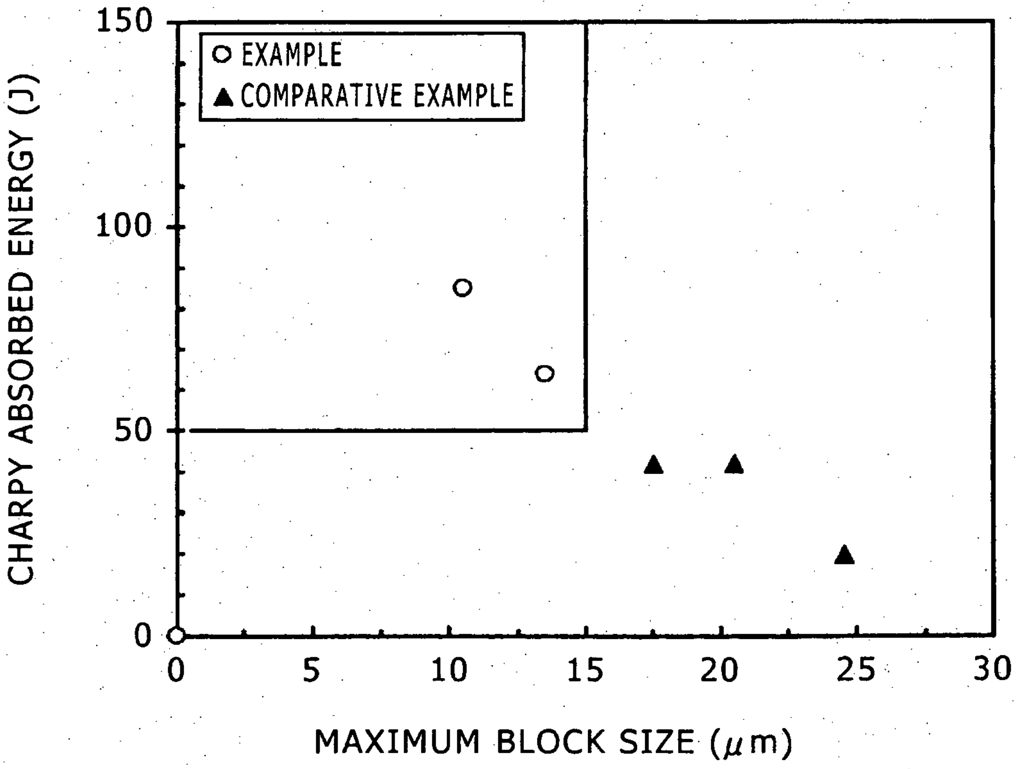

○ EXAMPLE
▲ COMPARATIVE EXAMPLE
CHARPY ABSORBED ENERGY (J)
150
100
50
0
0
5
10
15
20
25
30
MAXIMUM BLOCK SIZE (μm)

FIG. 3

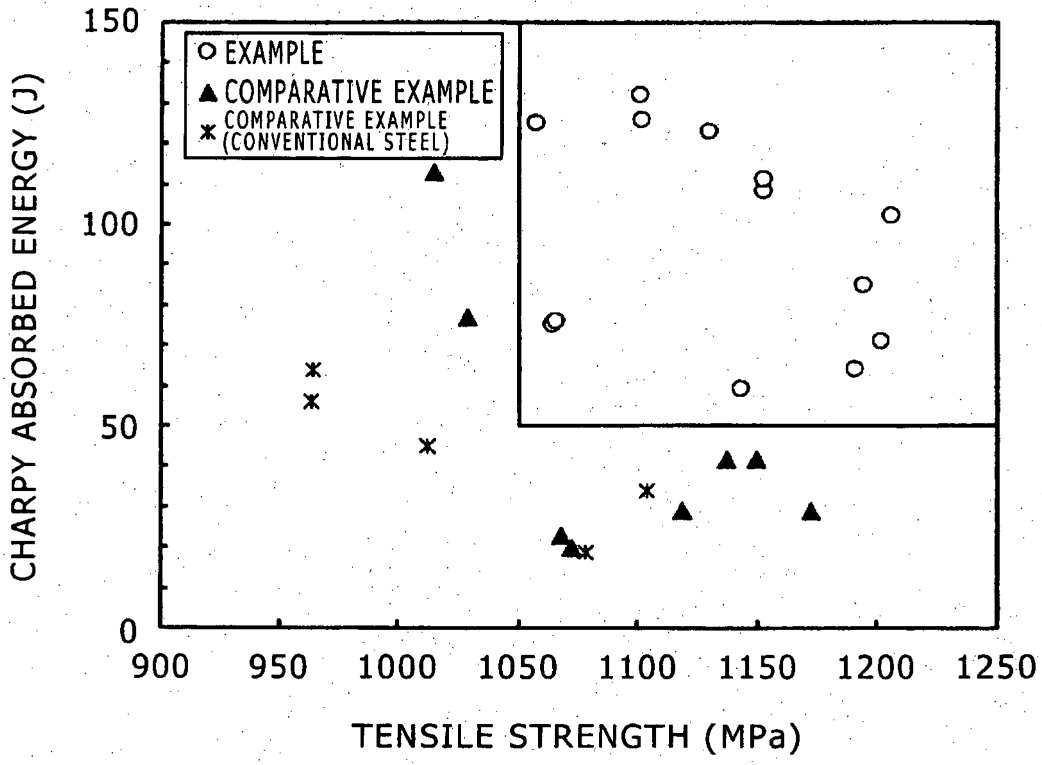

○ EXAMPLE
▲ COMPARATIVE EXAMPLE
✱ COMPARATIVE EXAMPLE (CONVENTIONAL STEEL)
CHARPY ABSORBED ENERGY (J)
0
50
100
150
TENSILE STRENGTH (MPa)
900
950
1000
1050
1100
1150
1200
1250

FIG.4

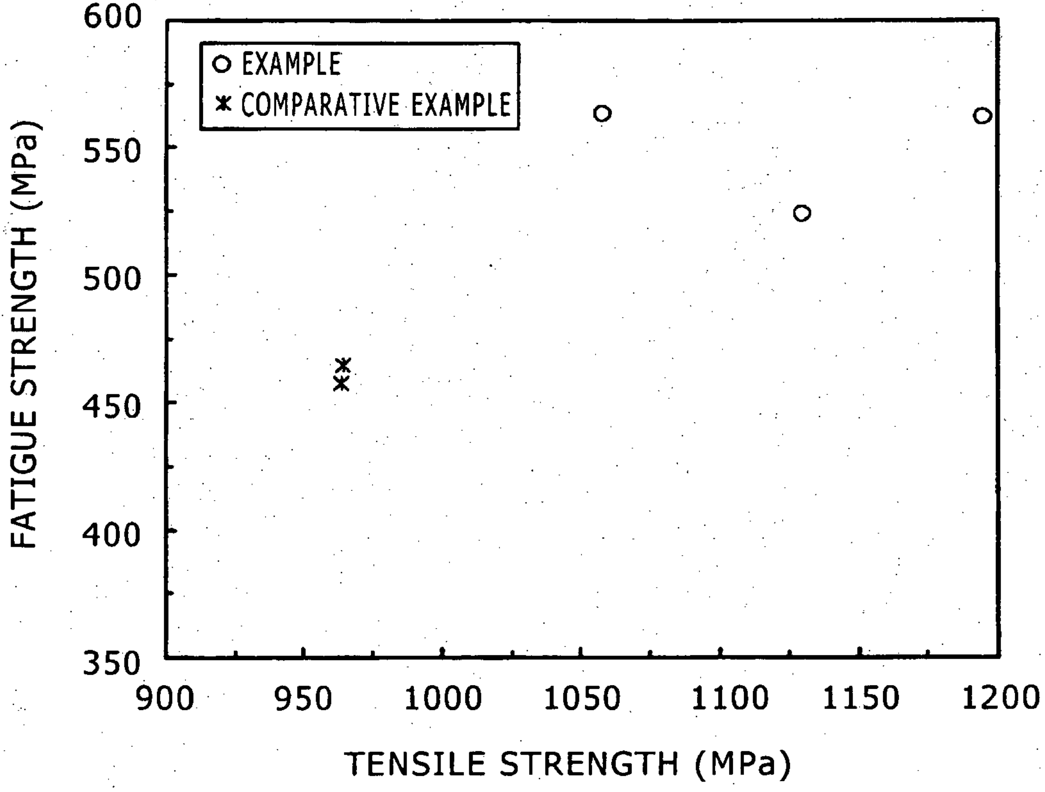

○ EXAMPLE
✱ COMPARATIVE EXAMPLE
FATIGUE STRENGTH (MPa)
600
550
500
450
400
350
900
950
1000
1050
1100
1150
1200
TENSILE STRENGTH (MPa)

FIG. 5

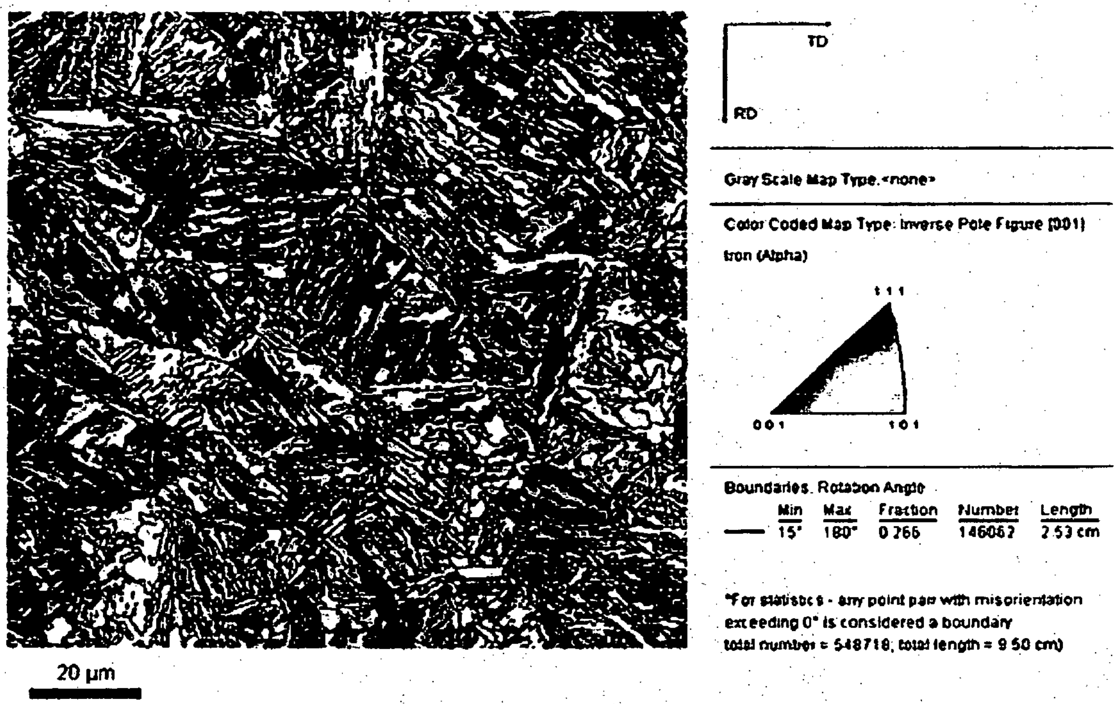
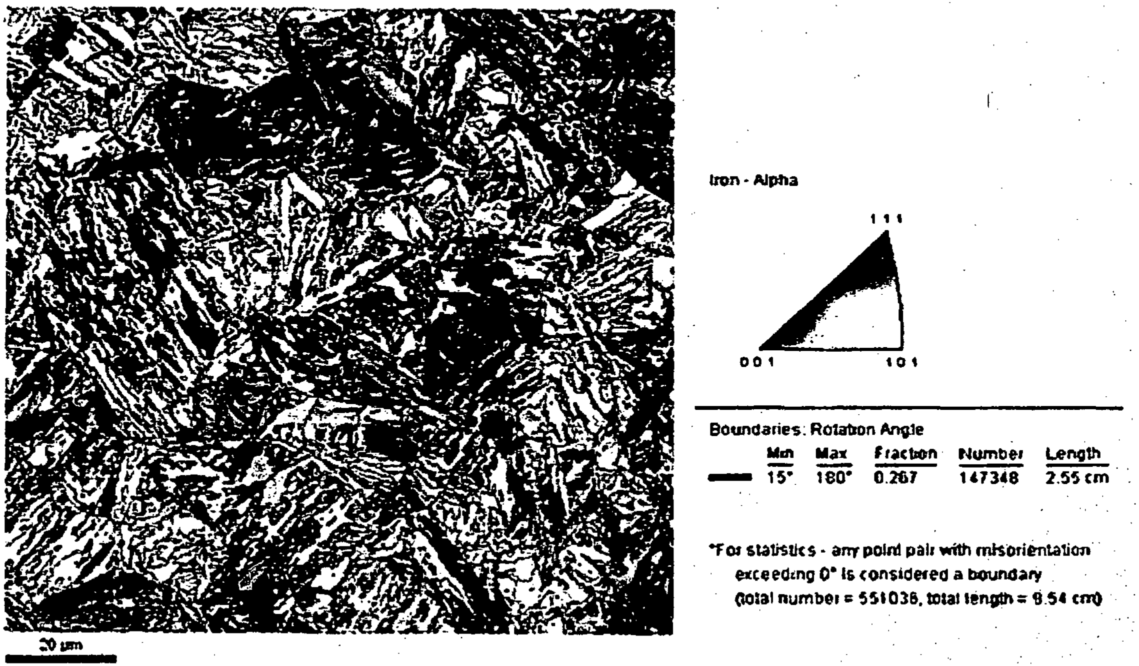

TD
RD
Gray Scale Map Type: <none>
Color Coded Map Type: Inverse Pole Figure [001]
Iron (Alpha)
111
001
101
Boundaries: Rotation Angle
Min Max Fraction Number Length
15° 180° 0.266 146062 2.53 cm
*For statistics - any point pair with misorientation
exceeding 0° is considered a boundary
total number = 548718, total length = 9.50 cm)
20 μm

FIG. 6



Boundaries: Rotation Angle

	Min	Max	Fraction	Number	Length
▬	15°	180°	0.267	147348	2.55 cm

*For statistics - any point pair with misorientation exceeding 0° is considered a boundary (total number = 551036, total length = 8.54 cm)

FIG. 7

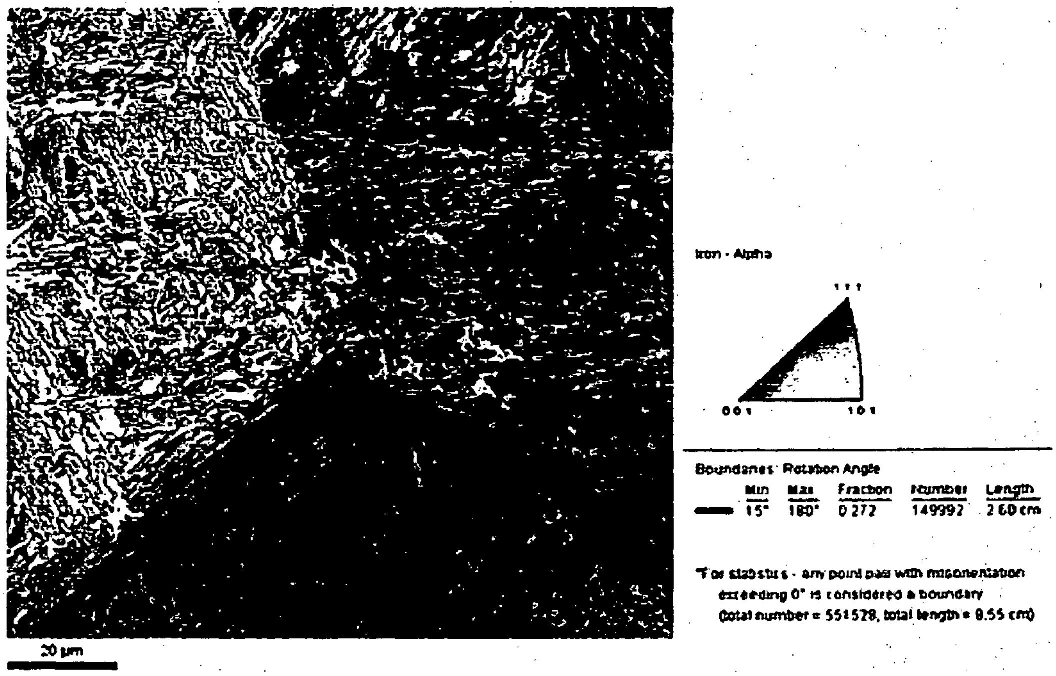
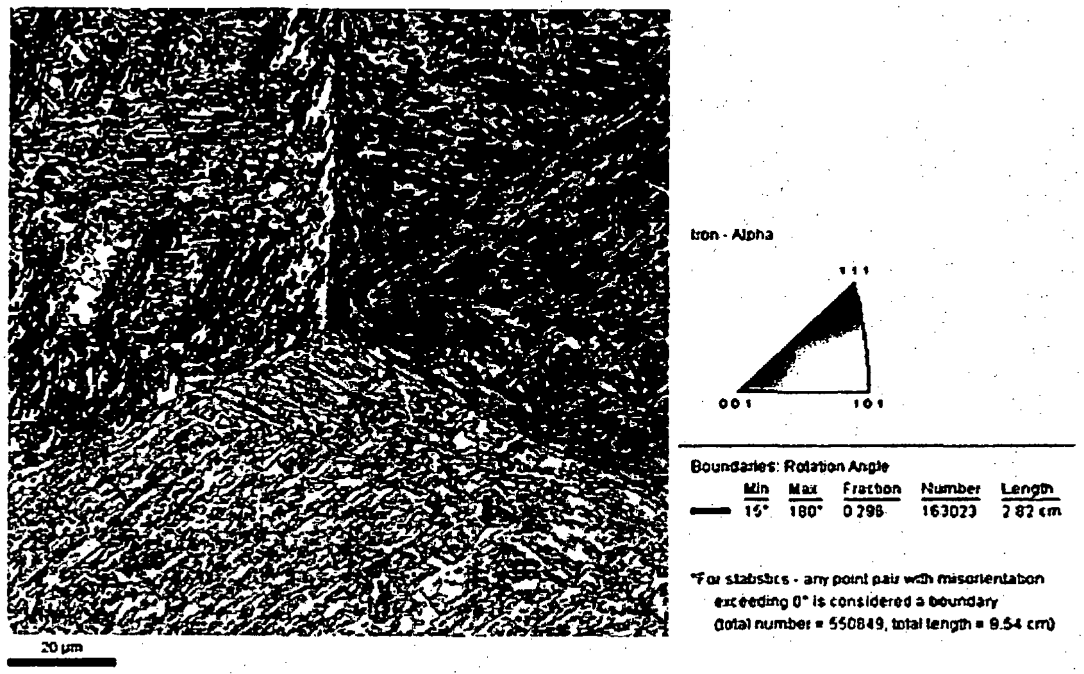

20 µm
Iron - Alpha
111
001
101
Boundaries: Rotation Angle
Min Max Fraction Number Length
15° 180° 0.272 149992 2.60 cm
*For statistics - any point pair with misorientation exceeding 0° is considered a boundary (total number = 551528, total length = 8.55 cm)

FIG. 8

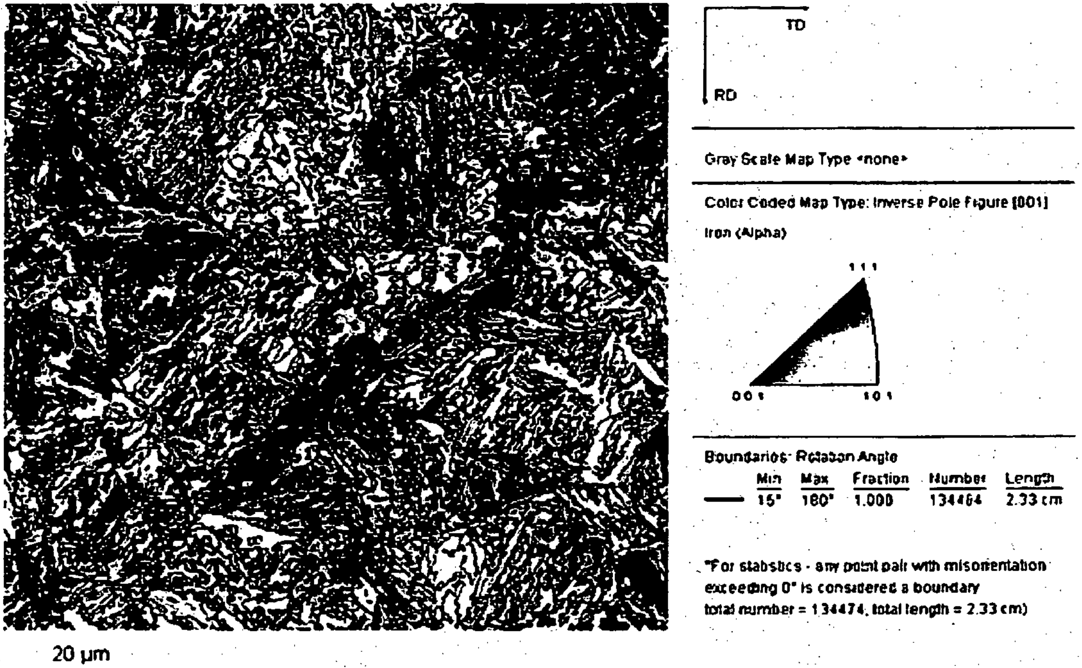


Boundaries: Rotation Angle

	Min	Max	Fraction	Number	Length
▬	15°	180°	0.298	163023	2.82 cm

*For statistics - any point pair with misorientation exceeding 0° is considered a boundary (total number = 550849, total length = 9.54 cm)

FIG. 9



Boundaries: Rotation Angle

	Min	Max	Fraction	Number	Length
—	15°	180°	1.000	134464	2.33 cm

*For statistics - any point pair with misorientation exceeding 0° is considered a boundary
total number = 134474, total length = 2.33 cm)

FIG.10

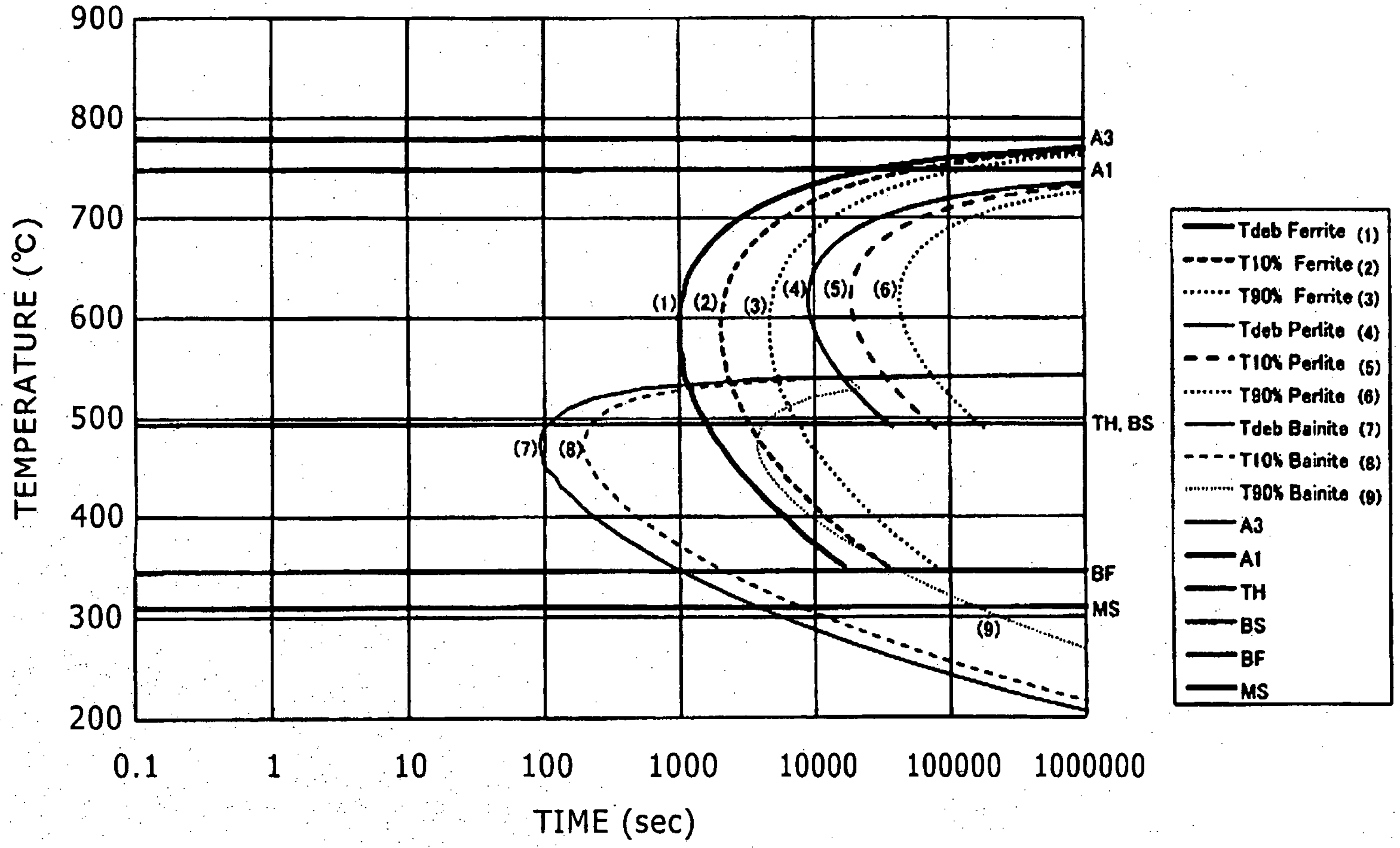

900
800
700
600
500
400
300
200
TEMPERATURE (°C)
0.1
1
10
100
1000
10000
100000
1000000
TIME (sec)
A3
A1
TH, BS
BF
MS
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)
(9)
Tdeb Ferrite (1)
T10% Ferrite (2)
T90% Ferrite (3)
Tdeb Perlite (4)
T10% Perlite (5)
T90% Perlite (6)
Tdeb Bainite (7)
T10% Bainite (8)
T90% Bainite (9)
A3
A1
TH
BS
BF
MS

FIG.11

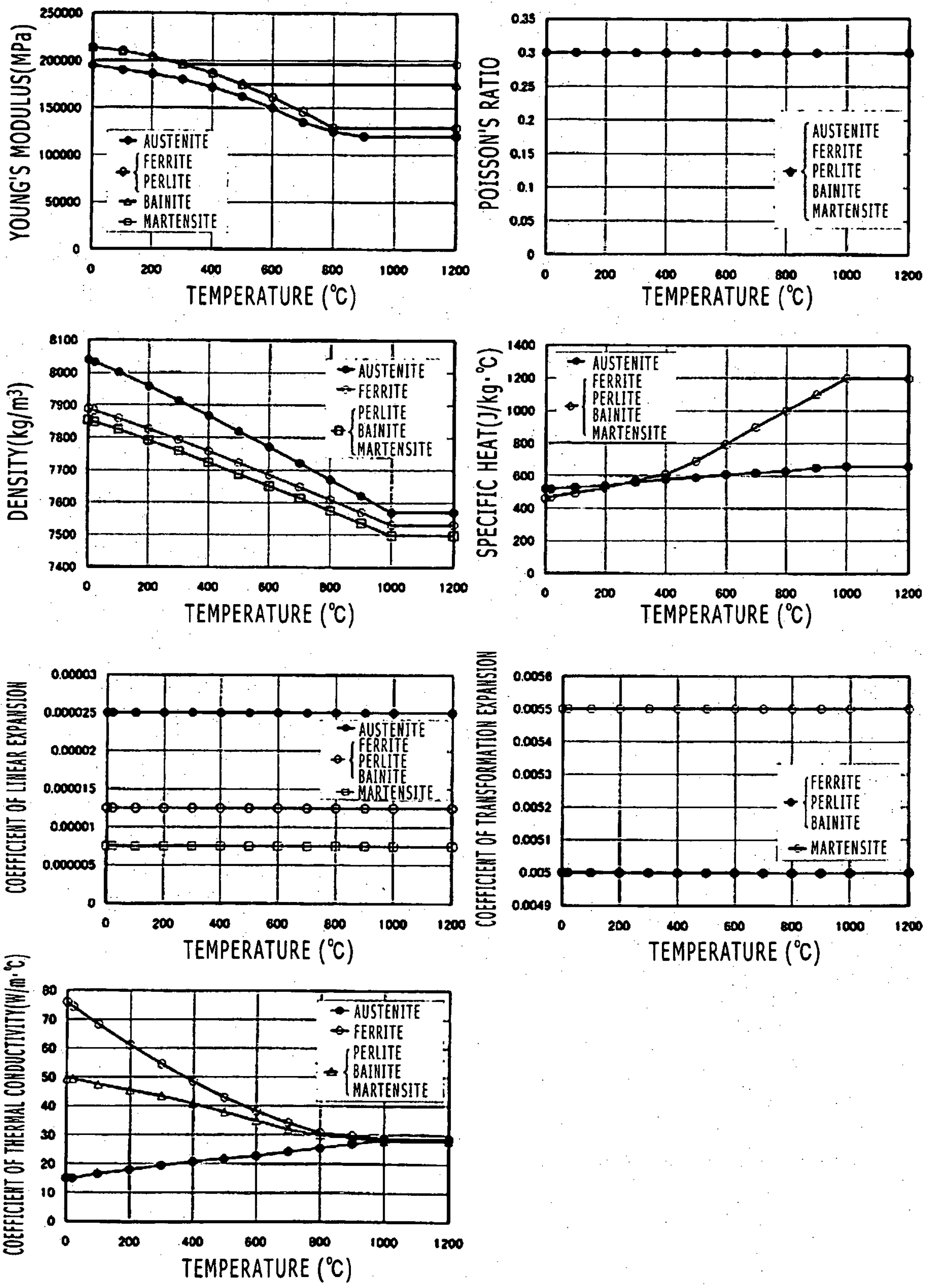
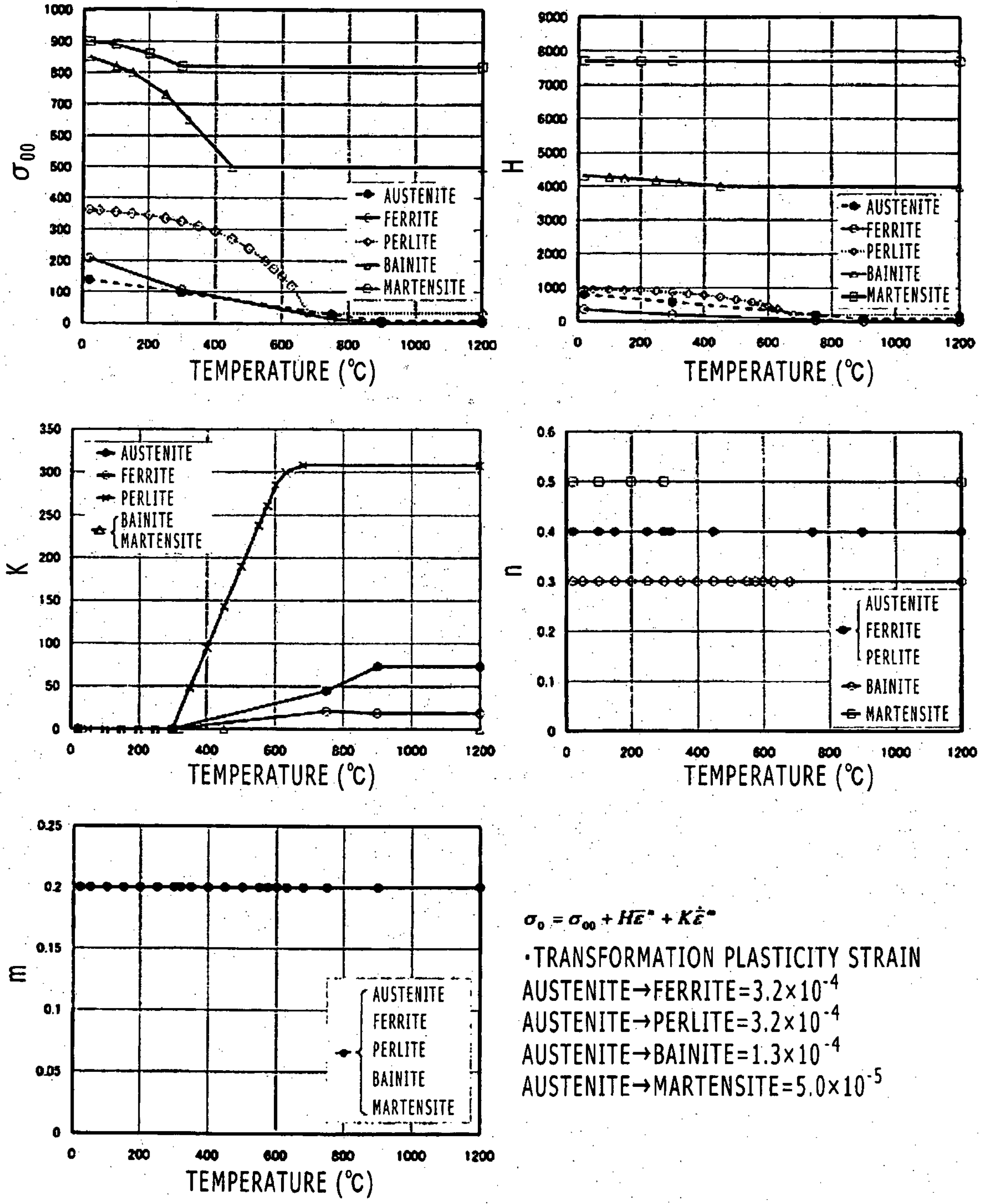

YOUNG'S MODULUS(MPa)
250000
200000
150000
100000
50000
0
0
200
400
600
800
1000
1200
TEMPERATURE (℃)
AUSTENITE
FERRITE
PERLITE
BAINITE
MARTENSITE
POISSON'S RATIO
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
TEMPERATURE (℃)
AUSTENITE
FERRITE
PERLITE
BAINITE
MARTENSITE
DENSITY(kg/m³)
8100
8000
7900
7800
7700
7600
7500
7400
TEMPERATURE (℃)
AUSTENITE
FERRITE
PERLITE
BAINITE
MARTENSITE
SPECIFIC HEAT(J/kg·℃)
1400
1200
1000
800
600
400
200
0
TEMPERATURE (℃)
AUSTENITE
FERRITE
PERLITE
BAINITE
MARTENSITE
COEFFICIENT OF LINEAR EXPANSION
0.00003
0.000025
0.00002
0.000015
0.00001
0.000005
0
TEMPERATURE (℃)
AUSTENITE
FERRITE
PERLITE
BAINITE
MARTENSITE
COEFFICIENT OF TRANSFORMATION EXPANSION
0.0056
0.0055
0.0054
0.0053
0.0052
0.0051
0.005
0.0049
TEMPERATURE (℃)
FERRITE
PERLITE
BAINITE
MARTENSITE
COEFFICIENT OF THERMAL CONDUCTIVITY(W/m·℃)
80
70
60
50
40
30
20
10
0
TEMPERATURE (℃)
AUSTENITE
FERRITE
PERLITE
BAINITE
MARTENSITE

FIG.12



$$\sigma_0 = \sigma_{00} + H\bar{\varepsilon}^n + K\dot{\bar{\varepsilon}}^m$$

·TRANSFORMATION PLASTICITY STRAIN
AUSTENITE→FERRITE=3.2×10^{-4}
AUSTENITE→PERLITE=3.2×10^{-4}
AUSTENITE→BAINITE=1.3×10^{-4}
AUSTENITE→MARTENSITE=5.0×10^{-5}

FIG.13A

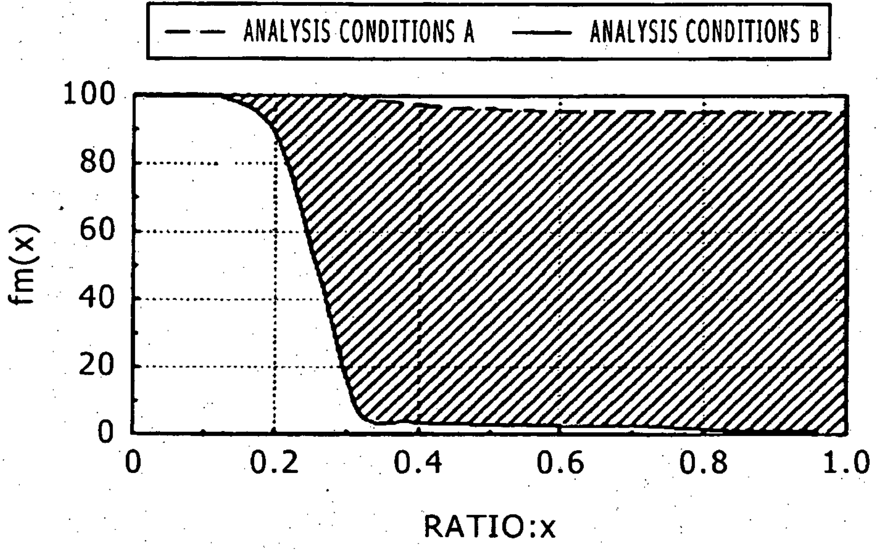


FIG.13B

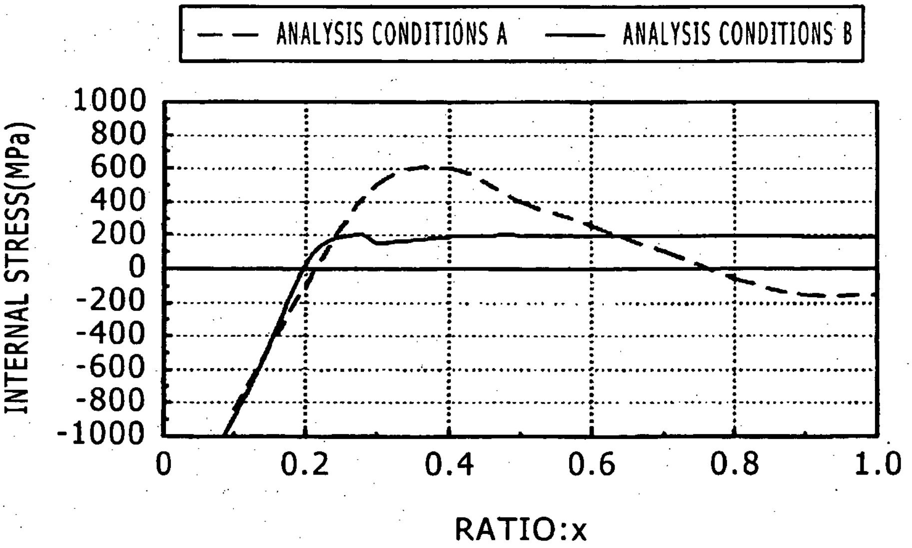


FIG.14A

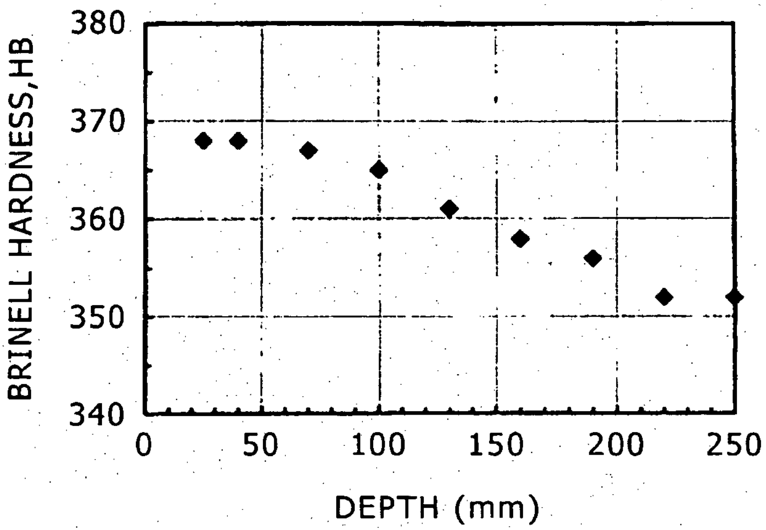
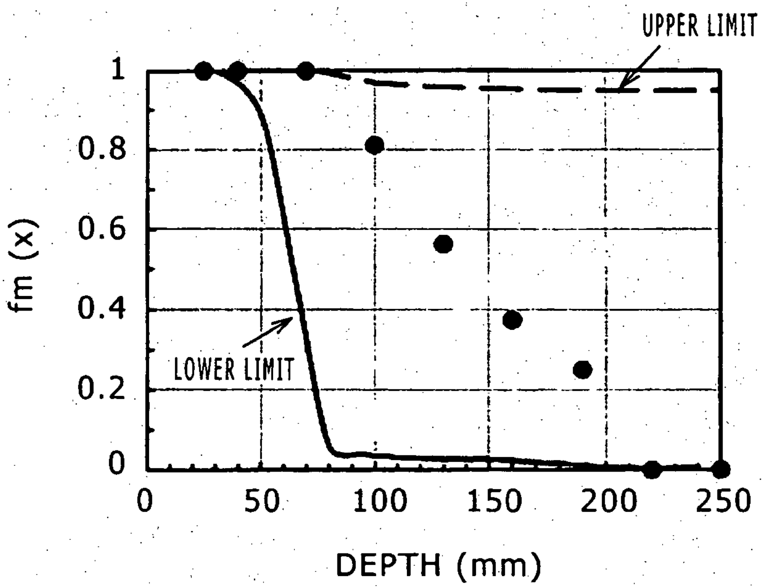


FIG.14B



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- JP 3896365 B **[0003]**
- JP 2010248540 A **[0003]**
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- JP 2009173961 A **[0003]**
- JP 2003147436 A **[0003]**