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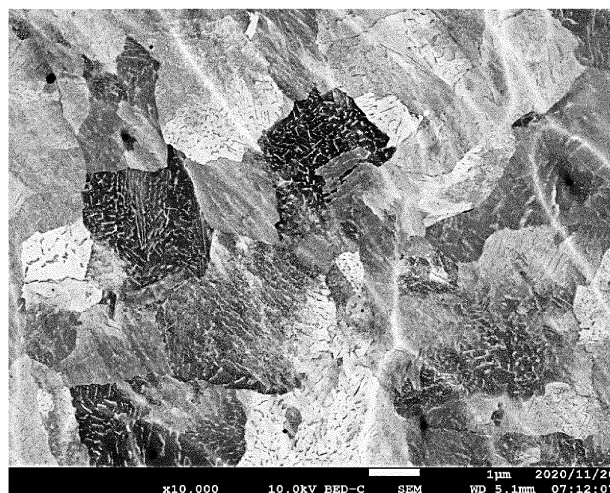
(54) **HEAT-TREATED STEEL MATERIAL AND HEAT TREATMENT METHOD FOR STEEL MATERIAL**

(57) To provide a heat-treated steel excellent in both tensile strength and toughness.

A heat-treated steel contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder

being Fe and unavoidable impurities, wherein an average crystal grain size at a grain boundary setting angle of 15° is $10 \times C + 7 (\mu\text{m})$ or less (wherein, C represents a carbon content (%)).

FIG.14



SWRH62A, DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 450°C: BSE IMAGE

Description

TECHNICAL FIELD

[0001] The present invention relates to a heat-treated steel and a heat treatment method for a steel.

BACKGROUND ART

[0002] Wires and wire ropes made by twisting multiple wires are made of steel, which is referred to as wire rods produced by hot rolling by steel manufacturers, such as specifically hard carbon steel wire rods (JIS G 3506) and piano wire rods (JIS G 3502). The wire rods such as hard carbon steel wire rods and piano wire rods produced by the steel manufacturers generally have large variations in tensile strength in a longitudinal direction, and in order to manufacture high-quality wires, wire ropes, and the like with stable quality in the longitudinal direction, heat treatment is performed on the wire rods. The wire rods produced by the steel manufacturers generally have a minimum diameter of about 5.5 mm. In order to manufacture finer wires, heat-treated wire rods are drawn. When the diameter of the wire rod is rapidly reduced by one wire drawing, the toughness may be deteriorated. To avoid this, heat treatment and wire drawing may be alternately performed multiple times.

[0003] The heat treatment performed on wire rods and wire drawn materials in order to provide stable quality is generally referred to as "patenting". In patenting, the wire rods and wire drawn materials before patenting (steels before heat treatment) are heated to a predetermined temperature, and the steels before heat treatment are then cooled by passing through a medium (for example, molten lead) heated to a predetermined temperature lower than the heating temperature. The patenting can produce the heat-treated steel (wire) having little variation in tensile strength in the longitudinal direction and having moderate toughness. For example, the heat-treated steel may be plated and then braided to be used as wire mesh or gabion, or the heat-treated steel may be drawn. The drawn heat-treated steel may be shipped as it is, or may be shipped after plating and coating. The multiple wires of the drawn heat-treated steel may be twisted to manufacture wire ropes, or may be further plated with brass to manufacture steel cords. In any case, patenting is a very important process in a process of manufacturing high-quality wires, wire ropes, steel cords, or the like.

[0004] In order to prevent troubles such as wire breakage during wire drawing, it is essential to achieve both the tensile strength and the toughness. Therefore, the heat-treated steel (steel before wire drawing, which is generally targeted for wire drawing) preferably has a structure referred to as pearlite in which ferrite and cementite (an intermetallic compound of Fe (iron) and C (carbon)) are alternately arranged in layers. Pearlite appears when the steel is heated as described above to have the crystal structure transformed from body-centered

cubic to face-centered cubic (austenitized) and the heated steel is rapidly cooled (see Patent Document 1, for example).

[0005] If the heating for obtaining the austenitized steel is insufficient, the cementite is not dissolved during heating, resulting in a decrease in the tensile strength of the heat-treated steel and a deterioration in the toughness of the steel after wire drawing. For example, when the steel to be heat-treated has the large thickness (diameter), a surface (surface layer) portion of the steel may be sufficiently heated, but a center (center layer) portion thereof may be insufficiently heated. In general, in order to avoid insufficient heating (to ensure complete austenitization), the steel is heated for a long period of time with a margin. Unfortunately, this may grow crystal grains (austenite grains) especially at the surface portion. The large crystal grain size may make a metallographic structure rough and reduce the toughness.

CITATION LIST

PATENT LITERATURE

[0006] PATENT LITERATURE 1: JP3599551 B2

SUMMARY OF INVENTION

TECHNICAL PROBLEM

[0007] An object of the present invention is to provide a heat-treated steel excellent in both tensile strength and toughness.

[0008] Another object of the present invention is to reduce heat radiated when a cooling medium tank is kept warm, thereby reducing the cost of fuel.

[0009] A further object of the present invention is to obtain a heat-treated steel having a wider range of tensile strength on the higher strength side than conventional steel from the steel of the same composition (same steel grade).

[0010] A still further object of the present invention is to provide tensile strength equivalent to that of a heat-treated steel to which alloying elements are added, without adding expensive alloying elements to a heat-treated steel to provide higher strength.

SOLUTION TO PROBLEM

[0011] As described above, conventionally, the heat-treated steel with both tensile strength and toughness has preferably pearlite in which ferrite and cementite are alternately arranged in layers. However, according to the inventor's tests and considerations, it was found that a heat-treated steel with both tensile strength and toughness can be provided even if it has no pearlite in which ferrite and cementite are alternately arranged in layers (even if the metallographic structure has little pearlite).

[0012] It was also confirmed that a heat-treated steel

according to the present invention has several properties different from a conventional heat-treated steel. As described below, the heat-treated steel according to the present invention can be defined from (1) a crystal grain size, (2) the number of crystal grains, (3) a GOS (Grain Orientation Spread) value, (4) a cross section, (5) a reduction of area, and (6) a S-S curve.

[0013] Focusing on (1) the crystal grain size, a heat-treated steel according to a first aspect of the invention which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities is characterized in that an average crystal grain size at a grain boundary setting angle of 15° is $10 \times C + 7$ (μm) or less (wherein C represents a carbon content (%)).

[0014] Similarly, focusing on (1) the crystal grain size, the heat-treated steel according to the first aspect of the invention is further characterized in that (average crystal grain size at a surface portion at a grain boundary setting angle of 15°)/(average crystal grain size at a center portion at a grain boundary setting angle of 15°) is 0.70 or more and 1.10 or less.

[0015] Focusing on (2) the number of crystal grains, a heat-treated steel according to a second aspect of the invention which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities is characterized in that the value of (the number of crystal grains at a grain boundary setting angle of 5°)/(the number of crystal grains at a grain boundary setting angle of 15°) is $5.4 \times C - 0.95$ or less, or the value of (the number of crystal grains at a grain boundary setting angle of 2°)/(the number of crystal grains at a grain boundary setting angle of 15°) is $9.8 \times C - 1.9$ or less (wherein C represents a carbon content (%)).

[0016] Focusing on (3) the GOS value, a heat-treated steel according to a third aspect of the invention which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities is characterized in that a GOS value at a grain boundary setting angle of 15° is $11 \times (C - 0.42) + 5.3$ or less (wherein C represents a carbon content (%)).

[0017] Similarly, focusing on (3) the GOS value, a heat-treated steel according to a fourth aspect of the invention which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities is characterized in that a cumulative frequency of a GOS value in a range of 0° to 10° at a grain boundary setting angle of 15° is $-0.1C^3 - 1.3C^2 + 1.1C + 0.7$ or more (wherein C represents a carbon content (%)).

[0018] The heat-treated steel according to the present invention may include an iron carbide ($\text{Fe}_{2-2.5}\text{C}$, Fe_{2-3}C , or the like) different from cementite (Fe_3C) included in

conventionally known pearlite and bainite structures. In addition, the iron carbide included in the heat-treated steel according to the present invention (referred to as "special cementite" in the examples) is characterized by a shape different from the cementite included in the conventionally known pearlite and bainite structures, that is, many branched, bent, or curved portions.

[0019] Focusing on (4) the cross section, a heat-treated steel according to a fifth aspect of the invention which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities is characterized in that when a structure is observed with a backscattered electron (BSE) image, in a layered structure of ferrite and an iron carbide, an area fraction of the branched, bent, or curved iron carbide is 9% or more in a field of view. The branched, bent, or curved iron carbide in the BSE image also looks like a mottled pattern.

[0020] Similarly, focusing on (4) the cross section, a heat-treated steel according to a sixth aspect of the invention which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% of Si with the remainder being Fe and unavoidable impurities is characterized in that when a structure is observed with a scanning electron microscope (SEM), in a layered structure of ferrite and an iron carbide, a spherical protrusion is observed on a surface of the iron carbide.

[0021] Further, focusing on (4) the cross section, a heat-treated steel according to a seventh aspect of the invention which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities is characterized in that when a structure is observed with a scanning electron microscope (SEM), in a layered structure of ferrite and an iron carbide, a surface of the iron carbide has unevenness, and a rod-shaped or plate-shaped relatively isotropic iron carbide, which is three-dimensionally comb-shaped or mesh-shaped, is produced.

[0022] Focusing on (5) the reduction of area, a heat-treated steel according to an eighth aspect of the invention which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities is characterized in that when a tensile strength is TS (MPa), a reduction of area is $-0.000064\text{TS}^2 + 0.09\text{TS} + 46$ (%) or more.

[0023] Further, focusing on (6) the S-S curve, a heat-treated steel according to a ninth aspect of the invention which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities is characterized in that a difference in proof stress obtained by subtracting a 0.2% proof stress obtained in a S-S curve from a 0.4% proof stress obtained in the S-S curve is $45 \times C - 3$ (MPa) or less

(wherein C represents a carbon content (%)).

[0024] According to the present invention, a heat-treated steel with both high tensile strength and excellent toughness is provided.

[0025] A heat treatment method for a steel according to the present invention is characterized by including the steps of: preparing a steel containing 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities; causing the steel itself to generate heat to directly heat the steel; and passing the heated steel through a bath in which a cooling medium capable of isothermal transformation is stored to cool the steel, wherein a temperature gradient is the largest in a final stage of heating of the heating step, and the heated steel is allowed to enter the cooling medium immediately after the steel reaches a predetermined maximum heating temperature in the final stage of heating of the heating step to start the cooling without maintaining the predetermined maximum heating temperature. The heating step may involve heating using electric current or high frequency. Molten metal such as molten lead, or other cooling media can be used to cool the steel.

[0026] A heat treatment method for a steel according to the present invention can be also defined as follows. That is, in a heat treatment method for a steel according to another aspect of the present invention, a steel is heated from room temperature to 800°C or more within a few seconds, and the heated steel is cooled to 620°C or less within a few seconds without maintaining a maximum heating temperature, the steel containing 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities.

[0027] This heat treatment method can produce the heat-treated steel as described above with both high tensile strength and excellent toughness.

BRIEF DESCRIPTION OF DRAWINGS

[0028]

[FIG. 1] FIG. 1 is a block diagram schematically showing a patenting device.

[FIG. 2] FIG. 2 is a graph showing a temperature change of a steel patented using a gas furnace.

[FIG. 3] FIG. 3 is a graph showing a temperature change of a steel patented using the patenting device of FIG. 1.

[FIG. 4] FIG. 4 shows a table providing a steel grade and its composition.

[FIG. 5] FIG. 5 shows an optical microscope image of a conventional product.

[FIG. 6] FIG. 6 shows an optical microscope image of the conventional product.

[FIG. 7] FIG. 7 shows an optical microscope image of a developed product.

[FIG. 8] FIG. 8 shows an optical microscope image of the developed product.

[FIG. 9A] FIG. 9A shows an SEM image of the conventional product.

[FIG. 9B] FIG. 9B shows an SEM image of the conventional product.

[FIG. 10A] FIG. 10A shows an SEM image of the developed product.

[FIG. 10B] FIG. 10B shows an SEM image of the developed product.

[FIG. 11A] FIG. 11A shows an SEM image of the conventional product.

[FIG. 11B] FIG. 11B shows an SEM image of the conventional product.

[FIG. 12A] FIG. 12A shows an SEM image of the developed product.

[FIG. 12B] FIG. 12B shows an SEM image of the developed product.

[FIG. 13] FIG. 13 shows a BSE image of the conventional product.

[FIG. 14] FIG. 14 shows a BSE image of the developed product.

[FIG. 15] FIG. 15 shows a BSE image of the developed product.

[FIG. 16] FIG. 16 is a partially enlarged schematic diagram of the BSE image of the conventional product.

[FIG. 17] FIG. 17 is a partially enlarged schematic diagram of the BSE image of the developed product.

[FIG. 18A] FIG. 18A shows an SEM image of a developed product.

[FIG. 18B] FIG. 18B shows an SEM image of the developed product.

[FIG. 19] FIG. 19 shows a BSE image of the developed product.

[FIG. 20A] FIG. 20A shows an SEM image of the developed product.

[FIG. 20B] FIG. 20B shows an SEM image of the developed product.

[FIG. 21] FIG. 21 shows a BSE image of the developed product.

[FIG. 22A] FIG. 22A shows an SEM image of a conventional product.

[FIG. 22B] FIG. 22B shows an SEM image of a developed product.

[FIG. 23A] FIG. 23A shows a BSE image of the conventional product.

[FIG. 23B] FIG. 23B shows a BSE image of the developed product.

[FIG. 24A] FIG. 24A shows an SEM image of the developed product.

[FIG. 24B] FIG. 24B shows a BSE image of the developed product.

[FIG. 25A] FIG. 25A shows an SEM image of the developed product.

[FIG. 25B] FIG. 25B shows an SEM image of the developed product.

[FIG. 26] FIG. 26 is a schematic diagram showing

an example of a shape of a peculiar shaped portion appearing in the BSE image of the developed product.

[FIG. 27] FIG. 27 shows a relationship between a carbon content and a percentage of a peculiar shaped portion for each of the developed products and the conventional products.

[FIG. 28] FIG. 28 shows a relationship between a grain boundary setting angle and an average crystal grain size for each of the developed products and the conventional products.

[FIG. 29] FIG. 29 shows a relationship between a carbon content and an average crystal grain size at a grain boundary setting angle of 15° for each of the developed products and the conventional products.

[FIG. 30] FIG. 30 shows a relationship between an average crystal grain size at a center portion and a ratio of an average crystal grain size in the vicinity of a surface to at the center portion for each of the developed products and the conventional products.

[FIG. 31] FIG. 31 shows a grain boundary setting angle and a ratio of the number of crystal grains at grain boundary setting angles of 5° and 2° to the number of crystal grains at a grain boundary setting angle of 15° for each of the developed products and the conventional products.

[FIG. 32] FIG. 32 shows a relationship between a carbon content and the number of crystal grains at a grain boundary setting angle of 5°/the number of crystal grains at a grain boundary setting angle of 15° for each of the developed products and the conventional products.

[FIG. 33] FIG. 33 shows a relationship between a carbon content and the number of crystal grains at a grain boundary setting angle of 2°/the number of crystal grains at a grain boundary setting angle of 15° for each of the developed products and the conventional products.

[FIG. 34] FIG. 34 shows a relationship between a grain boundary setting angle and an average GOS value for each of the developed products and the conventional products.

[FIG. 35] FIG. 35 shows a relationship between a carbon content and an average GOS value for each of the developed products and the conventional products.

[FIG. 36] FIG. 36 shows a relationship between a GOS value up to a cumulative frequency and a cumulative frequency at a grain boundary setting angle of 15° for each of the developed products and the conventional products.

[FIG. 37] FIG. 37 shows a relationship between a carbon content and a cumulative frequency up to a GOS value of 10° at a grain boundary setting angle of 15° for each of the developed products and the conventional products.

[FIG. 38] FIG. 38 shows a relationship between true strain and tensile strength for each of the developed

products and the conventional products.

[FIG. 39A] FIG. 39A shows an SEM image of the developed product.

[FIG. 39B] FIG. 39B shows an SEM image of the developed product.

[FIG. 40A] FIG. 40A shows an SEM image of the developed product.

[FIG. 40B] FIG. 40B shows an SEM image of the developed product.

[FIG. 41] FIG. 41 shows a relationship between true strain and tensile strength for each of the developed products and the conventional products.

[FIG. 42] FIG. 42 shows a relationship between true strain and tensile strength for each of the developed products and the conventional products.

[FIG. 43] FIG. 43 shows a relationship between tensile strength and a reduction of area for each of the developed products and the conventional products.

[FIG. 44] FIG. 44 shows a S-S curve for each of the developed products and the conventional products.

[FIG. 45] FIG. 45 shows a S-S curve for each of the developed products and the conventional products.

[FIG. 46] FIG. 46 is a partially enlarged view of FIG. 44.

[FIG. 47] FIG. 47 shows a relationship between a carbon content and 0.4% proof stress - 0.2% proof stress for each of the developed products and the conventional products.

DESCRIPTION OF EMBODIMENTS

[0029] FIG. 1 schematically shows a patenting device. In the following description, a steel before patenting is simply referred to as a "steel 11", and a steel after patenting is referred to as a "heat-treated steel 12" to distinguish from each other.

[0030] The patenting device includes a power source 13, a feed roll 14, a bath 15, and a molten lead 16 stored in the bath 15.

[0031] The steel 11 is supplied in the form of linear body (wire rods). The steel 11 unreeled from a payoff reel (not shown) runs at a constant speed from left to right in FIG. 1, passes through the feed roll 14, and is immersed in the molten lead 16 stored in the bath 15 for a predetermined period of time.

[0032] First, heat treatment (heating treatment) is performed on the steel 11. The power source 13 provided in the patenting device is connected to the feed roll 14 and the bath 15 to form a closed circuit including the power source 13, the feed roll 14, the molten lead 16, and the bath 15. On the left side (upstream side) of the feed roll 14, an insulating device (not shown) is provided such that current is not applied to the steel 11. In a section from the feed roll 14 to the liquid surface of the molten lead 16 stored in the bath 15, the steel 11 is energized and heated by the current supplied from the power source 13.

[0033] The steel 11 is most heated at the point imme-

diately before entering the liquid surface of the molten lead 16 stored in the bath 15. The heating temperature of the steel 11 (the maximum temperature of the steel 11) is set to 975°C or less in order to exhibit the properties described later. This is because if the heating temperature is too high, crystal grains (austenite grains) will grow and the metallographic structure will become coarse, resulting in a decrease in toughness, especially a reduction of area. However, insufficient heating leads to the non-solution of an iron carbide (cementite as an example), which is an intermetallic compound of Fe and C. Therefore, the heating temperature of the steel 11 is preferably set to 800°C or higher. The heating temperature of the steel 11 can be controlled by adjusting the voltage or current of the power source 13. The heating time is adjusted by the path length from the feed roll 14 to the liquid surface of the molten lead 16 and the running speed of the steel 11.

[0034] The molten lead 16 stored in the bath 15 is heated to a constant temperature by a gas furnace (an electric heater may be used). The temperature of the molten lead 16 is lower than the heating temperature of the steel 11 described above, and the steel 11, which has been heated to the maximum temperature immediately before entering the liquid surface of the molten lead 16, starts cooling as soon as it enters the molten lead 16.

[0035] The temperature of the molten lead 16 (lead furnace temperature), that is, an isothermal transformation temperature is set to 620°C or less. This is because the steel 11 is rapidly cooled to obtain the precipitation of pearlite and carbide from austenite. However, if the steel 11 is cooled too rapidly, martensite or the like will appear to make the product brittle, and thus the lower limit temperature of the molten lead 16 is set to about 350°C.

[0036] The patented steel which has been immersed in the molten lead 16 and then drawn out from the bath 15, that is, the heat-treated steel 12 is then washed with water, coated, and drawn if necessary.

[0037] FIG. 2 shows a temperature change (temperature rise curve) of the steel 11 patented using a gas furnace (heat-treated steel 12), and FIG. 3 shows a temperature change (temperature rise curve) of the steel 11 patented using the patenting device shown in FIG. 1 (heat-treated steel 12). In both graphs of FIGS. 2 and 3, the temperature drops sharply at the timing when the steel 11 enters the molten lead 16. It should be noted that the scale of the time axis (horizontal axis) differs between FIG. 2 and FIG. 3.

[0038] Referring to FIG. 2, when the gas furnace is used, the steel 11 is gradually heated. In an atmosphere heating furnace as a typical gas furnace, the time required for heating is proportional to the wire diameter of the steel 11. The thinner the wire diameter, the shorter the heating time, and the thicker the wire diameter, the longer the heating time. FIG. 2 and FIG. 3 show the graphs of the steel 11 with a wire diameter of $\phi 2.11$, and when the gas furnace is used, it takes about 40 seconds

to reach the maximum temperature (target heating temperature). On the other hand, referring to FIG. 3, when the patenting device shown in FIG. 1 is used, the steel 11 reaches the maximum temperature (target heating temperature) in several seconds. The patenting device shown in FIG. 1 can provide the constant rate of temperature rise regardless of the wire diameter.

[0039] Comparing the graph in FIG. 2 and the graph in FIG. 3, the shapes of the temperature rise curves are significantly different. In the graph of FIG. 2, the rate of temperature rise slows down from around 723°C at which austenitization starts, and the ratio of the time required for austenitization increases, while in the graph of FIG. 3, the rate of temperature rise increases at 723°C or more, and the ratio of time required for austenitization decreases. Further, in FIG. 2, after the maximum temperature is reached, it is maintained for about 20 seconds, while in FIG. 3, the cooling starts immediately after the maximum temperature is reached.

[0040] The steel 11 as a starting wire rod, and the heat-treated steel 12 obtained by patenting the steel 11 are carbon steels including iron (Fe) and carbon (C). The carbon content (carbon concentration) of 0.38% (mass%; the same applies hereinafter) or more facilitates obtaining sufficient strength, and the carbon content of 1.05% or less prevents the deterioration of workability and the reduction of fatigue limit.

[0041] In addition to Fe and C, manganese (Mn), chromium (Cr), and silicon (Si) may be included in the heat-treated steel 12.

[0042] Manganese (Mn) is contained as a deoxidizer. The content is limited to 1.0% or less in order to prevent the deterioration of workability.

[0043] Chromium (Cr) is generally effective in refining pearlite and improving the toughness. The content is limited to 0.50% or less as addition of a large amount of Cr adversely causes a decrease in toughness.

[0044] Silicon (Si) is used as a deoxidizing agent. The content is limited to about 1.5% in order to avoid ductility deterioration.

[0045] In addition, other elements such as vanadium (V) (0.50% or less), molybdenum (Mo) (0.25% or less), boron (B) (0.005% or less), titanium (Ti) (0.050%), nickel (Ni) (0.50% or less), aluminum (0.10% or less), zirconium (Zr) (0.050% or less) and the like may be added to the steel 11 (heat-treated steel 12) depending on applications.

[0046] In the following description, the heat-treated steel 12 which is obtained by heating as shown in FIG. 2 and ensuring the time of maintaining the maximum temperature for about 20 seconds, is referred to as a "conventional product", and the heat-treated steel 12 which is obtained by heating as shown in FIG. 3 and starting cooling immediately after the maximum temperature is reached, is referred to as a "developed product" to distinguish from each other. FIG. 4 summarizes the names of the steel grades of the multiple steels 11 (heat-treated steels 12) and their compositions described below.

(Optical microscope image) (FIGS. 5 to 8)

[0047] FIGS. 5 to 8 are optical microscope images of the heat-treated steels 12 obtained by respective different patenting methods as shown in FIGS. 2 and 3 although all the steels 11 before heat treatment are the same (all SWRH62A with a diameter of 2.11 mm). FIGS. 5 and 6 are the optical microscope images of the conventional product, and FIGS. 7 and 8 are the optical microscope images of the developed product. The optical microscope images shown in FIGS. 5 to 8 are obtained by photographing the center portion and its surrounding area of the heat-treated steels 12 after the heat-treated steels 12 are polished longitudinally and etched with Nital.

[0048] FIG. 5 is an optical microscope image of the conventional product obtained when the temperature of the molten lead 16 is set to 565°C, and FIG. 6 is an optical microscope image of the conventional product obtained when the temperature of the molten lead 16 is set to 450°C. When the temperature of the molten lead 16 is set to 565°C, the metallographic structure is a pearlite structure (FIG. 5), and when the temperature of the molten lead 16 is set to 450°C, the metallographic structure is a bainite structure (FIG. 6). In the conventional product, the difference in metallographic structure when the temperature of the molten lead 16 is set to 565°C and 450°C appears clearly.

[0049] FIG. 7 is an optical microscope image of the developed product obtained when the temperature of the molten lead 16 is set to 565°C, and FIG. 8 is an optical microscope image of the developed product obtained when the temperature of the molten lead 16 is set to 450°C. Compared to FIGS. 5 and 6, it can be seen that the developed product has finer crystals than the conventional product. Further, whether the temperature of the molten lead 16 is 565°C or 450°C, the metallographic structure has the characteristics similar to the pearlite structure, and the characteristics of the bainite structure do not appear. It can be seen that whether the temperature of the molten lead 16 is set to 565°C or 450°C, there is no clear difference in metallographic structure in the optical microscope images compared to the conventional product.

(Scanning electron microscope image) (FIGS. 9A to 12B)

[0050] FIGS. 9A to 12B are scanning electron microscope images of the heat-treated steels 12 obtained by respective different patenting methods as shown in FIGS. 2 and 3 although all the steels 11 before heat treatment are the same (all SWRH62A with a diameter of 2.11 mm). FIGS. 9A, 9B, 11A, and 11B are the scanning electron microscope images of the conventional product, and FIGS. 10A and 10B are the scanning electron microscope images of the developed product. Similar to the optical microscope images described above, the scanning electron microscope images are also obtained by

photographing the wire center and its surrounding area of the heat-treated steels 12 after the heat-treated steels 12 are polished longitudinally and etched with Nital.

[0051] FIG. 9A and 9B are both the scanning electron microscope images (hereinafter referred to as SEM images) of the conventional product obtained when the temperature of the molten lead 16 is set to 565°C. FIGS. 9A and 9B show the SEM images at a magnification of 10,000 and 50,000, respectively. A large amount of plate-like (layered) cementite (Fe_3C) (white linear portions in FIGS. 9A and 9B) is identified in the layered structure of ferrite and cementite (pearlite structure). The surface of cementite is smooth, and a large amount of cementite has the nearly uniform plate thickness (layer thickness) (approximately 30 nm).

[0052] FIGS. 10A and 10B are both the SEM images of the developed product obtained when the temperature of the molten lead 16 is set to 565°C. FIGS. 10A and 10B show the SEM images at a magnification of 10,000 and 50,000, respectively. A large number of plate-like (layered) structures is identified. The white portions in FIGS. 10A and 10B include cementite (Fe_3C), but may include an iron carbide different from cementite (for example, $\text{Fe}_{2-2.5}\text{C}$, Fe_{2-3}C), and spherical protrusions can be seen scattered on the surface of the iron carbide. Further, the multiple iron carbides have the non-uniform plate thickness (layer thickness) (approximately 60 nm) which is thick compared to the conventional product.

[0053] In the following description, the iron carbide (Fe_3C , $\text{Fe}_{2-2.5}\text{C}$, Fe_{2-3}C , or the like) constituting the layered structure identified in the developed product is referred to as "special cementite" to distinguish it from "cementite" (Fe_3C), which is an iron carbide constituting the layered structure identified in the conventional product.

[0054] FIGS. 11A and 11B are SEM images of the conventional product obtained when the temperature of the molten lead 16 is set to 450°C. FIGS. 11A and 11B show the SEM images at a magnification of 10,000 and 50,000, respectively. The cementite appearing in white in FIGS. 11A and 11B is not plate-shaped (layered), and has a bainite structure rather than a pearlite structure.

[0055] FIGS. 12A and 12B are SEM images of the developed product obtained when the temperature of the molten lead 16 is set to 450°C. FIGS. 12A and 12B show the SEM images at a magnification of 10,000 and 50,000, respectively. Spherical protrusions (unevenness portions) are seen scattered on the surface of the special cementite appearing in white in FIGS. 12A and 12B, and rod-shaped or plate-shaped relatively isotropic portions with unique shapes are identified. Further, comb-shaped and mesh-like portions as a combination of these portions, as well as three-dimensionally mesh-like portions like tree roots are also identified. This structure is neither found in the conventional pearlite structure nor bainite structure.

(Backscattered electron image) (FIGS. 13 to 15) (FIGS. 16 to 17)

[0056] FIGS. 13 to 15 are Backscattered Electron (BSE) images of the heat-treated steels 12 obtained by respective different patenting methods as shown in FIGS. 2 and 3 although all the steels 11 before heat treatment are the same (all SWRH62A with a diameter of 2.11 mm), and FIG. 13 is the BSE image of the conventional product, and FIGS. 14 and 15 are the BSE images of the developed product (both at a magnification of 10,000). FIGS. 14 and 15 differ in the temperature of the lead furnace. Unlike the optical microscope image and the scanning electron microscope image described above, the backscattered electron image is obtained by photographing the longitudinal direction of the heat-treated steel 12 after the heat-treated steel 12 is polished and milled with argon gas. FIG. 16 shows a partially enlarged schematic diagram of the BSE image of the conventional product shown in FIG. 13, and FIG. 17 shows a partially enlarged schematic diagram of the BSE image of the developed product shown in FIG. 14.

[0057] FIG. 13 is the BSE image of the conventional product obtained when the temperature of the molten lead 16 is set to 565°C. FIG. 14 shows the BSE image of the developed product when the temperature of the molten lead 16 is set to 450°C, and FIG. 15 shows the BSE image of the developed product when the temperature of the molten lead 16 is set to 565°C.

[0058] As shown in FIGS. 13 and 16, in the BSE images of the conventional product, the layered structure with ferrite and cementite alternately arranged in layers is identified within the prior austenite grain boundary. In the BSE images of the conventional product, the cementite appears as a plurality of parallel and elongated streaks.

[0059] Meanwhile, as shown in FIGS. 14, 15, and 17, the layered structure of ferrite and special cementite is also identified in the BSE images of the developed product. However, it can be seen that there is very little layered special cementite (streaks that are parallel to each other and elongated in the BSE image), the layer thickness (the thickness of the streaks in the BSE image) is non-uniform, and there are many branched, bent, or curved portions (an area fraction in the field of view is 9% or more). In the BSE image of the developed product, the special cementite looks like a mottled pattern. In the developed product when the temperature of the molten lead 16 is set to 565°C (FIG. 15), the special cementite extends straighter than in the developed product when the temperature of the molten lead 16 is set to 450°C (FIG. 14), but the special cementite does not grow and has many branched, bent, curved portions compared to the conventional product (FIG. 13).

(SEM image and BSE image of high carbon steel SWRS92A)

[0060] In FIGS. 18A to 21, SWRS92A is used as the

steel grade, and FIGS. 18A and 18B are SEM images of the developed product obtained when the temperature of the molten lead 16 is set to 565°C (the magnification in FIG. 18A is 10,000 times, and the magnification in FIG. 18B is 50,000 times). FIG. 19 is a BSE image of the developed product obtained when the temperature of the molten lead 16 is set to 565°C. FIGS. 20A and 20B are SEM images of the developed product obtained when the temperature of the molten lead 16 is set to 450°C, with magnifications of 10,000 and 50,000, respectively. FIG. 21 is a BSE image of the developed product obtained when the temperature of the molten lead 16 is set to 450°C. The SEM images in FIGS. 18A, 18B, 20A, and 20B are obtained by photographing the longitudinal direction of the heat-treated steels 12 after the heat-treated steels 12 are polished and etched with Nital. The BSE images in FIGS. 19 and 21 are obtained by photographing the longitudinal direction of the heat-treated steel 12 after the heat-treated steel 12 is polished and milled with argon gas.

[0061] Referring to FIGS. 18A and 18B, in the SEM images of the developed product, spherical protrusions can be seen scattered on the surface of the special cementite. Referring to FIG. 20A and 20B, when the temperature of the molten lead 16 is lowered (450°C), the peculiar shape of the special cementite is prominent. Referring to FIG. 19 and 21, in the BSE images of the developed product, whether the temperature of the molten lead 16 is set to 565°C (FIG. 19) or 450°C (FIG. 21), there is little layered special cementite and the special cementite looks like a mottled pattern.

(SEM image and BSE image of medium carbon steel SWRH42A)

[0062] In FIGS. 22A and 22B, SWRH42A is used as the steel grade. FIG. 22A is an SEM image of the conventional product and FIG. 22B is an SEM image of the developed product obtained when the temperature of the molten lead 16 is set to 565°C. Comparing FIGS. 22A and 22B, the developed product (FIG. 22B) includes more pro-eutectoid ferrite than the conventional product (FIG. 22A). Meanwhile, the difference in shape between the cementite of the conventional product and the special cementite of the developed product cannot be easily seen.

[0063] In FIGS. 23A and 23B, SWRH42A is used as the steel grade. FIG. 23A is a BSE image of the conventional product obtained when the temperature of the molten lead 16 is set to 565°C, and FIG. 23B is a BSE image of the developed product obtained when the temperature of the molten lead 16 is set to 565°C. Compared to the SEM images of FIGS. 22A and 22B, the BSE images of FIGS. 23A and 23B clearly show the difference in shape between the cementite of the conventional product and the special cementite of the developed product. It can be seen that in the conventional product (FIG. 23A), the cementite is almost straight, while in the developed product

(FIG. 23B), the special cementite has many branched, bent, or curved portions.

[0064] In FIGS. 24A and 24B, SWRH42A is used as the steel grade. FIG. 24A is an SEM image of the developed product obtained when the temperature of the molten lead 16 is set to 450°C, and FIG 24B is a BSE image of the developed product obtained when the temperature of the molten lead 16 is set to 450°C. Comparing the SEM image of the conventional product when the temperature of the molten lead 16 is set to 565°C (FIG. 22A) and the SEM image of the developed product when the temperature of the molten lead 16 is set to 450°C (FIG. 24A), it can be seen that the developed product shown in FIG. 24A has the fine special cementite. Further, comparing the BSE image of the conventional product when the temperature of the molten lead 16 is set to 565°C (FIG. 23A) and the BSE image of the developed product when the temperature of the molten lead 16 is set to 450°C (FIG. 24B), it can be seen that the shape of the special cementite in the developed product has many branched, bent, or curved portions. The BSE images are easier than the SEM images to identify the difference in shape of the cementite of the conventional product and the special cementite of the developed product.

(SEM image of steel grade SWRH62A)

[0065] FIGS. 25A and 25B are both SEM images of the developed product using the steel grade SWRH62A and the molten lead 16 at 400°C. FIG. 25A is the SEM image at a magnification of 3,500, and FIG. 25B is the SEM image at a magnification of 10,000. Also in the SEM images of the developed product shown in FIGS. 25A and 25B, the special cementite has many branched, bent, or curved portions.

[0066] A possible factor that the metallographic structure in the developed product different from that in the conventional product appears is as follows. That is, in the conventional product, the carbon atoms are sufficiently diffused due to the long heating time of the heat treatment. Then, rapid cooling starts from a state in which the carbon concentration in the austenite is uniform. When the temperature of the molten lead 16 is 565°C, nucleation occurs from the austenite grain boundary, and a pearlite structure grows from the produced nuclei. When the temperature of the molten lead 16 is set to 450°C, ferrite is produced, the carbon atoms extruded from the ferrite are concentrated, and granular cementite is produced while the ferrite grows, resulting in an upper bainite structure.

[0067] On the other hand, in the developed product, due to the very short heating time of the heating treatment, during heating, the undissolved carbide remains in the nano-order, or remains to the extent that it cannot be observed as undissolved carbide, and the carbon atoms are regarded as being not diffused completely. Rapid cooling starts from a state in which the carbon concentration in the austenite is non-uniform, and the nucleation

of the carbide occurs at the point where the carbon concentration is high. In the conventional product, at the temperature of the molten lead 16 (565°C) at which the pearlite structure is produced, the same production mechanism as that in the pearlite structure is also generated, but due to the non-uniform carbon concentration, branched, bent, or curved special cementite is produced. Further, at the temperature of the molten lead 16 (450°C) at which the bainite structure is produced, the nucleation starts at the point where the carbon concentration in the austenite is high, resulting in a production mechanism different from that in the pearlite structure. The special cementite with many branched, bent, or curved portions is produced.

[0068] In addition, at the temperature of the molten lead 16 (450°C) at which the bainite structure is produced, the higher the carbon content, the smaller the ferrite portion before solution treatment, the carbon concentration in the austenite is easily uniformed, and the proportion of the produced bainite structure increases. In the developed product, when the temperature of the molten lead 16 is relatively low, such as 450°C, the bainite structure is mixed with the special cementite with many branched, bent, or curved portions.

[0069] The extent to which branched, bent, or curved portions (hereinafter referred to as peculiar shaped portions) are included is observed as follows. That is, the heat-treated steel 12 is polished in the longitudinal direction to form a cross section in the longitudinal direction, and five or more images are taken at a magnification of 10,000 or more with the range from the center within 1/2 of the diameter of the heat-treated steel 12 being an imaging range, and the BSE images with a total area of 500 μm^2 are taken. In the taken image, lines are drawn to form a grid in both the vertical and horizontal directions so that they are spaced at intervals of 0.5 μm at the magnification at the time of photographing. A plurality of rectangular frames of 0.5 μm square at the magnification at the time of photographing is divided into rectangular frames with peculiar shaped portions and rectangular frames without peculiar shaped portions. That is, among the plurality of rectangular frames, the rectangular frames including the branched peculiar shaped portions as shown in FIGS. 26A and 26B, the rectangular frames including the peculiar shaped portions bent 80° or more as shown in FIGS. 26C, 26D, and 26E, and the rectangular frames having the peculiar shaped portions curved within a radius of curvature of 0.5 μm as shown in FIG. 26F are counted. When one peculiar shaped portion extends across the multiple rectangular frames, only the rectangular frame including the branched, bent, or curved portion is counted. Further, when one cementite or special cementite is branched, bent, or curved within the different rectangular frames, each of the rectangular frames is counted. When the shape of the peculiar shaped portion is unclear and cannot be determined in the BSE image depending on the orientation of the shape of the peculiar shaped portion, the rectangular frame with such a

shape is excluded from counting. When the ratio of the rectangular frames with unclear shapes of the peculiar shaped portions to all the rectangular frames is 5% or more, the image is not used and an image is taken again.

[0070] FIG. 27 shows a percentage of the peculiar shaped portion in the BSE image based on the count of the rectangular frames with the peculiar shaped portion described above for each of the conventional products and the developed products with different carbon contents. FIG. 27 shows that the developed products (white circles) have a higher percentage of the peculiar shaped portions than the conventional products (black circles), and that the developed product includes 9% or more of the peculiar shaped portions.

[0071] In order to ascertain the properties of the developed product (heat-treated steel 12) having a structure different from the conventional product, various measurements in addition to the image analysis described above are performed. The measurements are also performed on the conventional product. The measurement results are described below.

[0072] FIG. 28 is a graph with a grain boundary setting angle (°) on the horizontal axis and an average crystal grain size (μm) on the vertical axis, in which dashed lines represent the developed products and solid lines represent the conventional products. FIG. 22 shows the graphs (broken lines) for the five developed products of SWRH62A and the graphs (solid lines) for two conventional products of SWRH62A. The details (steel grade, diameter, isothermal transformation temperature (cooling temperature, lead furnace temperature)) of the five developed products and the details of the two conventional products are as follows.

Developed product (broken line)

[0073]

- (1) SWRH62A, φ2.11, isothermal transformation temperature 565°C
- (2) SWRH62A, φ1.06, isothermal transformation temperature 600°C
- (3) SWRH62A, φ2.11, isothermal transformation temperature 450°C
- (4) SWRH62A, φ2.11, isothermal transformation temperature 425°C
- (5) SWRH62A, φ1.06, isothermal transformation temperature 475°C

Conventional product (solid line)

[0074]

- (a) SWRH62A, φ2.11, isothermal transformation temperature 565°C
- (b) SWRH62A, φ1.06, isothermal transformation temperature 600°C

[0075] In the graph of FIG. 28, the grain boundary setting angle shown on the horizontal axis is an angle set in an EBSD (Electron Back Scattered Diffraction) analysis. In the EBSD analysis, a measurement area of a cross section of the polished sample is divided into measurement points (generally referred to as "pixels"), an electron beam is incident on each of the divided pixels, and the incident electron beam is reflected by the pixels. Based on the thus obtained reflected electrons, a crystal orientation for each of the pixels is measured. The obtained crystal orientation data is analyzed using the EBSD analysis software to calculate various parameters. The EBSD detector used here is manufactured by TSL Solutions KK, and employs regular hexagonal pixels as pixels.

[0076] In the EBSD analysis software, using the crystal orientation obtained for each pixel, the boundary at which the difference in crystal orientation between adjacent pixels is greater than or equal to the grain boundary setting angle described above is regarded as a "grain boundary" and the area enclosed by the grain boundary is regarded as a "crystal grain". When the grain boundary setting angle (grain boundary setting value) is decreased, the crystal grain size decreases and the number of crystals in the observation area increases. Conversely, when the grain boundary setting angle is increased, the crystal grain size increases and the number of crystals in the observation area decreases. The EBSD analysis evaluates the crystal orientation of ferrite.

[0077] Referring to FIG. 28, it can be seen that for the conventional products (see the solid lines), in the EBSD analysis, the larger the grain boundary setting angle, the larger the average crystal grain size (converted to the diameter of a circle with an area equivalent to a crystal grain area), while for the developed products (see the broken lines), in the EBSD analysis, the average crystal grain size remains almost constant regardless of the grain boundary setting angle. As the grain boundary setting angle increases, the difference between the average crystal grain size of the conventional products (solid lines) and the average crystal grain size of the developed products (broken lines) increases.

[0078] FIG. 29 shows the measurements of an average crystal grain size when the grain boundary setting angle is set to 15° for each of the conventional product and the developed product with different carbon contents. In FIG. 29, the horizontal axis represents a carbon content (mass%), and the vertical axis represents an average crystal grain size (μm) when the grain boundary setting angle is set to 15° for a center range of the heat-treated steel 12 (within 1/4 of the diameter on one side from the center and within 1/2 of the diameter on both sides).

[0079] In FIG. 29, carbon contents and the average crystal grain sizes for the 19 types of developed products are indicated by white circles, and carbon contents and average crystal grain sizes for the 10 types of conventional products are indicated by black circles. The details (steel grade, diameter, isothermal transformation temperature (cooling temperature, lead furnace tempera-

ture)) of the 19 types of developed products and the details of the 10 types of conventional products are as follows.

Developed product

[0080]

- (1) SWRH42A, ϕ 2.11, isothermal transformation temperature 565°C
- (2) SWRH42A, ϕ 2.11, isothermal transformation temperature 450°C
- (3) SWRH62A, ϕ 2.11, isothermal transformation temperature 565°C
- (4) SWRH62A, ϕ 2.11, isothermal transformation temperature 450°C
- (5) SWRH62A, ϕ 2.11, isothermal transformation temperature 425°C
- (6) SWRH62A, ϕ 1.06, isothermal transformation temperature 600°C
- (7) SWRH62A, ϕ 1.06, isothermal transformation temperature 475°C
- (8) SWRH82A, ϕ 2.11, isothermal transformation temperature 565°C
- (9) SWRH82A, ϕ 2.11, isothermal transformation temperature 450°C
- (10) SWRH82B, ϕ 2.11, isothermal transformation temperature 565°C
- (11) SWRH82B, ϕ 2.11, isothermal transformation temperature 450°C
- (12) SWRH82B, ϕ 2.51, isothermal transformation temperature 450°C
- (13) SWRS92A, ϕ 2.11, isothermal transformation temperature 565°C
- (14) SWRS92A, ϕ 2.11, isothermal transformation temperature 450°C
- (15) 92A-Cr, ϕ 2.11, isothermal transformation temperature 565°C
- (16) 92A-Cr, ϕ 2.11, isothermal transformation temperature 450°C
- (17) 92B-Si, ϕ 2.11, isothermal transformation temperature 565°C
- (18) 102A-Cr, ϕ 2.11, isothermal transformation temperature 565°C
- (19) 102A-Cr, ϕ 2.11, isothermal transformation temperature 450°C

Conventional product

[0081]

- (a) SWRH42A, ϕ 2.11, isothermal transformation temperature 565°C
- (b) SWRH62A, ϕ 2.11, isothermal transformation temperature 565°C
- (c) SWRH62A, ϕ 1.06, isothermal transformation temperature 600°C
- (d) SWRH82A, ϕ 2.11, isothermal transformation

temperature 565°C

(e) SWRH82B, ϕ 2.11, isothermal transformation temperature 565°C

(f) SWRH82B, ϕ 2.51, isothermal transformation temperature 565°C

(g) SWRS92A, ϕ 2.11, isothermal transformation temperature 565°C

(h) 92A-Cr, ϕ 2.11, isothermal transformation temperature 565°C

(i) 92B-Si, ϕ 2.11, isothermal transformation temperature 580°C

(j) 102A-Cr, ϕ 2.11, isothermal transformation temperature 565°C

[0082] Referring to the graph of FIG. 29, a dashed line shown in the graph is a straight line representing " $10 \times$ carbon content (%) + 7" (μm). For all the conventional products (black circles), the average crystal grain size exceeds " $10 \times$ carbon content (%) + 7" μm when the grain boundary setting angle is set to 15° , while for all the developed products (white circles), the average crystal grain size is " $10 \times$ carbon content (%) + 7" μm or less when the grain boundary setting angle is set to 15° . The conventional product and the developed product can be clearly distinguished from each other in terms of the average crystal grain size at a grain boundary setting angle of 15° .

[0083] FIG. 30 is a graph with the horizontal axis representing an average crystal grain size (μm) at a center portion of the heat-treated steel 12, and the vertical axis representing the ratio of an average crystal grain size in the vicinity of a surface to the average crystal grain size at the center portion of the heat-treated steel 12 (average crystal grain size in the vicinity of the surface/average crystal grain size at the center portion). The value greater than 1.00 on the vertical axis means that a surface portion is rougher than the center portion, so to speak. Similar to the graph in FIG. 29, the graph in FIG. 30 is created using the average crystal grain size at a grain boundary setting angle of 15° obtained by the EBSD analysis, with black circles indicating the conventional products and white circles indicating the developed products. FIG. 30 also shows the measurement results of the multiple heat-treated steels 12 with different isothermal transformation temperature of the molten lead 16, wire types, wire diameters, or the like for the conventional products (black circles) and the developed products (white circles) (the same applies below).

[0084] Referring to FIG. 30, few developed products (white circles) have rough surfaces, that is, have the ratio of the average crystal grain size in the vicinity of the surface to that at the center portion (the value on the vertical axis) significantly exceeding 1.00, and the ratio falls within the range of 0.70 to 1.10. Meanwhile, most of the conventional products (black circles) also have the ratio falling within the range of 0.70 to 1.10. However, the conventional products having the ratio close to 1.10 are also found, and some conventional products have a slightly

rough surface. Some conventional products have the ratio of less than 0.7. The surface roughness is closely related to the product toughness. It can be seen that the developed products have the toughness equal to or higher than the conventional products.

[0085] FIG. 31 shows the measurement results using the same developed products and the same conventional products as the five types of developed products and the two types of conventional products used to create the graph in FIG. 28 and is a graph with the horizontal axis representing a grain boundary setting angle ($^{\circ}$) and the vertical axis representing the ratio of the number of crystal grains at grain boundary setting angles of 5° and 2° to the number of crystal grains at a grain boundary setting angle of 15° . The EBSD analysis software can calculate (count) the number of crystal grains at various grain boundary setting angles.

[0086] Referring to FIG. 31, the large difference in the calculated ratio occurs between the conventional products (solid lines) and the developed products (broken lines). The conventional products and the developed products also have the difference in the ratio.

[0087] FIG. 32 shows the measurement results of the same developed products and the same conventional products as the 19 types of developed products and the 10 types of conventional products used to create the graph of FIG. 29 and is a graph with the horizontal axis representing a carbon content and the vertical axis representing the ratio of the number of crystal grains at a grain boundary setting angle of 5° to the number of crystal grains at a grain boundary setting angle of 15° . In the graph of FIG. 32, a straight line indicating " $5.4 \times \text{carbon content (\%)} - 0.95$ " is indicated by a dashed line. All the developed products (white circles) are plotted in a graph area below the straight line, and all the conventional products (black circles) are plotted in a graph area above the straight line. The ratio of the number of crystal grains at a grain boundary setting angle of 5° to the number of crystal grains at a grain boundary setting angle of 15° also makes it possible to clearly distinguish between the developed product and the conventional product.

[0088] FIG. 33 shows the measurement results using the 19 types of developed products and the 10 types of conventional products, similarly described above, and is a graph with the horizontal axis representing a carbon content, and the vertical axis representing the ratio of the number of crystal grains at a grain boundary setting angle of 2° to the number of crystal grains at a grain boundary setting angle of 15° . In the graph of FIG. 33, a straight line representing " $9.8 \times \text{carbon content (\%)} - 1.9$ " is indicated by a dashed line. All the developed products (white circles) are plotted in a graph area below the straight line, and all the conventional products (black circles) are plotted in a graph area above the straight line. The ratio of the number of crystal grains at a grain boundary setting angle of 2° to the number of crystal grains at a grain boundary setting angle of 15° also makes it possible to clearly distinguish between the developed prod-

uct and the conventional product.

[0089] FIG. 34 shows the measurement results using the same developed products and the same conventional products as the five types of developed products and the two types of conventional products used to create the graph of FIG. 28, and a graph with the vertical axis representing a grain boundary setting angle ($^{\circ}$) and the vertical axis representing an average GOS value ($^{\circ}$).

[0090] A GOS (Grain Orientation Spread) value (also referred to as an average GOS value) is obtained by calculating and averaging misorientation for all the combinations of two pixels within the same crystal grain, and is used as an index representing strain. As described above, as the crystal grain boundary varies depending on the grain boundary setting angle, the GOS value varies when the grain boundary setting angle is changed. The GOS value is also a value calculated by the EBSD analysis software. Hereinafter, as the average GOS value, the value obtained from the area fraction is used.

[0091] Referring to FIG. 34, the GOS values of the developed products (dashed lines) are smaller than the GOS values of the conventional products (solid lines), and the greater the grain boundary setting angle, the greater the difference between the GOS values of the developed products and the GOS values of the conventional products. For example, focusing on the GOS values at a grain boundary setting angle of 15° , many of the developed products (dashed lines) have the GOS values of 6° or less, while all the conventional products (solid lines) have the GOS values exceeding 6° .

[0092] The GOS value also varies depending on the amount of carbon included in the heat-treated steel 12. Referring to FIG. 35, FIG. 35 shows the measurements when the grain boundary setting angle is set to 15° and is a graph with the horizontal axis representing a carbon content (%) in the heat-treated steel 12 and the vertical axis representing a GOS value ($^{\circ}$). The conventional products are plotted with black circles, and the developed products are plotted with white circles. Further, in the graph of FIG. 35, a straight line representing " $11 \times (\text{carbon content (\%)} - 0.42) + 5.3$ " is indicated by a dashed line.

[0093] Referring to FIG. 35, for the heat-treated steels 12 with a relatively low carbon content, the difference in GOS values at a grain boundary setting angle of 15° between the conventional products (black circles) and the developed products (white circles) is smaller, while for the heat-treated steels 12 with a relatively high carbon content, the difference in GOS values between the conventional products and the developed products is larger. All the developed products (white circles) have a GOS value of " $11 \times (\text{carbon content (\%)} - 0.42) + 5.3$ " or less at a grain boundary setting angle of 15° , while all the conventional products (black circles) have a GOS value exceeding " $11 \times (\text{carbon content (\%)} - 0.42) + 5.3$ " at a grain boundary setting angle of 15° .

[0094] FIG. 36 shows the measurement results of the multiple developed products and the multiple convention-

al products, and is a graph with the horizontal axis representing a GOS value ($^{\circ}$) and the vertical axis representing a cumulative frequency using the area fraction at a grain boundary setting angle of 15° .

[0095] Referring to FIG. 36, for the developed products (dashed lines), the cumulative frequencies using the area fraction up to the GOS value of 10° (in the range of 0° to 10°) exceed 80%. In FIG. 36, the cumulative frequency when the GOS value is 10° , for example, represents how much the cumulative frequencies at the GOS values in the range of 0° to 10° are included in the whole. On the other hand, for the conventional products (solid lines), the GOS values vary greatly, and no cumulative frequencies up to the GOS value of 10° (in the range of 0° to 10°) exceed 80%. The conventional products and the developed products also have a clear difference in cumulative frequencies up to the GOS value of 10° (in the range of 0° to 10°) at a grain boundary setting angle of 15° .

[0096] FIG. 37 is a graph with the horizontal axis representing a carbon content (%) and the vertical axis representing a cumulative frequency using the area fraction up to the GOS value of 10° at a grain boundary setting angle of 15° . The conventional products are plotted with black circles, and the developed products are plotted with white circles. In FIG. 37, a curve of $-0.1C^3 - 1.3C^2 + 1.1C + 0.7$ (wherein C represents the carbon content (%)) is indicated by a dashed line.

[0097] Referring to FIG. 37, for the developed products (white circles), even if the carbon content is changed, the cumulative frequencies up to the GOS value of 10° at a grain boundary setting angle of 15° are relatively large, while for the conventional products (black circles), as the carbon content increases, the cumulative frequencies up to the GOS value of 10° at a grain boundary setting angle of 15° decrease. Additionally, for the developed products (white circles), the cumulative frequencies up to the GOS value of 10° at a grain boundary setting angle of 15° exceed $-0.1C^3 - 1.3C^2 + 1.1C + 0.7$, while for the conventional products (black circles), the cumulative frequencies up to the GOS value of 10° at the grain boundary setting angle of 15° are below $-0.1C^3 - 1.3C^2 + 1.1C + 0.7$.

[0098] FIG. 38 shows a work hardening curve of the steel grade SWRH62A of the heat-treated steel 12 with true strain on the horizontal axis and tensile strength (MPa) on the vertical axis.

[0099] FIG. 38 shows graphs for the four developed products (all dashed lines) and graphs for the two conventional products (all solid lines). As the graphs for the developed products, the graphs (2 graphs) with the temperature (isothermal transformation temperature) of the molten lead 16 set to 425°C , and the graphs with the temperature set to 450°C and 565°C are shown. As the graphs for the conventional products, the graphs with the temperature of the molten lead 16 set to 450°C and 565°C are shown. The graphs (425°C No. 1 and 425°C No. 2) for the two developed products in which the temperature of the molten lead 16 is 425°C are obtained by varying the immersion time of the steel 11 (heat-treated steel 12)

in the molten lead 16.

[0100] Comparing the graphs of the dashed lines (developed products), it can be seen that the developed products with an isothermal transformation temperature of 425°C and 450°C are superior in tensile strength to the developed product with an isothermal transformation temperature of 565°C . It can be seen that the tensile strength of the developed product can be controlled by controlling the isothermal transformation temperature, that is, the temperature of the molten lead 16. In addition, even if the isothermal transformation temperature is lowered to 425°C , the heat-treated steel 12 with excellent tensile strength can be obtained, and the heat loss from the bath 15 can be reduced, and the fuel cost can be reduced by about 20% compared to the case when the isothermal transformation temperature (temperature of the molten lead 16) is set to 565°C .

[0101] FIGS. 39A and 39B are SEM images of the heat-treated steel 12 with an isothermal transformation temperature (lead furnace temperature) of 425°C and a longer immersion time (corresponding to the graph of " 425°C No. 1" in FIG. 38), and FIGS. 40A and 40B are SEM images of the heat-treated steel 12 with an isothermal transformation temperature (lead furnace temperature) of 425°C and a shorter immersion time (about half of No. 1) (corresponding to the graph of " 425°C No. 2" in FIG. 38). FIGS. 39A and 40A are the SEM images at a magnification of 3,500, and FIGS. 39B and 40B are the SEM images at a magnification of 10,000.

[0102] Micro-martensite cannot be found in the SEM images shown in FIGS. 39A and 39B and micro-martensite can be found in the SEM images shown in FIGS. 40A and 40B. However, referring to the graphs in FIG. 38, there is almost no difference between the graphs of 425°C No. 1 and 425°C No. 2, and both the developed products can achieve the higher strength than the conventional product at the same workability (true strain) while maintaining the toughness. The developed products can obtain the problem-free properties even if a small amount of micro-martensite exists.

[0103] FIG. 41 shows work hardening curves for other steel grades, specifically steel grades SWRH42A, SWRH82A, and SWRH82B of the developed products and the conventional products. The developed products with the temperature (isothermal transformation temperature) of the molten lead 16 set to 565°C and 450°C are shown. Also for the steel grades described above other than SWRH62A, when comparing the same steel grade of the conventional product and the developed product, the developed product is superior in tensile strength to the conventional product.

[0104] FIG. 42 shows work hardening curves for other steel grades, that is, the steel grades SWRS92A, 92A-Cr, 92B-Si, and 102A-Cr of the developed products and the conventional products. Also for the steel grades described above, the developed product is superior in tensile strength to the conventional product.

[0105] Compare FIGS. 38, 41, and 42 in terms of car-

bon contents. Focusing on the tensile strength of the developed product when the temperature of the molten lead 16 is set to 450°C, when comparing the same steel grade of the developed product and the conventional product, the lower the carbon content (see, for example, FIG. 38), the greater the slope of the work hardening curve of the developed product compared to the conventional product, and the higher the tensile strength of the developed product. Conversely, as the carbon content increases (see, for example, FIG. 42), the slope of the work hardening curve of the developed product approaches that of the conventional product. However, focusing on the tensile strength immediately after heat treatment (when the true strain is 0), when comparing the same steel grade of the developed product and the conventional product, the tensile strength of the developed product is higher than that of the conventional product for all the steel grades, indicating that the developed product is superior in tensile strength to the conventional product.

[0106] When the temperature of the molten lead 16 is set to 565°C, the difference in slope of the work hardening curves between the developed product and the conventional product is not as great as when the temperature of the molten lead 16 is 450°C. However, even when the temperature of the molten lead 16 is set to 565°C, comparing the same steel grade of the developed product and the conventional product, the tensile strength of the developed product is higher than that of the conventional product for all the steel grades, indicating that the developed product is superior in tensile strength to the conventional product.

[0107] For example, the work hardening curve of the steel grade SWRH82A of the developed product with the lead furnace temperature set to 450°C is almost the same as the work hardening curve of the steel grade SWRH82B (with a higher manganese content) also with the lead furnace temperature set to 450°C. Similarly, the work hardening curve of the steel grade SWRS92A of the developed product with the lead furnace temperature set to 450°C is almost the same as the work hardening curve of the steel grade 92A-Cr (with chromium added) of the developed product also with the lead furnace temperature set to 450°C. This means that the developed product can have high tensile strength without the addition of expensive alloying elements (manganese or chromium described above). In other words, the developed product achieves high strength without employing the steel grades containing expensive alloying elements (manganese, chromium, or the like). Cost reduction can be achieved.

[0108] FIG. 43 shows the measurements of a reduction of area during a tensile test for each of the conventional products and the developed products with the horizontal axis representing tensile strength during the tensile test and the vertical axis representing a reduction of area. The broken line shown in the graph is a curve representing $-0.000064 \times TS^2 + 0.09 \times TS + 46$ (%) (wherein TS represents the tensile strength (MPa)). For both the

developed products (white circles) and the conventional products (black circles), the reduction of area tends to decrease as the tensile strength increases. The developed products (white circles) have better reduction of area than the conventional products (black circles). Referring to FIG. 43, the reduction of area for all the developed products exceeds $-0.000064 \times TS^2 + 0.09 \times TS + 46$ %, while no reduction of area for all the conventional products exceeds $-0.000064 \times TS^2 + 0.09 \times TS + 46$ %. The conventional product and the developed product can also be clearly distinguished from each other by the reduction of area.

[0109] FIG. 44 shows S-S curves of the steel grade SWRH62A of the conventional product and the developed products with the horizontal axis representing an elongation (%) during the tensile test, and the vertical axis representing a load (tensile strength) (MPa) during the tensile test. FIG. 45 shows S-S curves of the steel grade 102A-Cr of the conventional product and the developed products.

[0110] When a force is applied to a material, the material initially deforms in proportion to the magnitude of the force, like a spring, and after a certain magnitude of force, it begins to deform significantly. This magnitude of the force is referred to as a yield point, and a region before the yield point is referred to as an elastic region and a region after the yield point is referred to as a plastic region. When the force is removed in the elastic region, the material returns to its original shape, but when the force is applied beyond the yield point to the plastic region, the material does not return to its original shape and remains deformed even when the force is removed.

[0111] Referring to FIG. 44, when the carbon content of the heat-treated steel 12 is relatively low, the yield points (the load with a sharp change in slope in FIG. 44 is the yield point) for the developed products (broken lines) are clear. On the other hand, the yield point for the conventional product (solid line) is unclear.

[0112] Referring to FIG. 45, when the carbon content of heat-treated steel 12 is relatively high, the yield points not only for the conventional product but also for the developed products are unclear.

[0113] FIG. 46 is a partially enlarged view of FIG. 44. The load (tensile strength) at the intersection of the S-S curve and a straight line β obtained by moving a straight line α in contact with the elastic region of the S-S curve parallel by 0.2% of elongation is referred to as "0.2% proof stress". The load (tensile strength) at the intersection of the S-S curve and a straight line γ obtained by moving the straight line α parallel by 0.4% of elongation is referred to as "0.4% proof stress".

[0114] FIG. 47 shows a graph with the horizontal axis representing a carbon content and the vertical axis representing a difference between the 0.4% proof stress and the 0.2% proof stress (hereinafter referred to as difference in proof stress) for each of a large number of developed products and conventional products. Further, in FIG. 47, a straight line representing $45 \times \text{carbon content}$

(%) - 3" (MPa) is indicated by a broken line. Regardless of the carbon content, the difference in proof stress of the developed products (white circles) is lower than that of the conventional products (black circles). In addition, the difference in proof stress of all the conventional products (black circles) exceeds " $45 \times \text{carbon content} - 3$ " MPa, while the difference in proof stress of all the developed products (white circles) is all " $45 \times \text{carbon content} - 3$ " MPa or less. The conventional products and the developed products can be also clearly distinguished from each other by the difference in proof stress.

[0115] Lowering the isothermal transformation temperature (lead furnace temperature) can provide the tensile strength equal to or higher than that of conventional products. As an example, when wire mesh is made using the heat-treated steel 12 of the developed product which has been plated, a product with higher strength and greater ductility than the conventional product can be obtained. Plating after heat treatment and knitting mesh to form wire mesh or gabion may provide high strength and impact resistance compared to the conventional products.

REFERENCE SIGNS LIST

[0116]

- 11: steel
- 12: heat-treated steel
- 13: power source
- 14: feed roll
- 15: bath
- 16: molten lead

Claims

1. A heat-treated steel which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities, **characterized in that:**
an average crystal grain size at a grain boundary setting angle of 15° is $10 \times C + 7$ (μm) or less (wherein C represents a carbon content (%)).
2. The heat-treated steel according to claim 1, **characterized in that**
(average crystal grain size at a surface portion at a grain boundary setting angle of 15°)/(average crystal grain size at a center portion at a grain boundary setting angle of 15°) is 0.70 or more and 1.10 or less.
3. A heat-treated steel which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities, **characterized in that:**

(the number of crystal grains at a grain boundary setting angle of 5°)/(the number of crystal grains at a grain boundary setting angle of 15°) is $5.4 \times C - 0.95$ or less (wherein C represents a carbon content (%)).

4. A heat-treated steel which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities, **characterized in that:**
(the number of crystal grains at a grain boundary setting angle of 2°)/(the number of crystal grains at a grain boundary setting angle of 15°) is $9.8 \times C - 1.9$ or less (wherein C represents a carbon content (%)).
5. A heat-treated steel which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities, **characterized in that:**
a GOS value at a grain boundary setting angle of 15° is $11 \times (C - 0.42) + 5.3$ or less (wherein C represents a carbon content (%)).
6. A heat-treated steel which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities, **characterized in that:**
a cumulative frequency of a GOS value in a range of 0° to 10° at a grain boundary setting angle of 15° is $-0.1C^3 - 1.3C^2 + 1.1C + 0.7$ or more (wherein C represents a carbon content (%)).
7. A heat-treated steel which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities, **characterized in that:**
when a structure is observed with a backscattered electron (BSE) image, in a layered structure of ferrite and an iron carbide, an area fraction of the branched, bent, or curved iron carbide is 9% or more in a field of view.
8. A heat-treated steel which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities, **characterized in that:**
when a structure is observed with a scanning electron microscope (SEM), in a layered structure of ferrite and an iron carbide, a spherical protrusion is observed on a surface of the iron carbide.
9. A heat-treated steel which contains 0.38 to 1.05%

by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities, **characterized in that:**

when a structure is observed with a scanning electron microscope (SEM), in a layered structure of ferrite and an iron carbide, a surface of the iron carbide has unevenness, and a rod-shaped or plate-shaped relatively isotropic iron carbide, which is three-dimensionally comb-shaped or mesh-shaped, is produced.

10. A heat-treated steel which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities, **characterized in that:**
when a tensile strength is TS (MPa), a reduction of area is $-0.000064TS^2 + 0.09TS + 46$ (%) or more.

11. A heat-treated steel which contains 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities, **characterized in that:**
a difference in proof stress obtained by subtracting a 0.2% proof stress obtained in a S-S curve from a 0.4% proof stress obtained in the S-S curve is $45 \times C - 3$ (MPa) or less (wherein C represents a carbon content (%)).

12. A heat treatment method for a steel, **characterized by** comprising the steps of:

preparing a steel containing 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities;
causing the steel itself to generate heat to directly heat the steel; and
passing the heated steel through a bath in which a cooling medium capable of isothermal transformation is stored to cool the steel, wherein a temperature gradient in a final stage of heating of the heating step is the largest, and the heated steel is allowed to enter the cooling medium immediately after the steel reaches a predetermined maximum heating temperature in the final stage of heating of the heating step to start the cooling without maintaining the predetermined maximum heating temperature.

13. A heat treatment method for a steel, comprising:
heating a steel from room temperature to 820°C or more within a few seconds, and cooling the heated steel to 620°C or less within a few seconds without maintaining a maximum heating temperature, the

steel containing 0.38 to 1.05% by mass of C, 0.0 to 1.0% by mass of Mn, 0.0 to 0.50% by mass of Cr, and 0.0 to 1.5% by mass of Si with the remainder being Fe and unavoidable impurities.

FIG.1

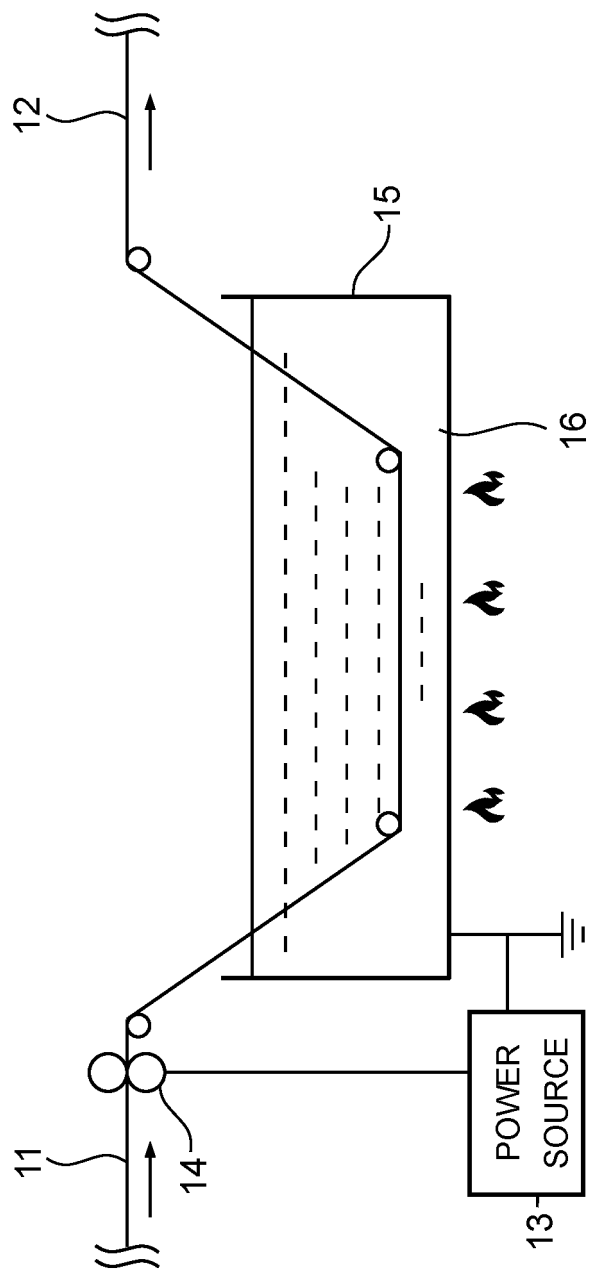


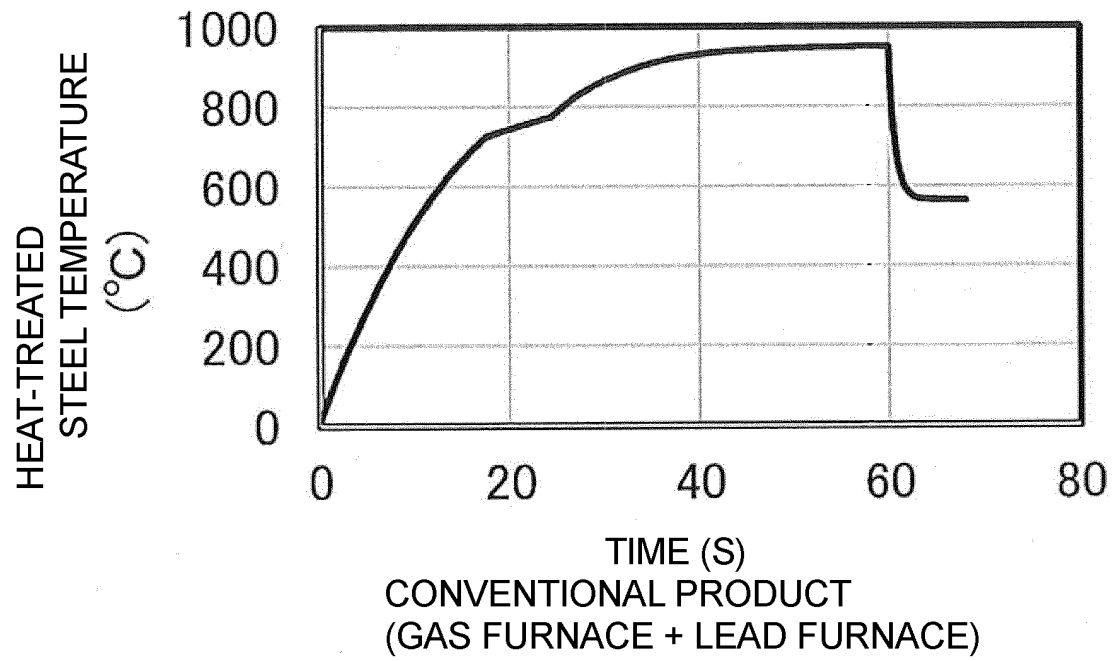
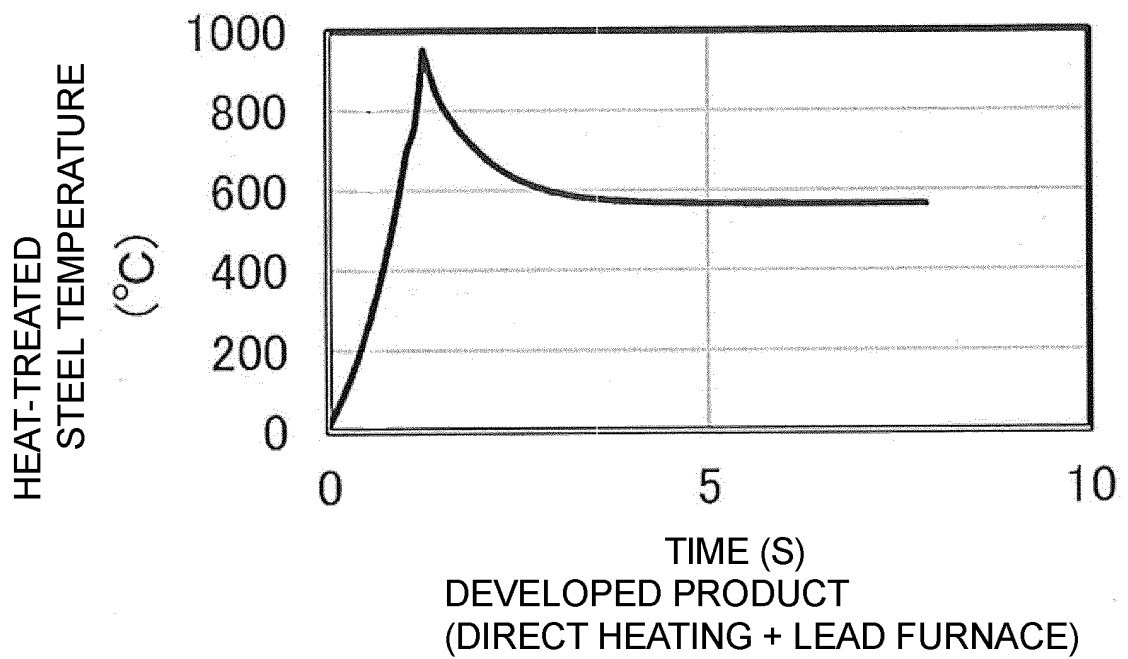
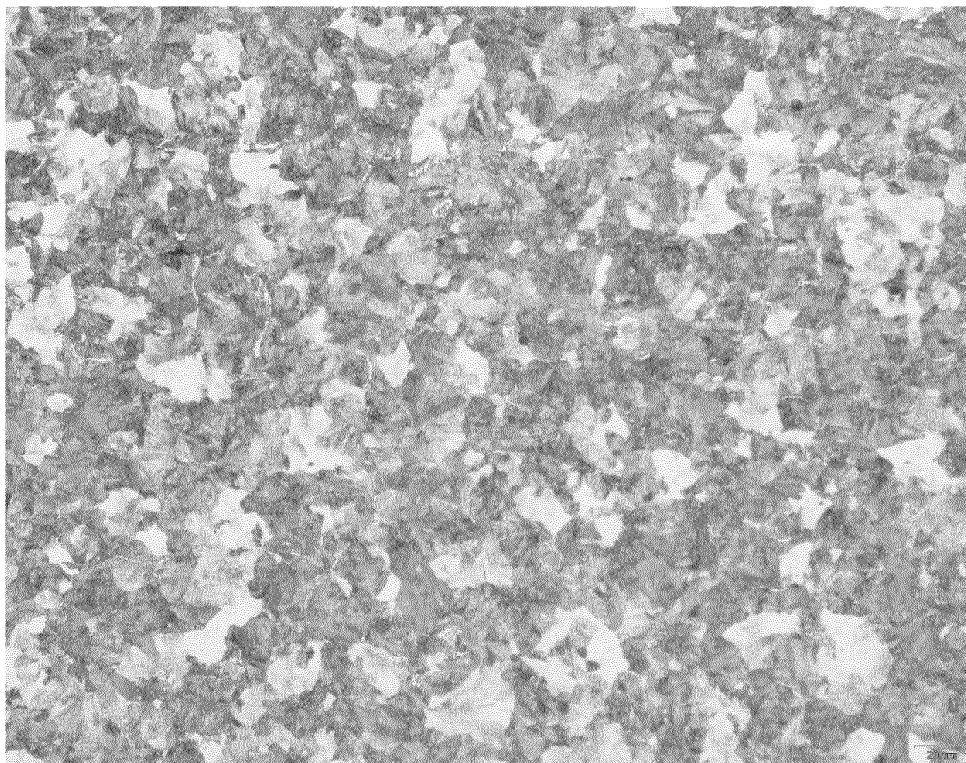
FIG.2**FIG.3**

FIG.4

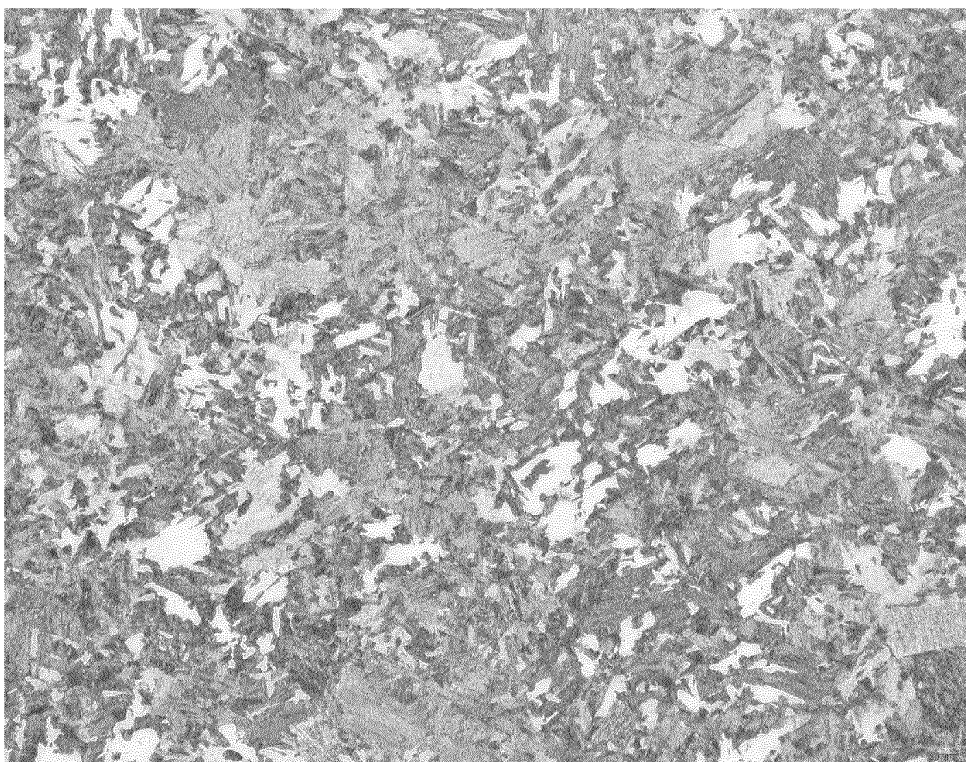
STEEL GRADE NAME	COMPOSITION (%)						
	C	Mn	Si	Cr	P	S	Cu
SWRH42A	0.44	0.50	0.20	0.02	0.018	0.006	-
SWRH62A	0.63	0.46	0.15	0.01	0.014	0.003	0.01
SWRH82A	0.82	0.47	0.18	0.028	0.006	0.007	0.01
SWRH82B	0.84	0.73	0.22	0.01	0.011	0.004	0.01
SWRS92A	0.91	0.49	0.19	0.01	0.008	0.007	0.01
92ACr	0.92	0.31	0.16	0.19	0.011	0.008	-
92BSi	0.94	0.73	0.94	0.01	0.009	0.003	0.00
102ACr	1.02	0.30	0.19	0.18	0.01	0.01	-

FIG.5



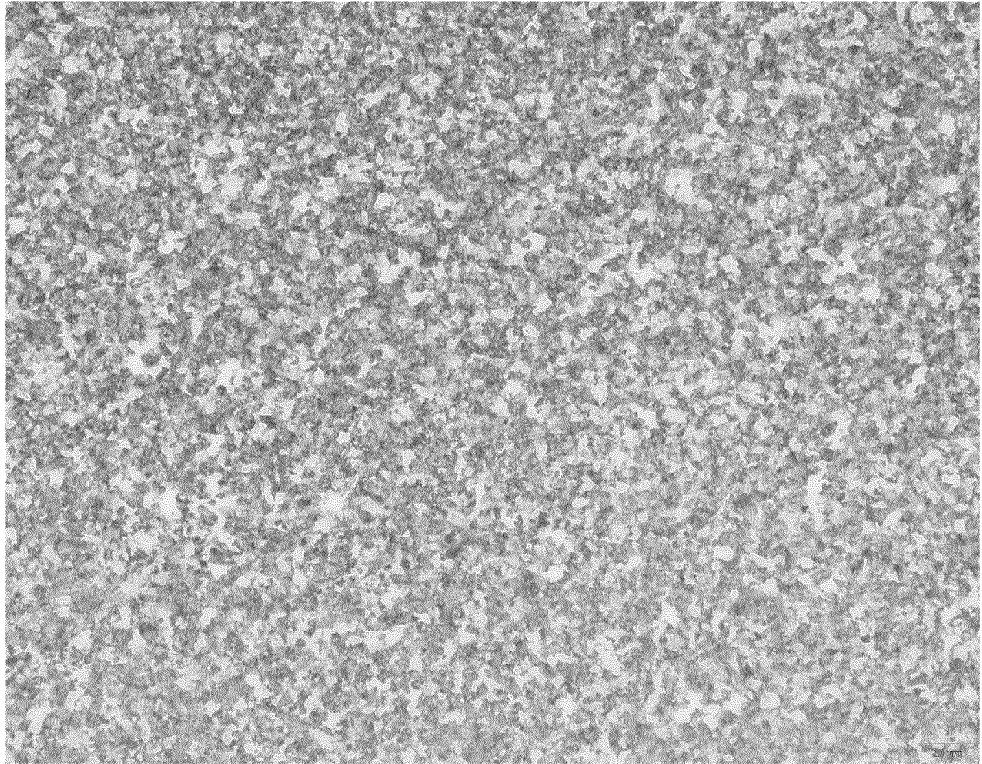
SWRH62A, CONVENTIONAL PRODUCT-LEAD FURNACE
TEMPERATURE 565°C: OPTICAL MICROSCOPE IMAGE

FIG.6



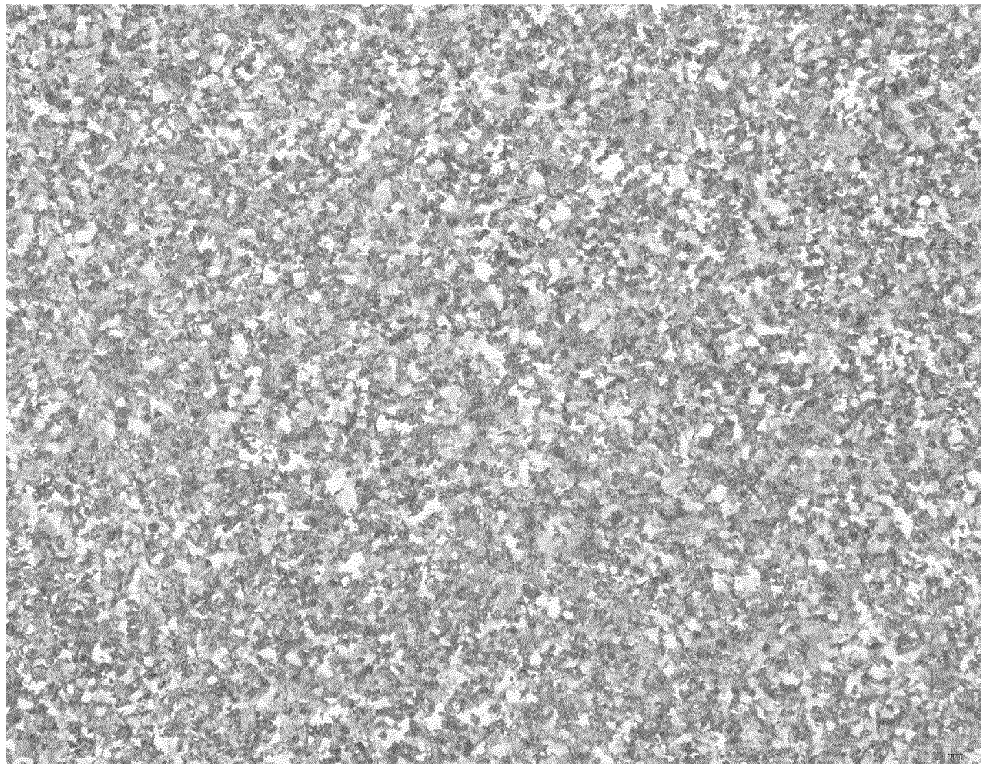
SWRH62A, CONVENTIONAL PRODUCT-LEAD FURNACE
TEMPERATURE 450°C: OPTICAL MICROSCOPE IMAGE

FIG.7



SWRH62A, DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 565°C: OPTICAL MICROSCOPE IMAGE

FIG.8



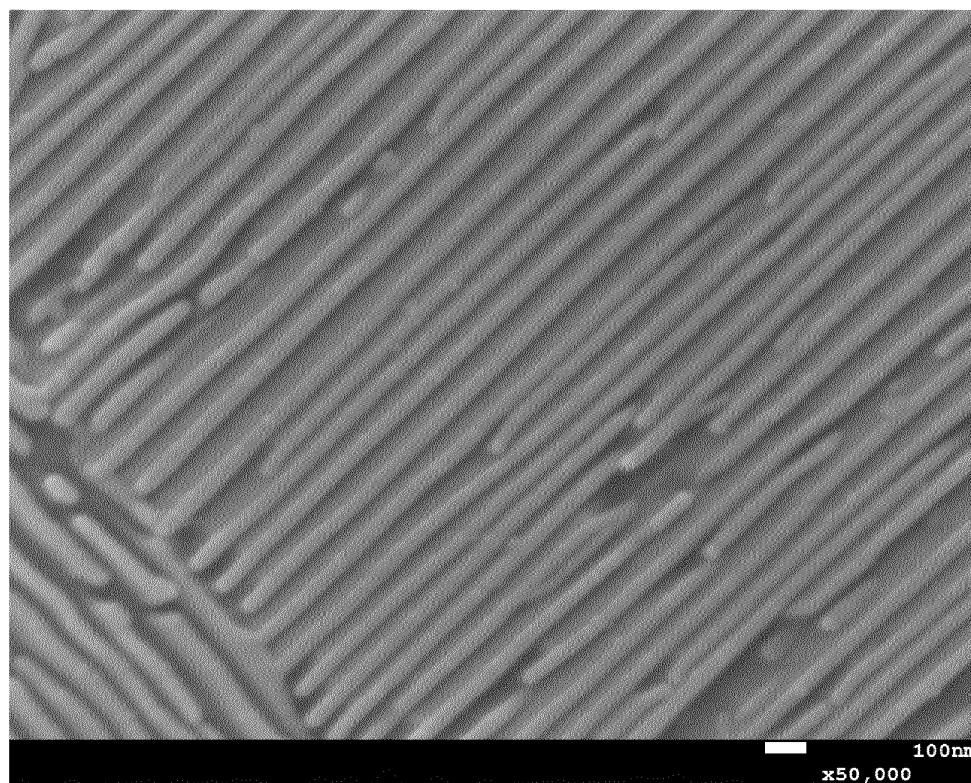
SWRH62A, DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 450°C: OPTICAL MICROSCOPE IMAGE

FIG.9A



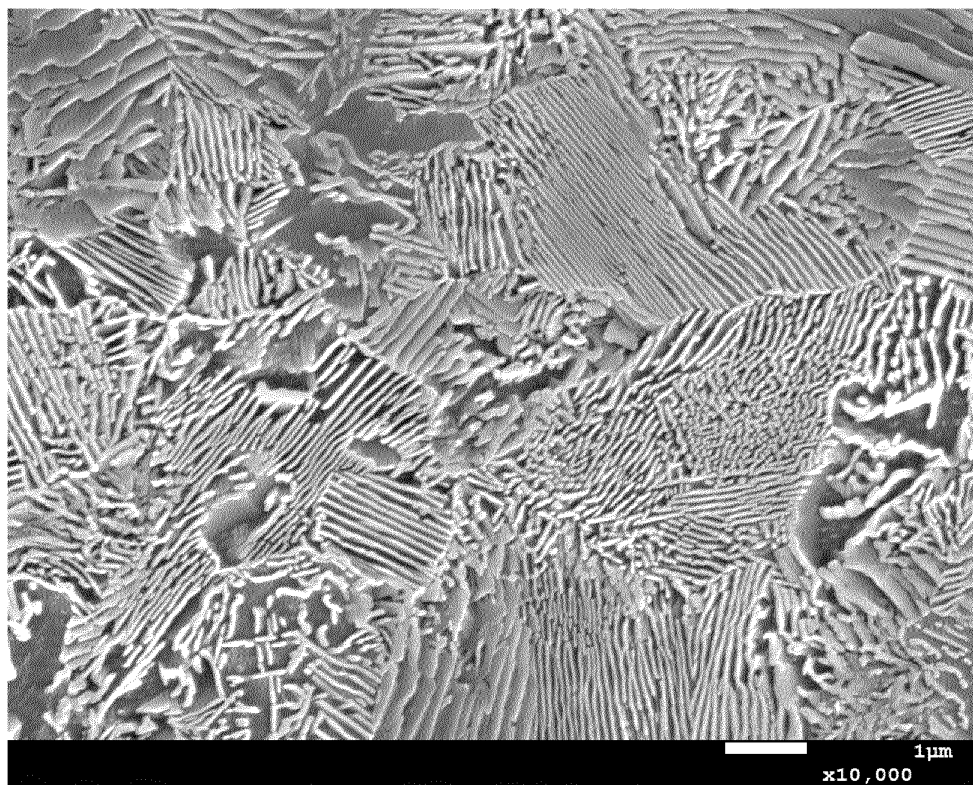
SWRH62A, CONVENTIONAL PRODUCT-LEAD FURNACE
TEMPERATURE 565°C: SEM IMAGE

FIG.9B



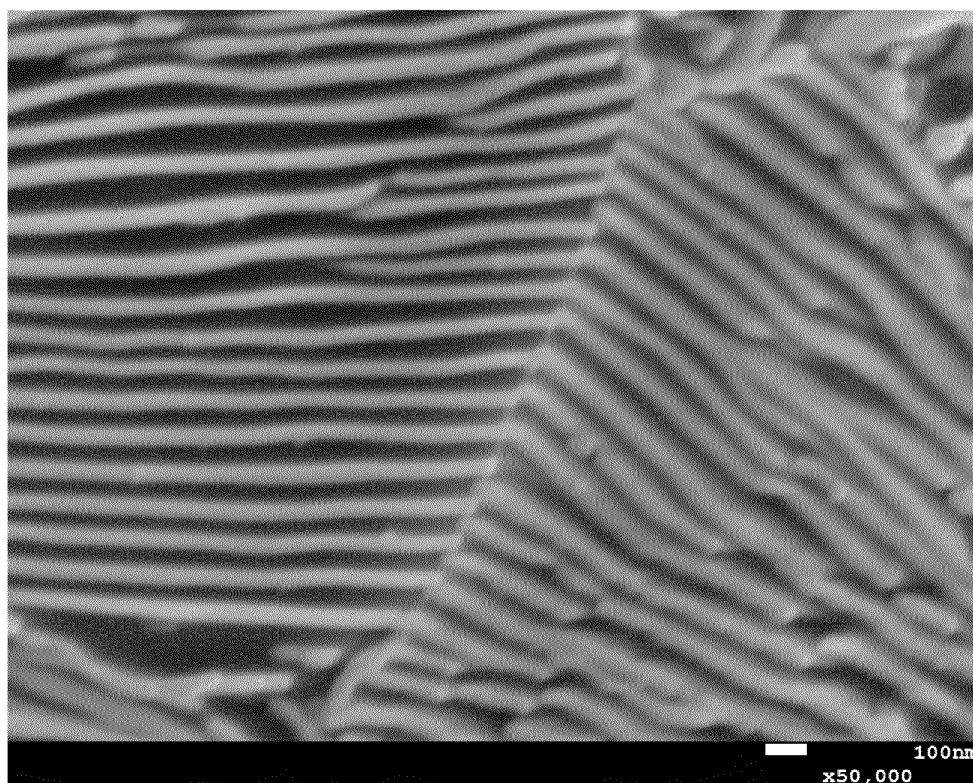
SWRH62A, CONVENTIONAL PRODUCT-LEAD FURNACE
TEMPERATURE 565°C: SEM IMAGE

FIG.10A



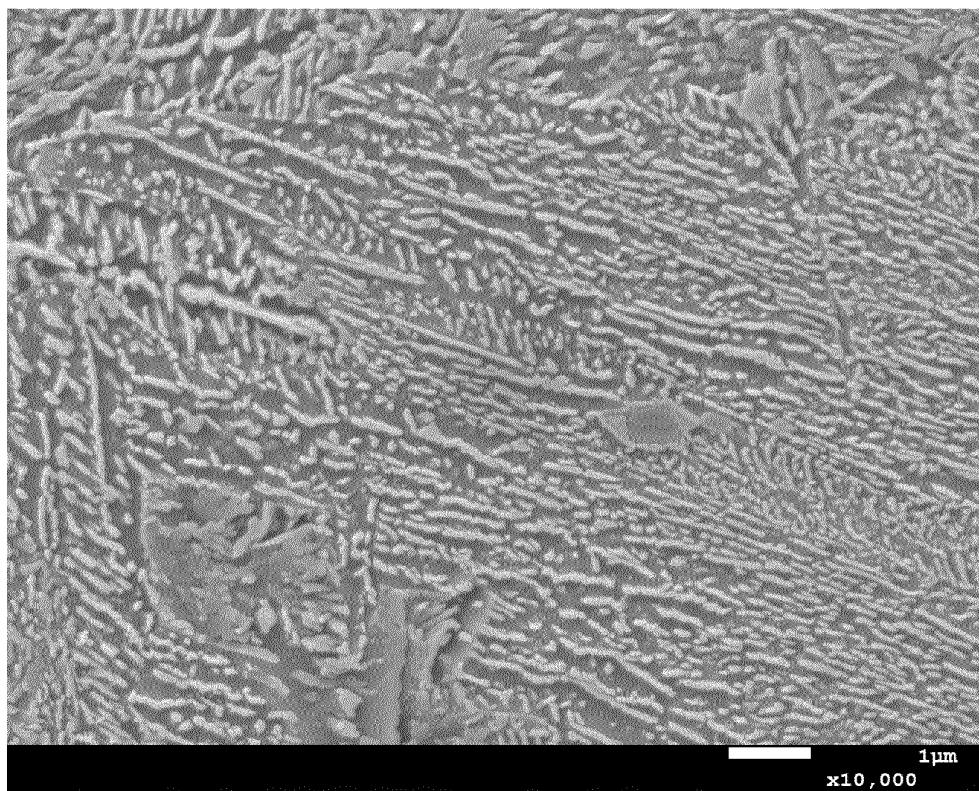
SWRH62A, DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 565°C: SEM IMAGE

FIG.10B



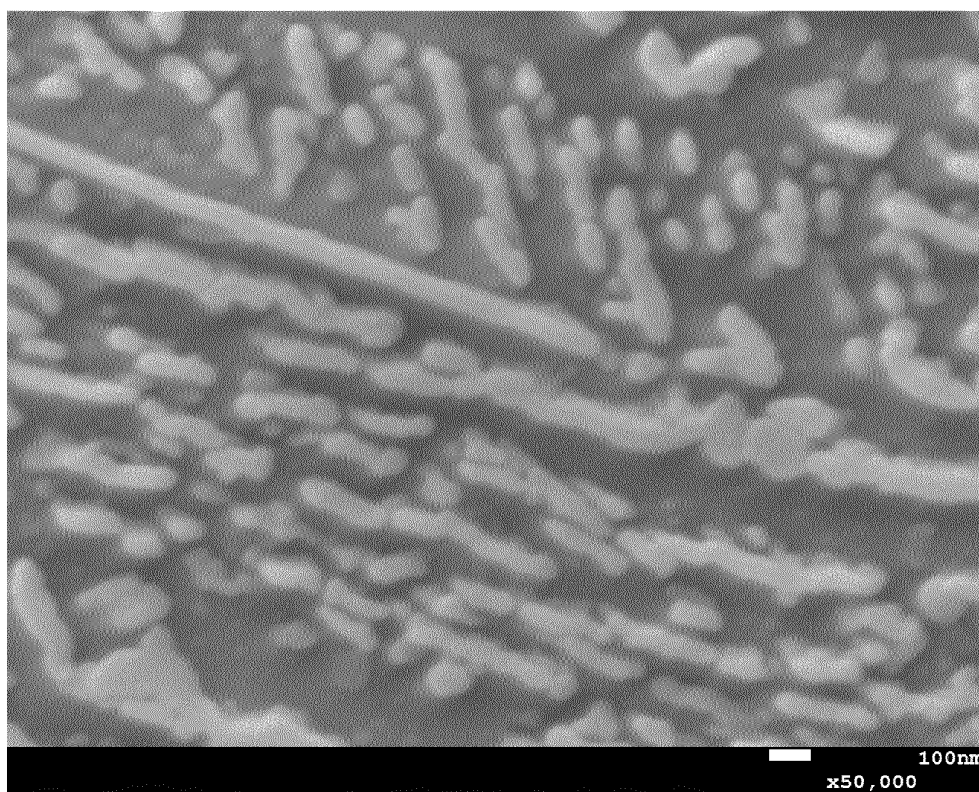
SWRH62A, DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 565°C: SEM IMAGE

FIG.11A



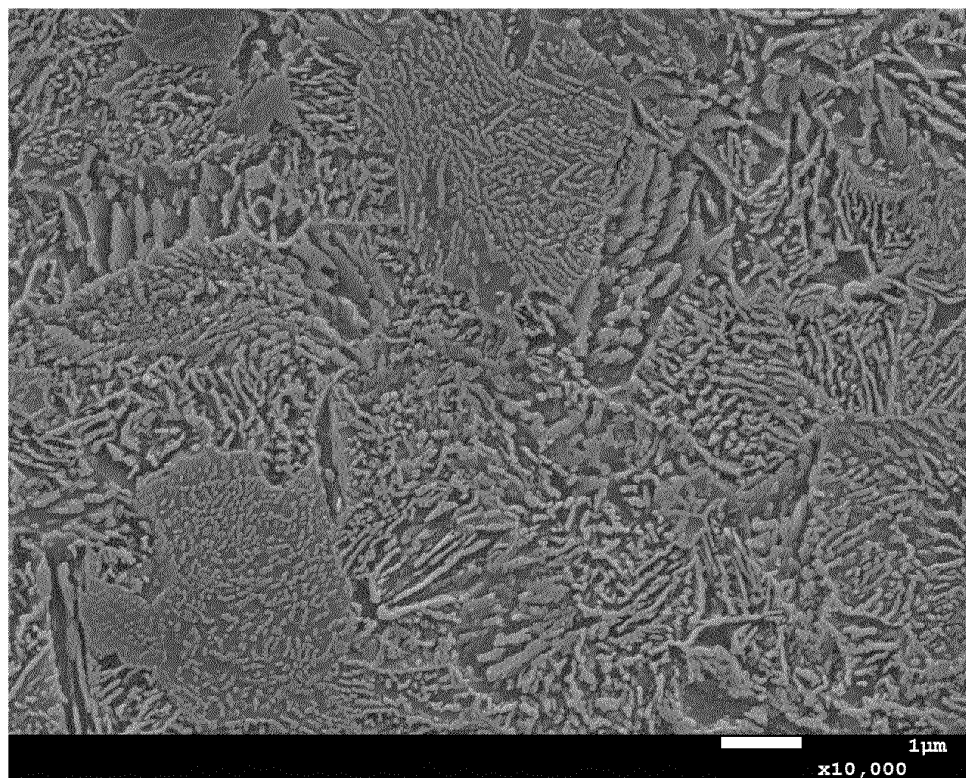
SWRH62A, CONVENTIONAL PRODUCT-LEAD FURNACE
TEMPERATURE 450°C: SEM IMAGE

FIG.11B



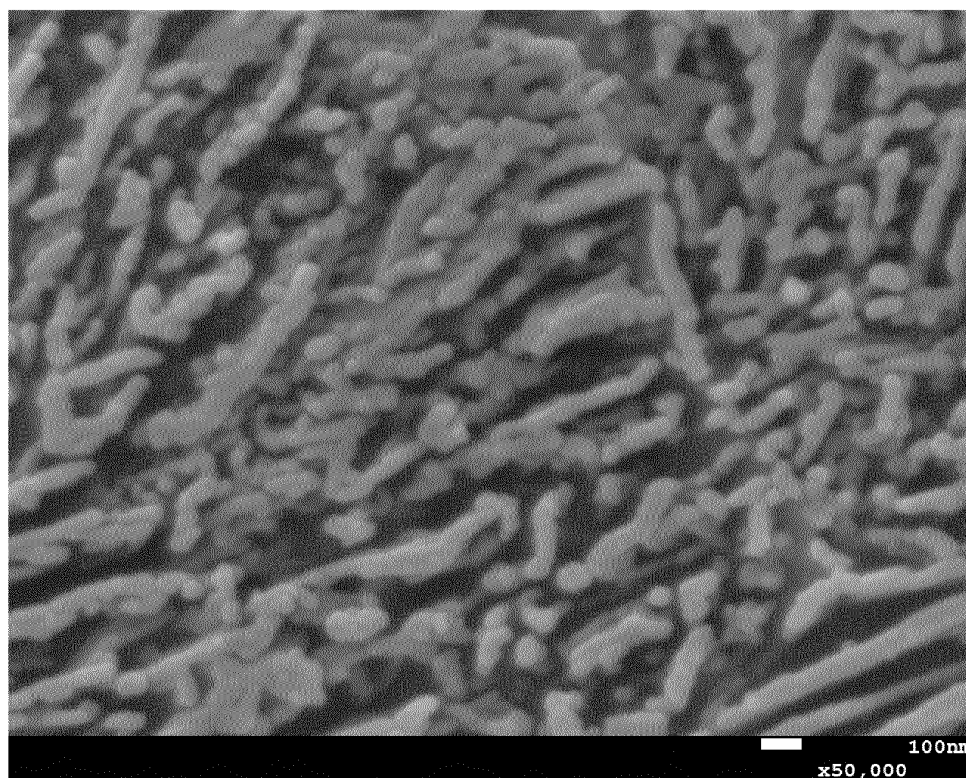
SWRH62A, CONVENTIONAL PRODUCT-LEAD FURNACE
TEMPERATURE 450°C: SEM IMAGE

FIG.12A



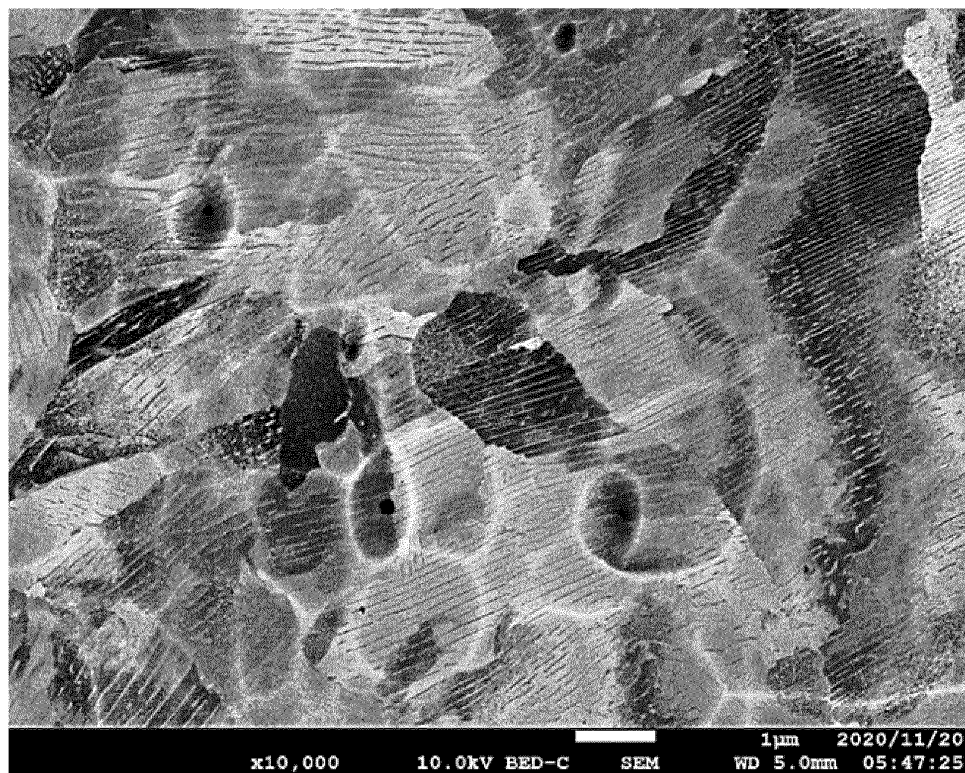
SWRH62A, DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 450°C: SEM IMAGE

FIG.12B



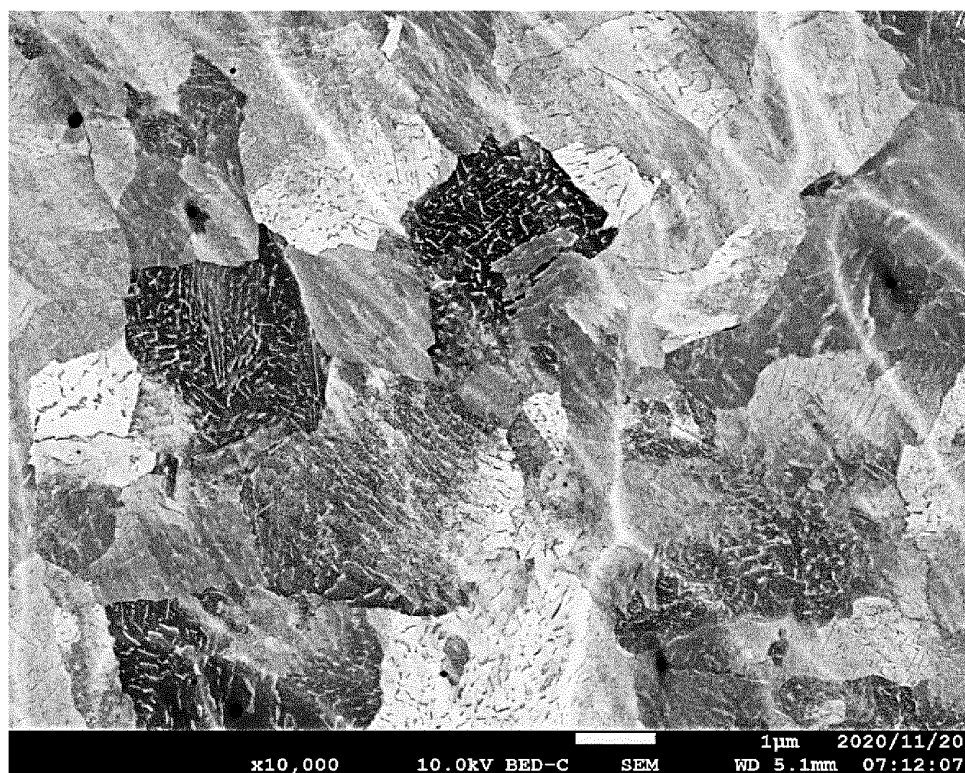
SWRH62A, DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 450°C: SEM IMAGE

FIG.13



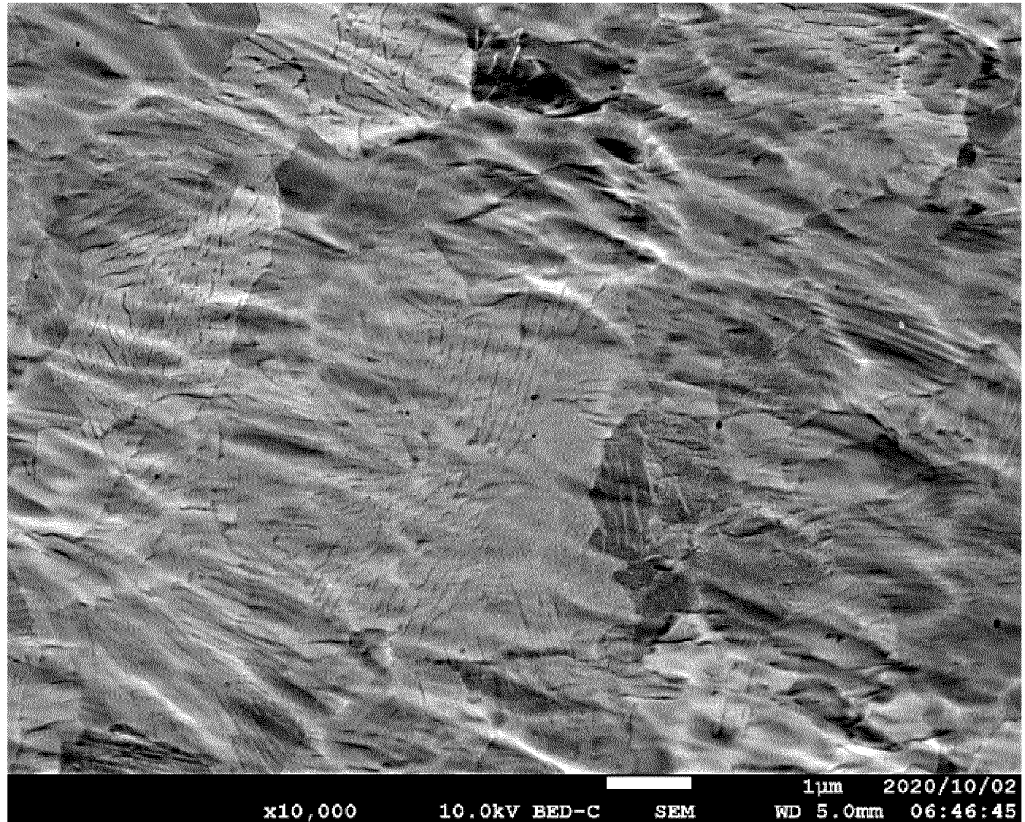
SWRH62A, CONVENTIONAL PRODUCT-LEAD FURNACE
TEMPERATURE 565°C: BSE IMAGE

FIG.14



SWRH62A, DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 450°C: BSE IMAGE

FIG.15



SWRH62A, DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 565°C: BSE IMAGE

FIG.16

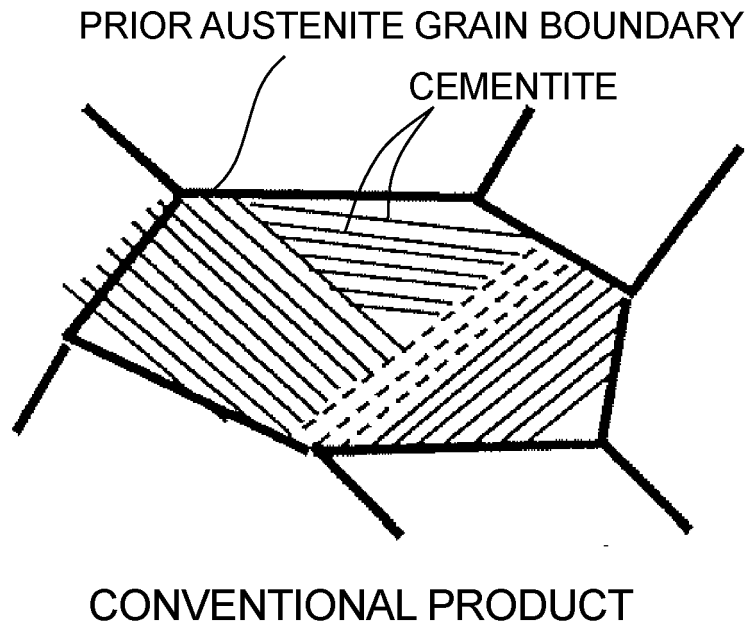


FIG.17

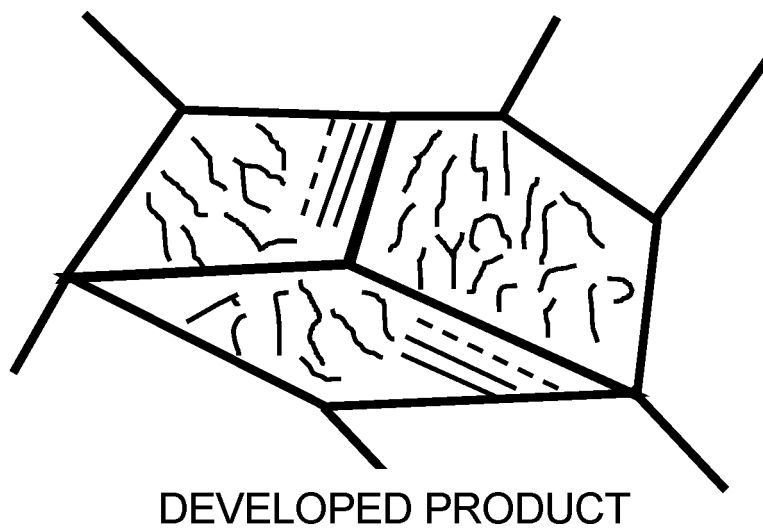
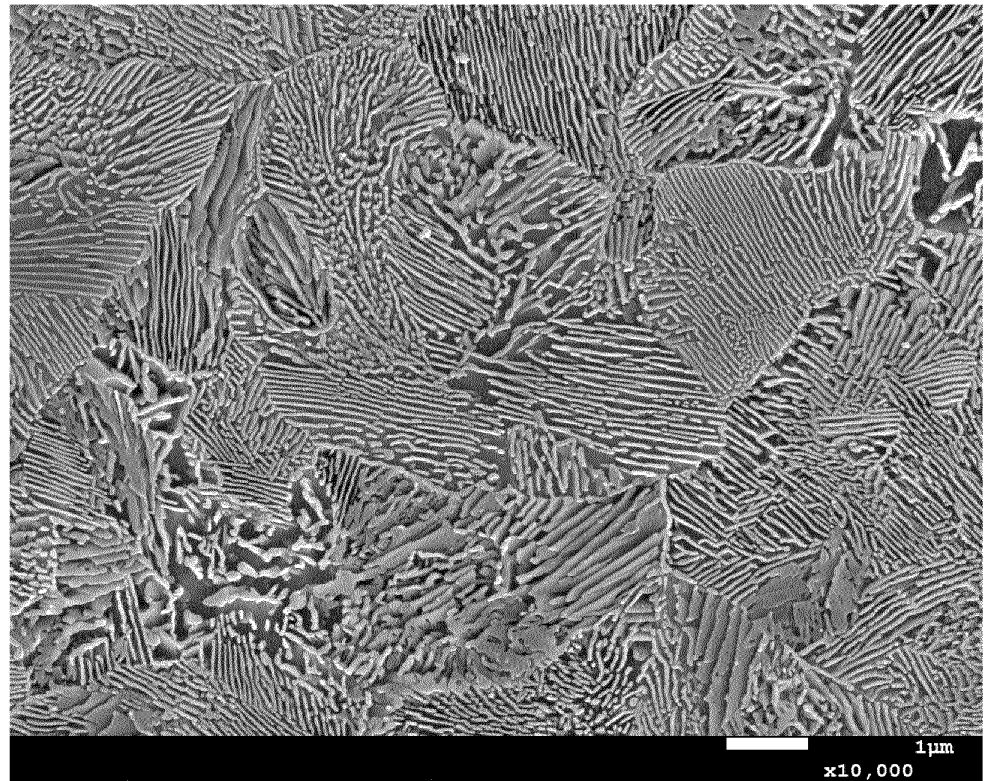
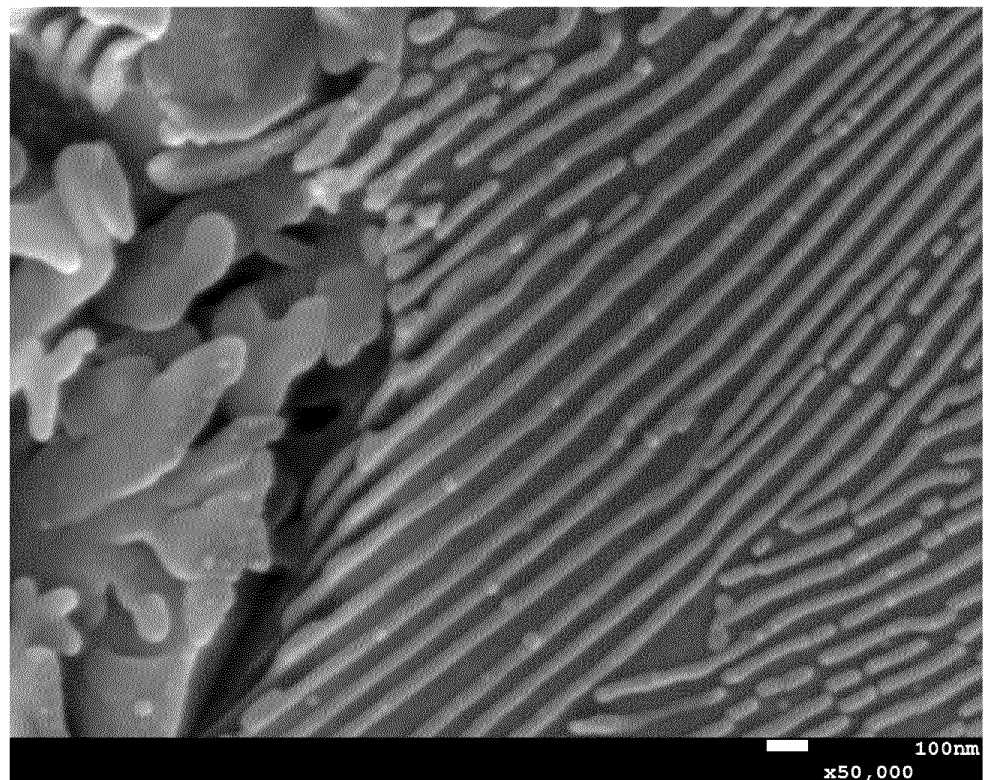


FIG.18A



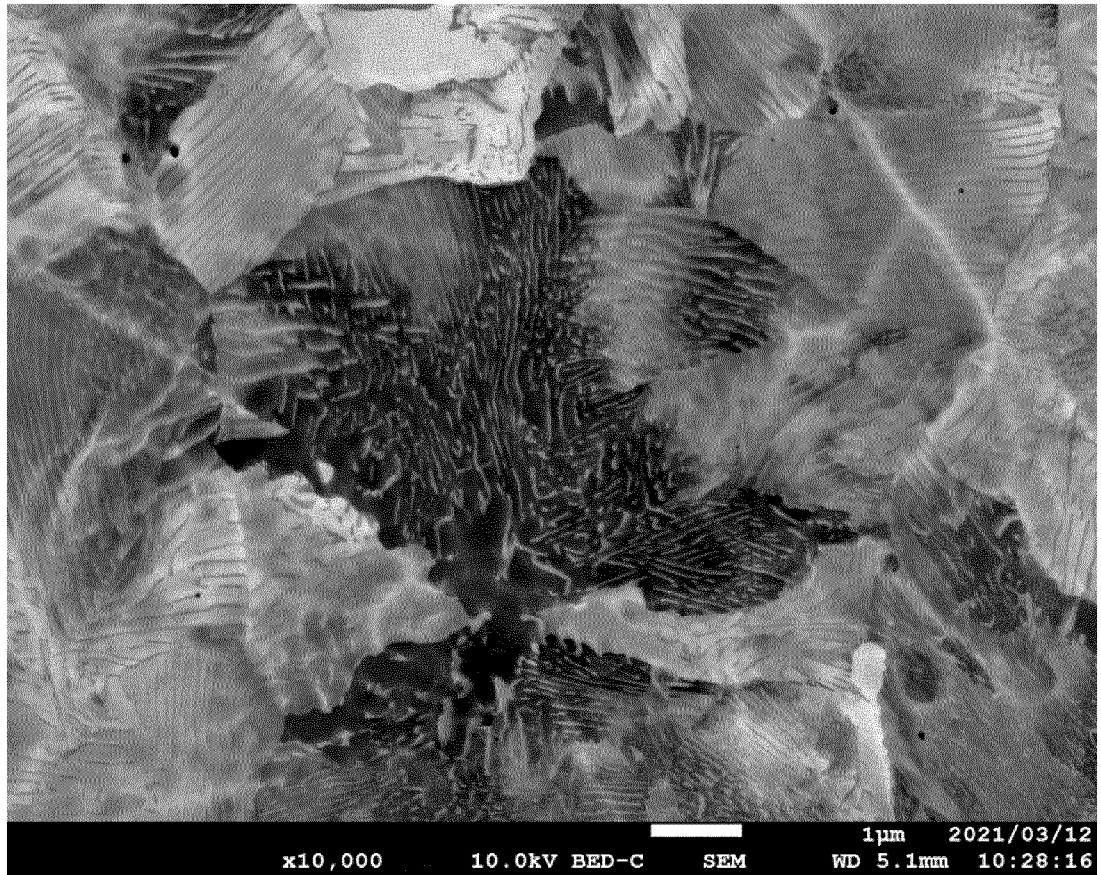
DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 565°C, SWRS92A: SEM IMAGE

FIG.18B



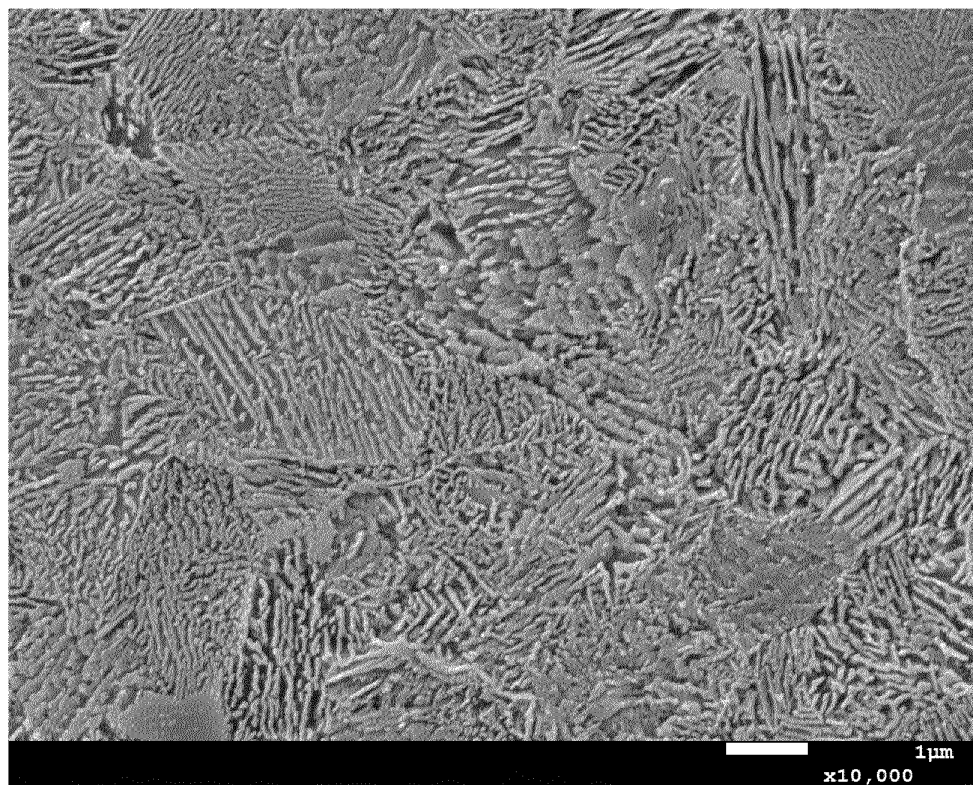
DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 565°C, SWRS92A: SEM IMAGE

FIG.19



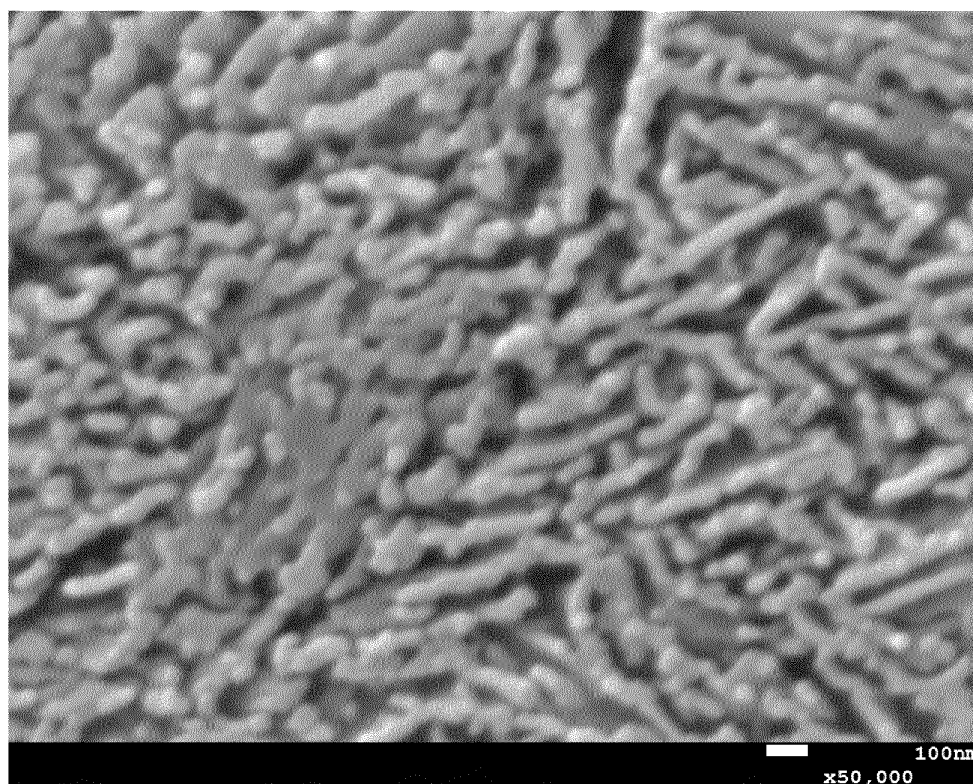
DEVELOPED PRODUCT-LEAD FURNACE TEMPERATURE
565°C, SWRS92A: BSE IMAGE

FIG.20A



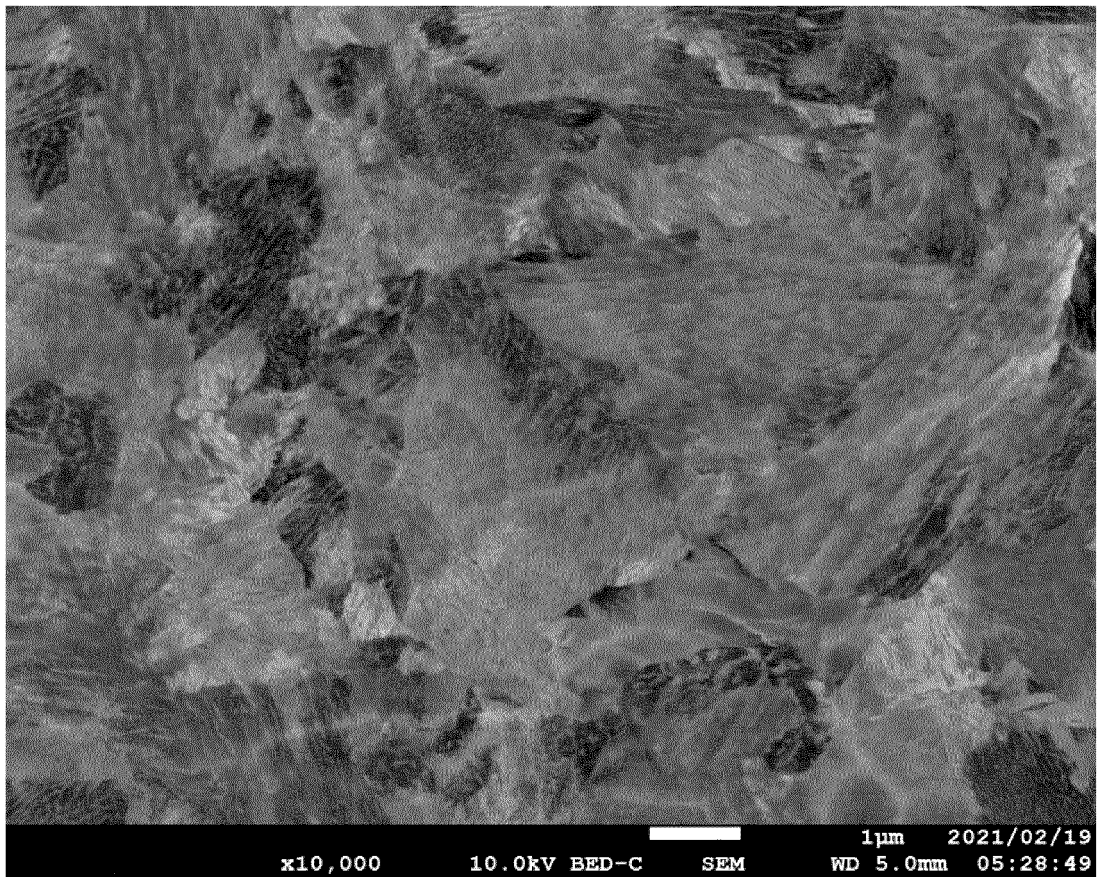
DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 450°C, SWRS92A: SEM IMAGE

FIG.20B



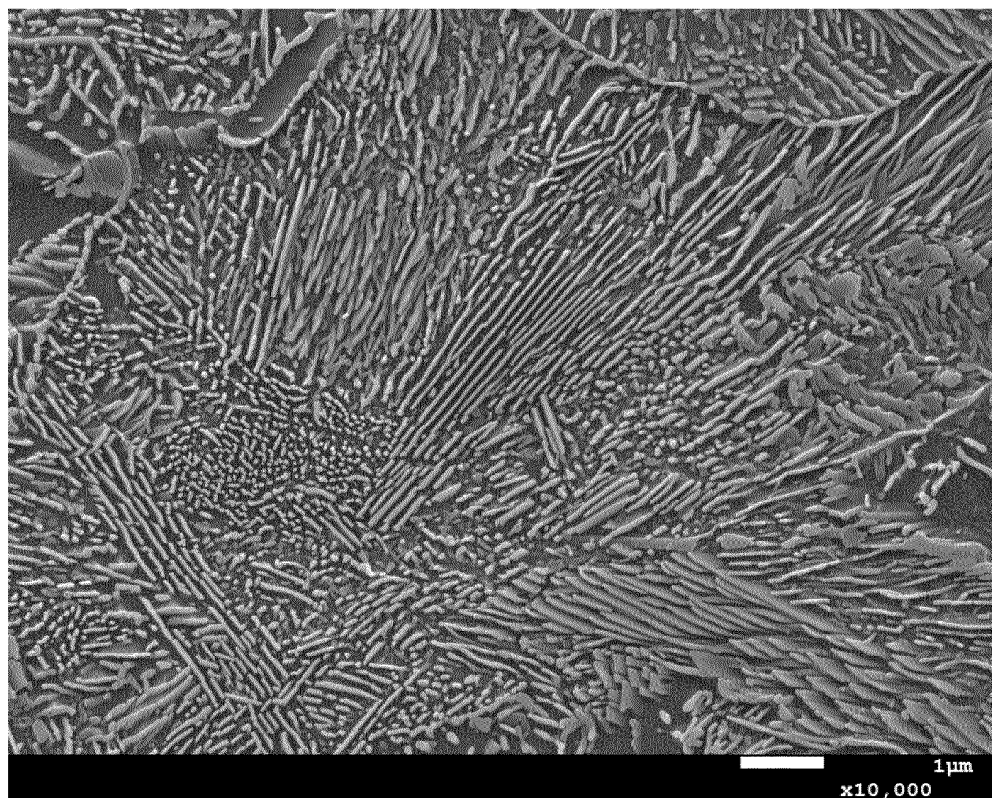
DEVELOPED PRODUCT-LEAD FURNACE
TEMPERATURE 450°C, SWRS92A: SEM IMAGE

FIG.21



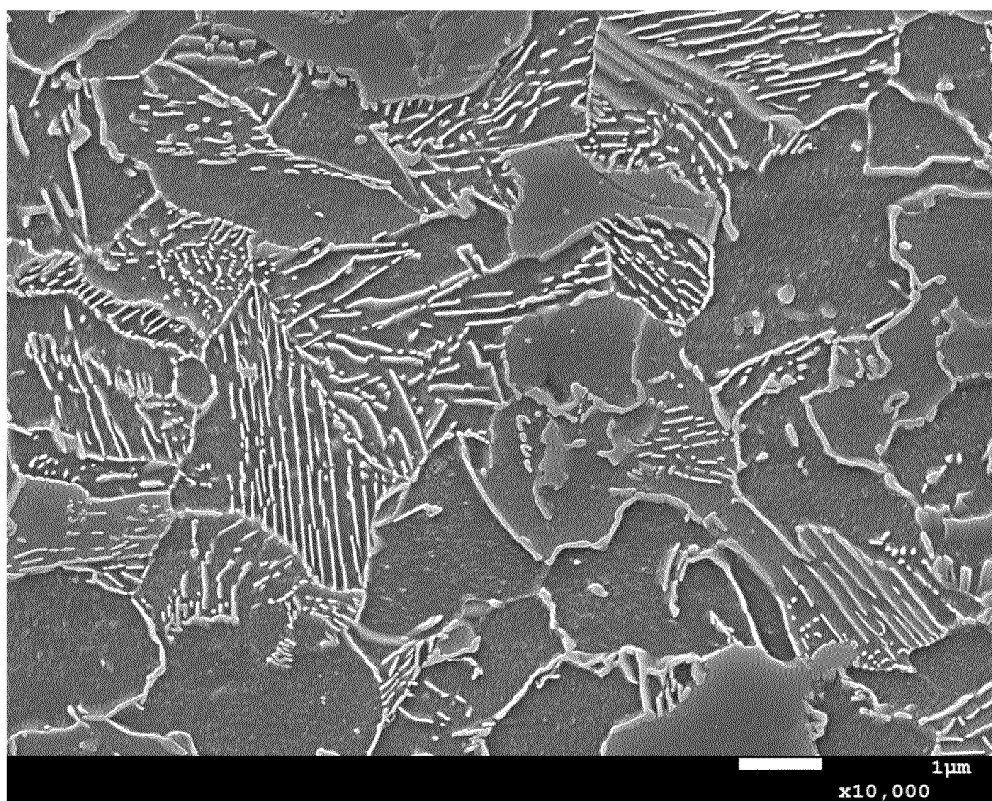
DEVELOPED PRODUCT-LEAD FURNACE TEMPERATURE 450°C,
SWRS92A: BSE IMAGE

FIG.22A



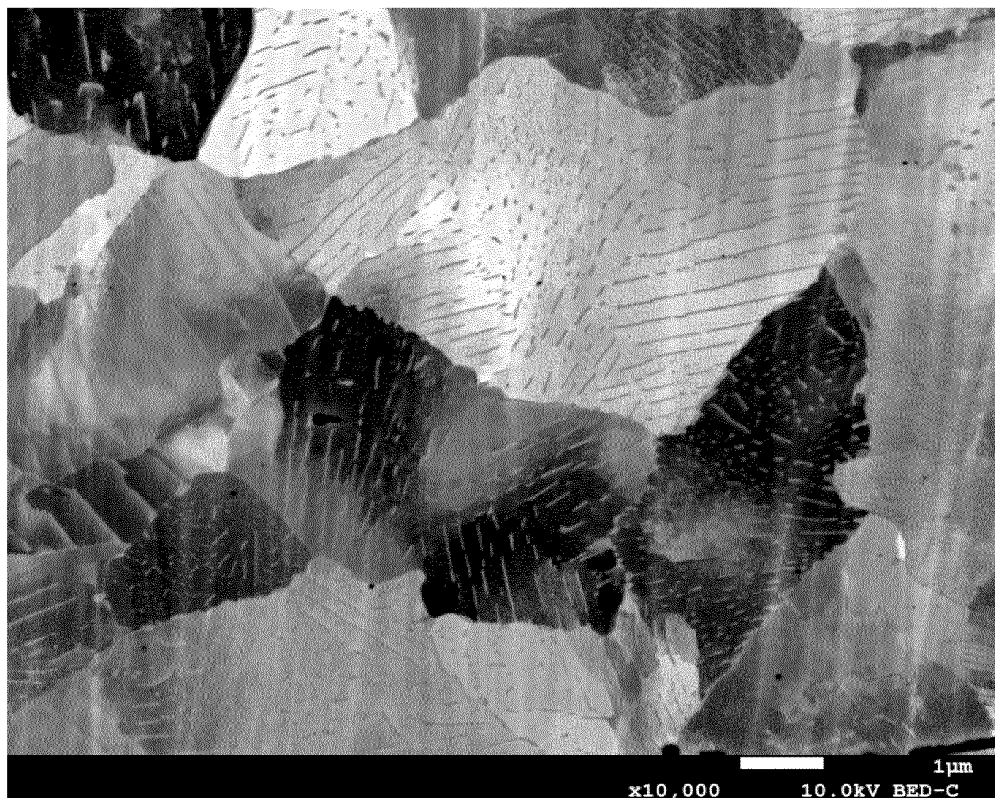
SWRH42A, CONVENTIONAL PRODUCT-565°C: SEM IMAGE

FIG.22B



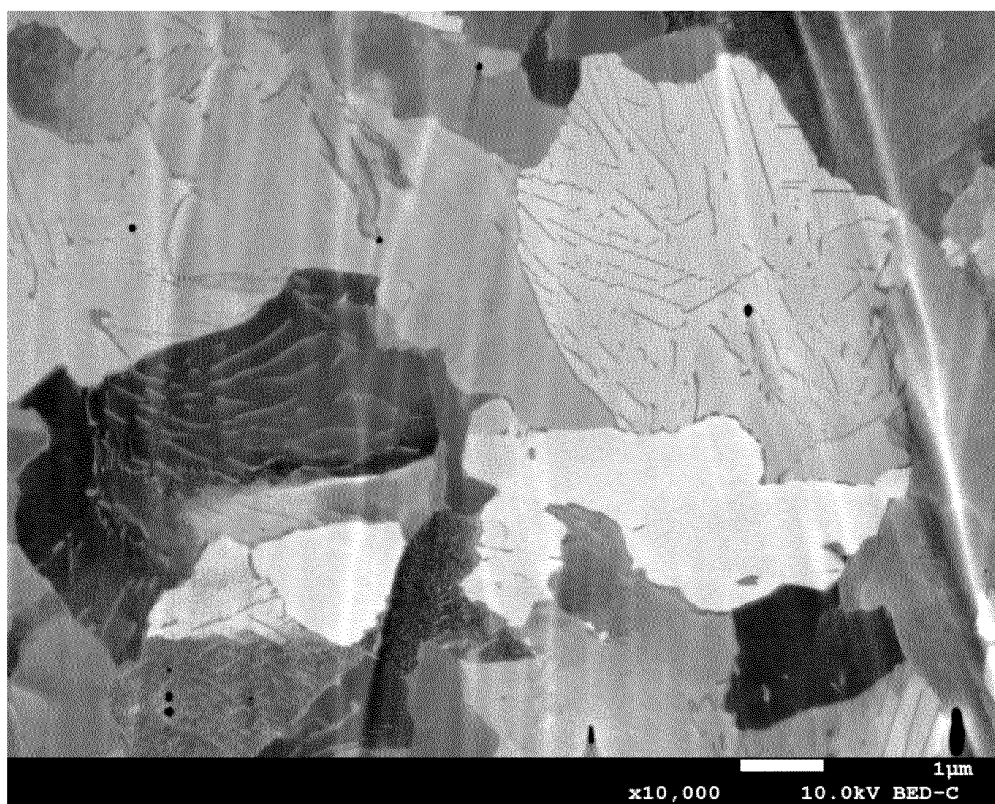
SWRH42A, DEVELOPED PRODUCT-565°C: SEM IMAGE

FIG.23A



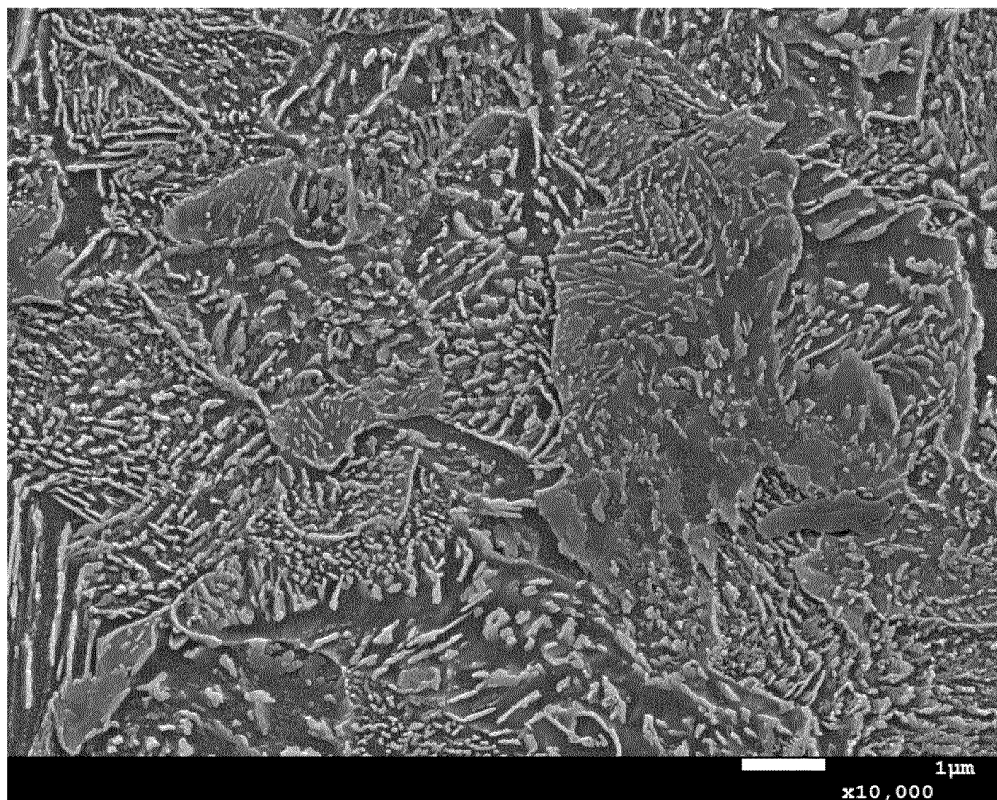
SWRH42A, CONVENTIONAL PRODUCT-565°C: BSE IMAGE

FIG.23B



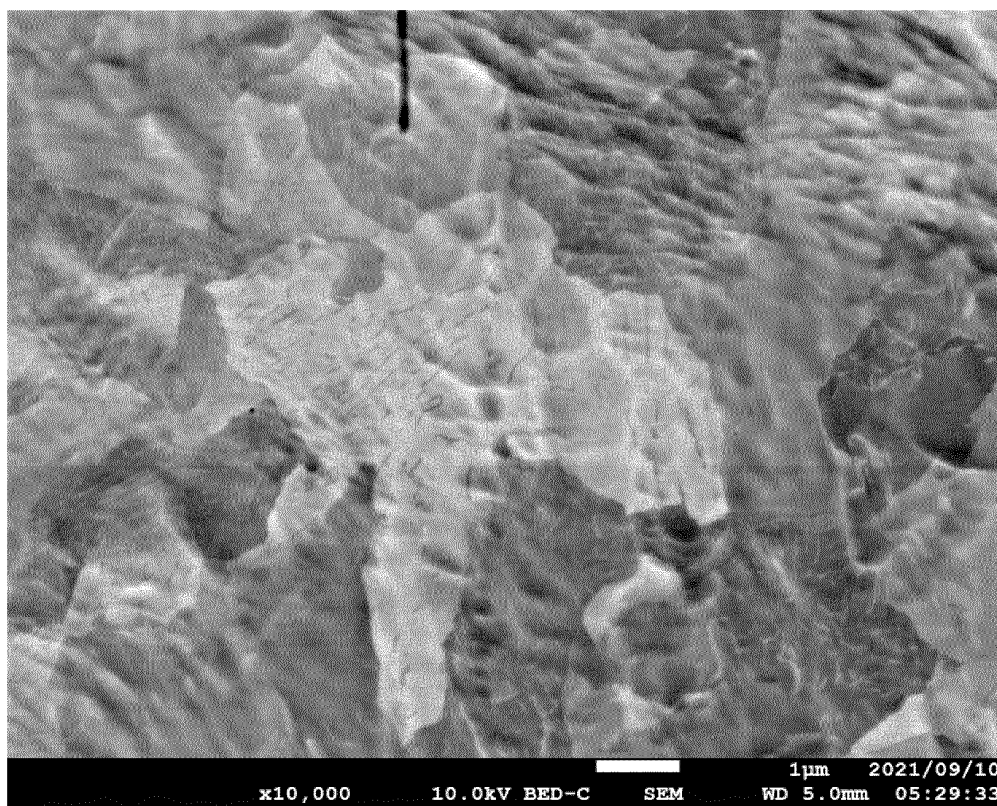
SWRH42A, DEVELOPED PRODUCT-565°C: BSE IMAGE

FIG.24A



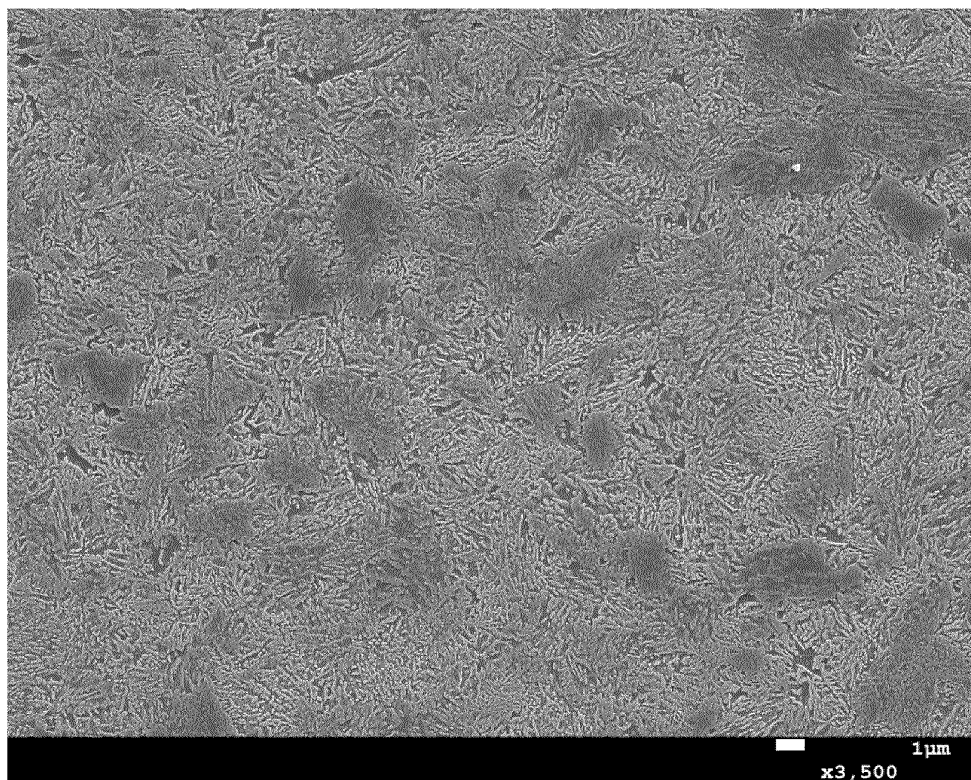
SWRH42A, DEVELOPED PRODUCT-450°C: SEM IMAGE

FIG.24B



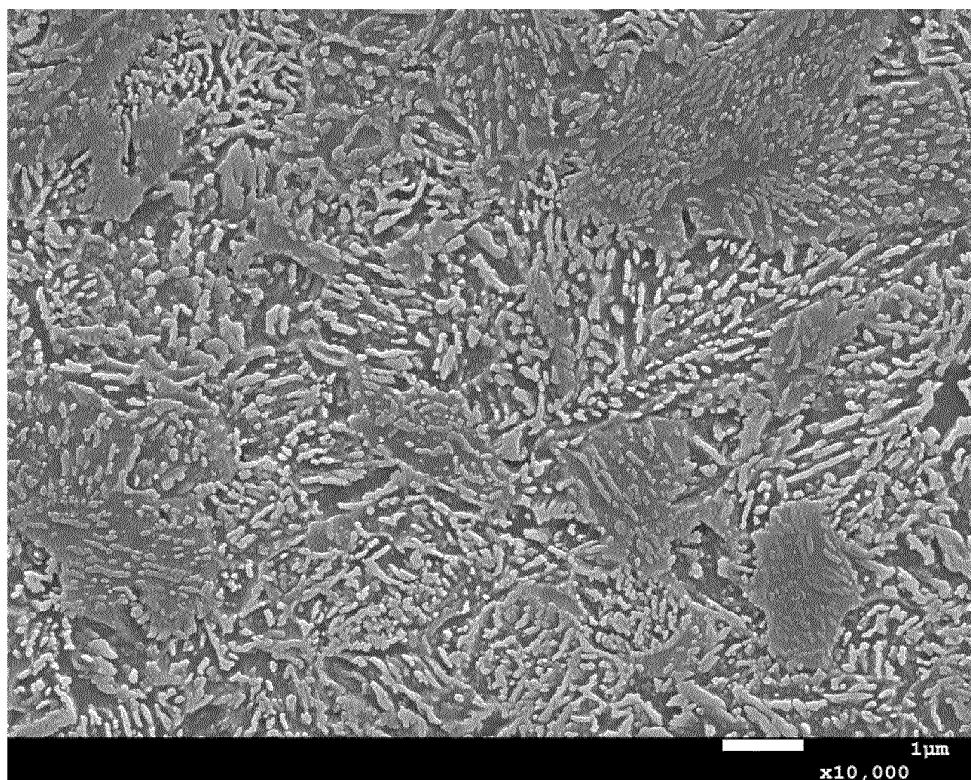
SWRH42A, DEVELOPED PRODUCT-450°C: BSE IMAGE

FIG.25A



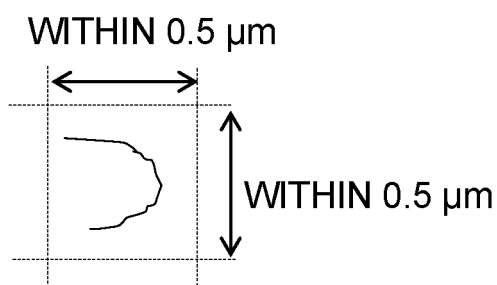
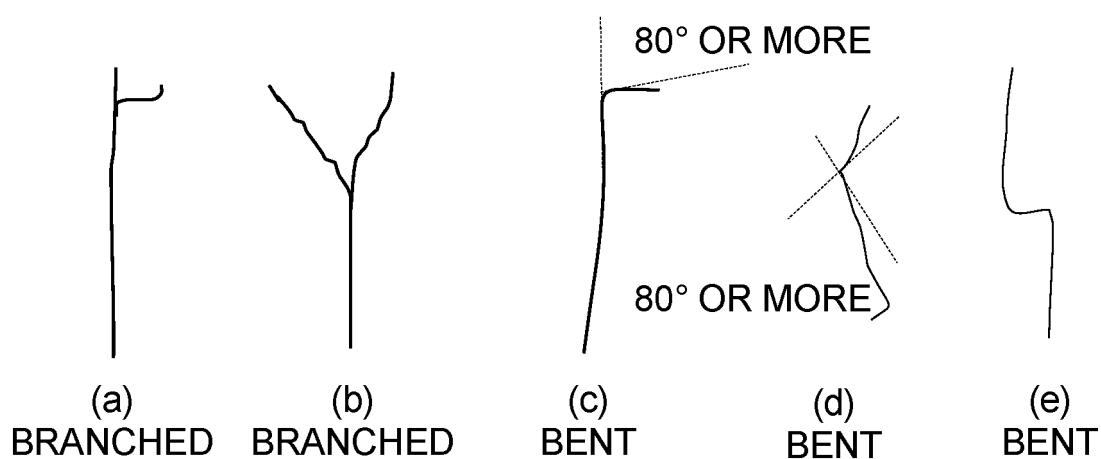
DEVELOPED PRODUCT-LEAD FURNACE TEMPERATURE 400°C,
SWRH62A: SEM IMAGE

FIG.25B



DEVELOPED PRODUCT-LEAD FURNACE TEMPERATURE 400°C,
SWRH62A: SEM IMAGE

FIG.26



(e) CURVED
CURVED PORTION
CURVED 150° OR MORE
WITHIN DIAMETER OF CURVATURE 0.5 μm

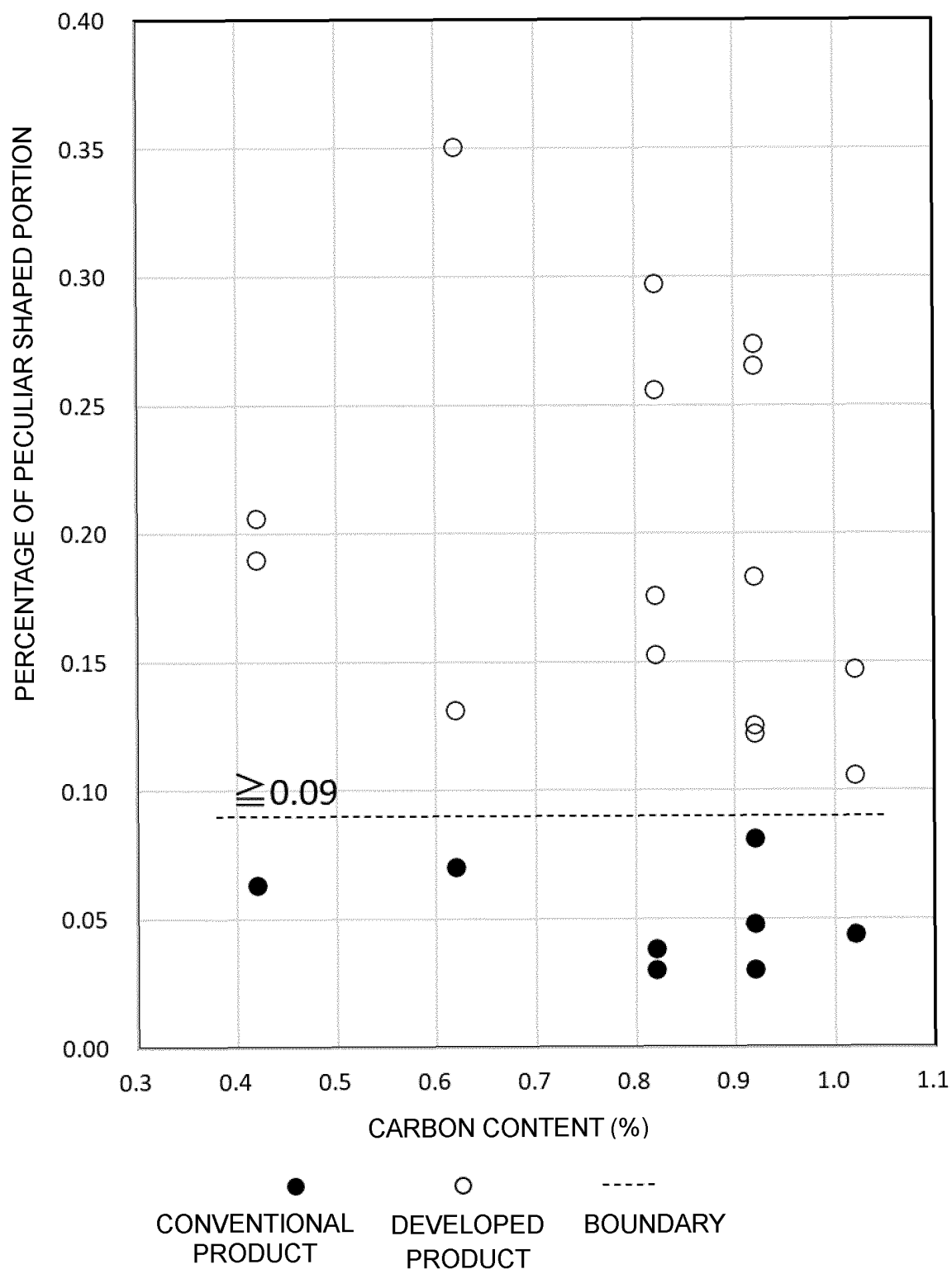
FIG.27

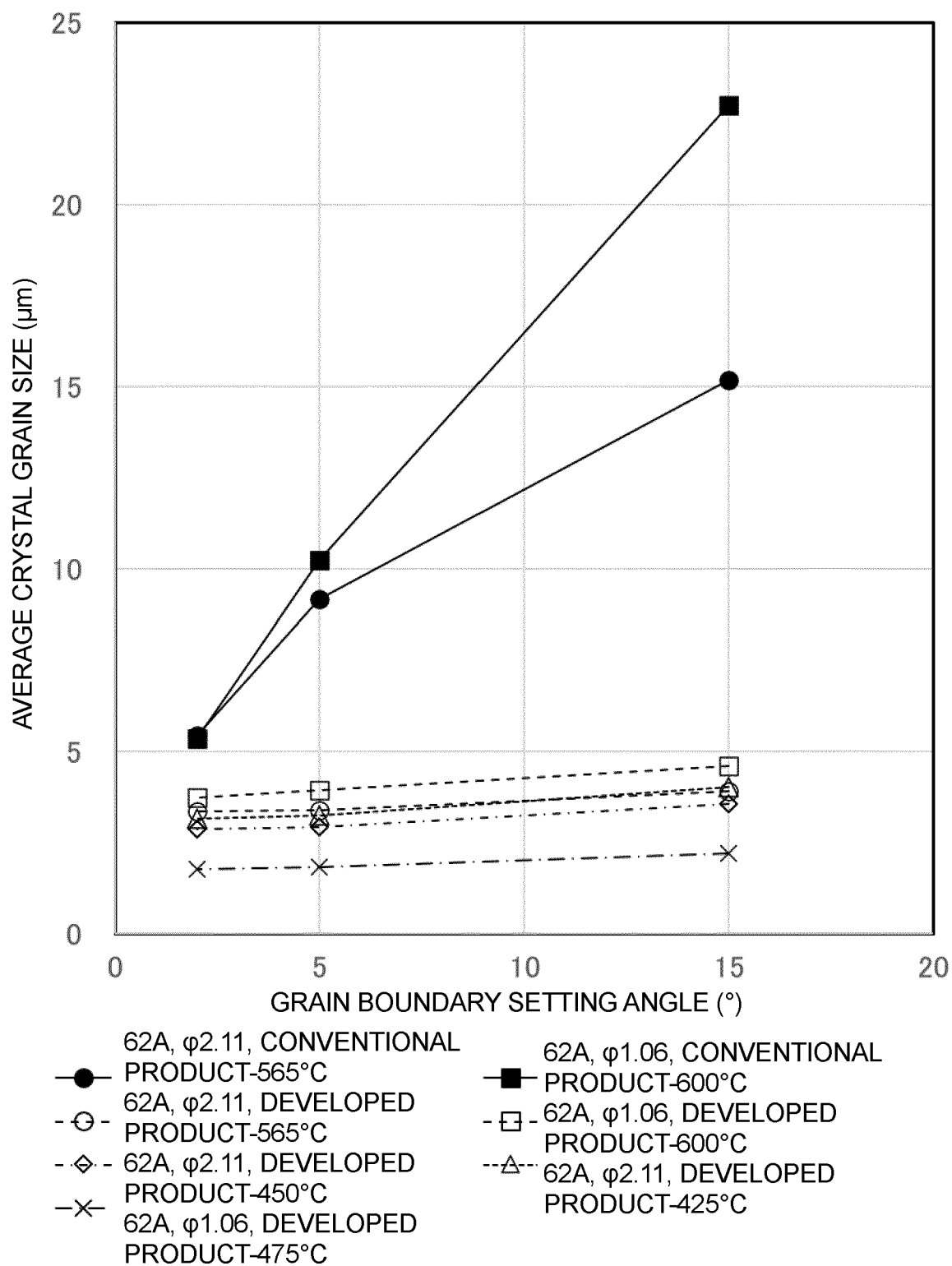
FIG.28

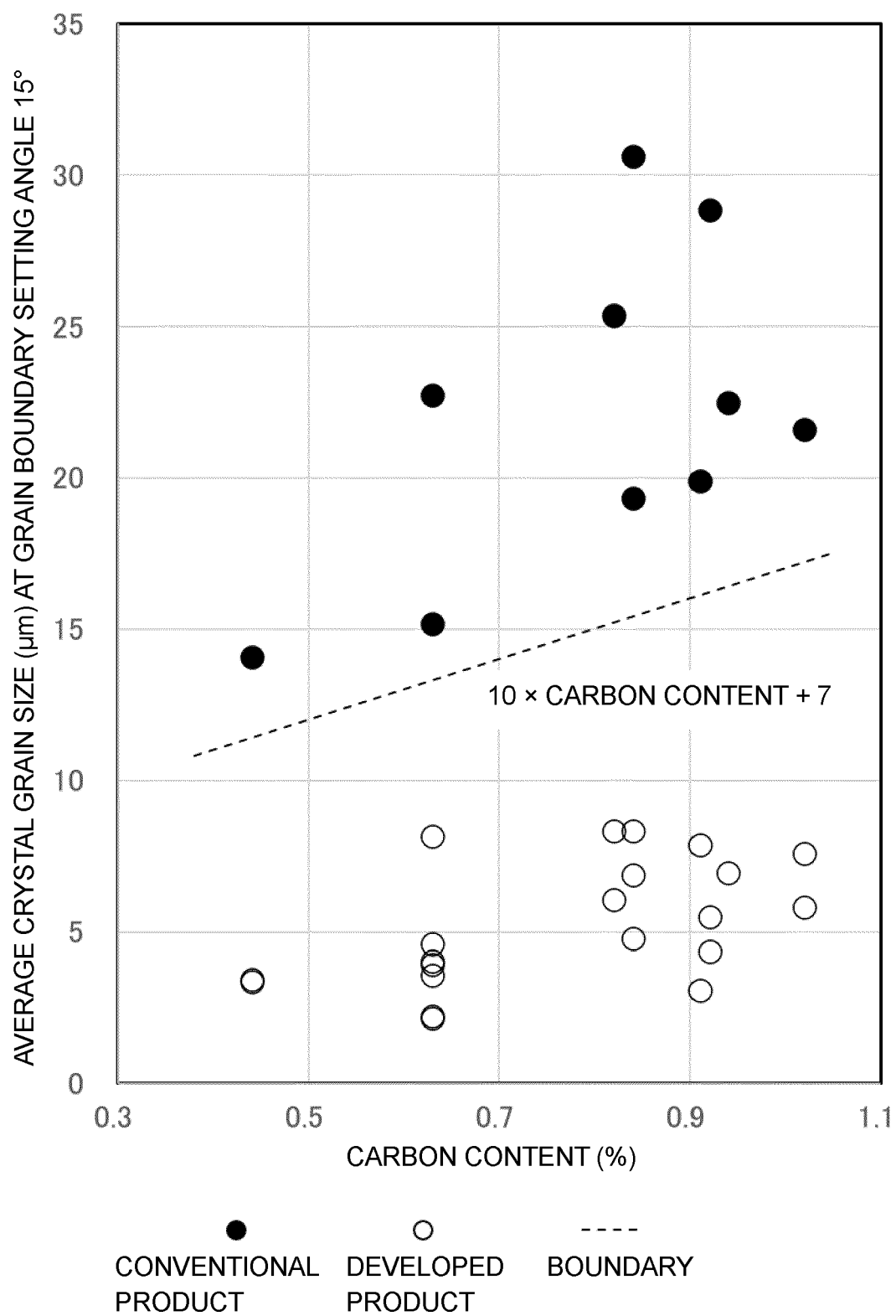
FIG.29

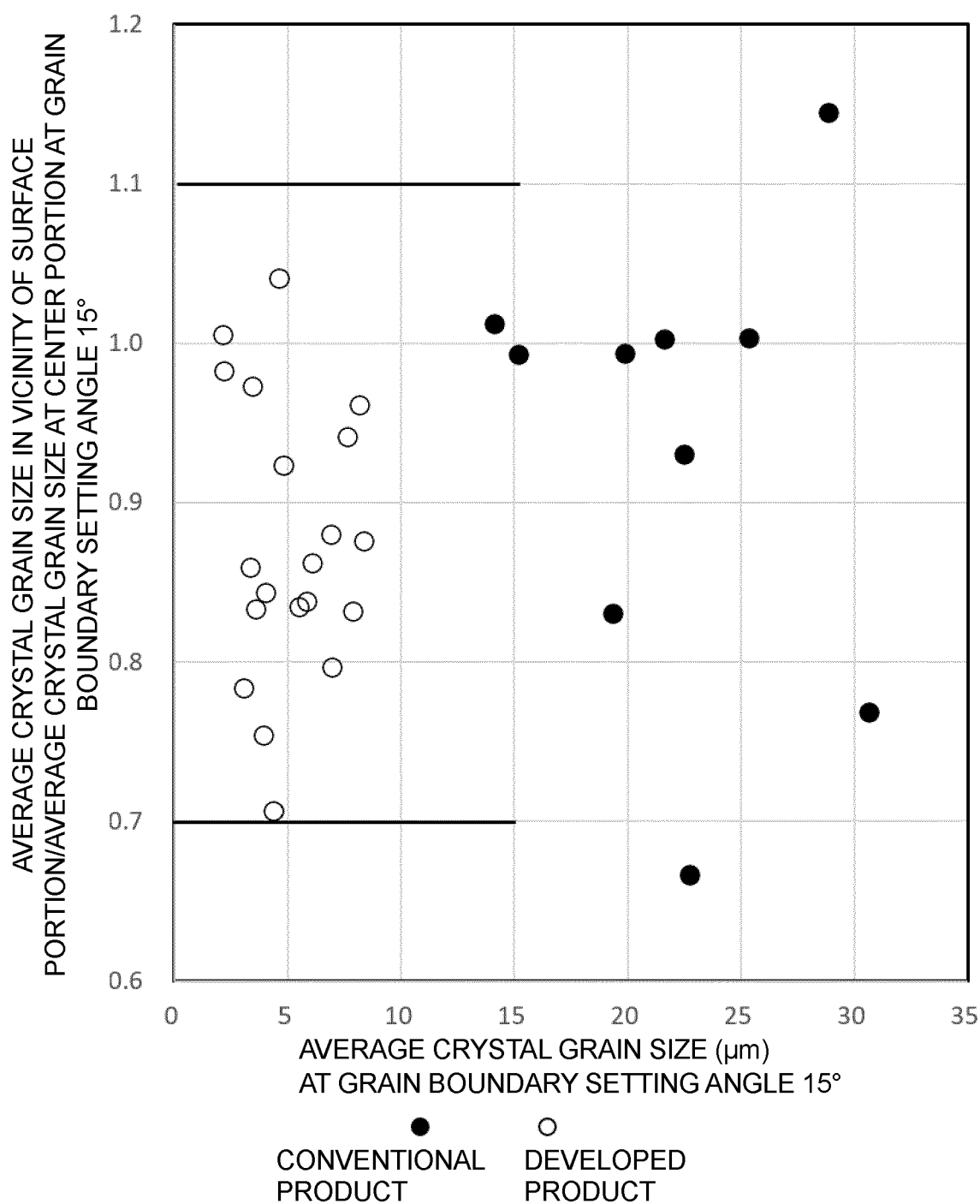
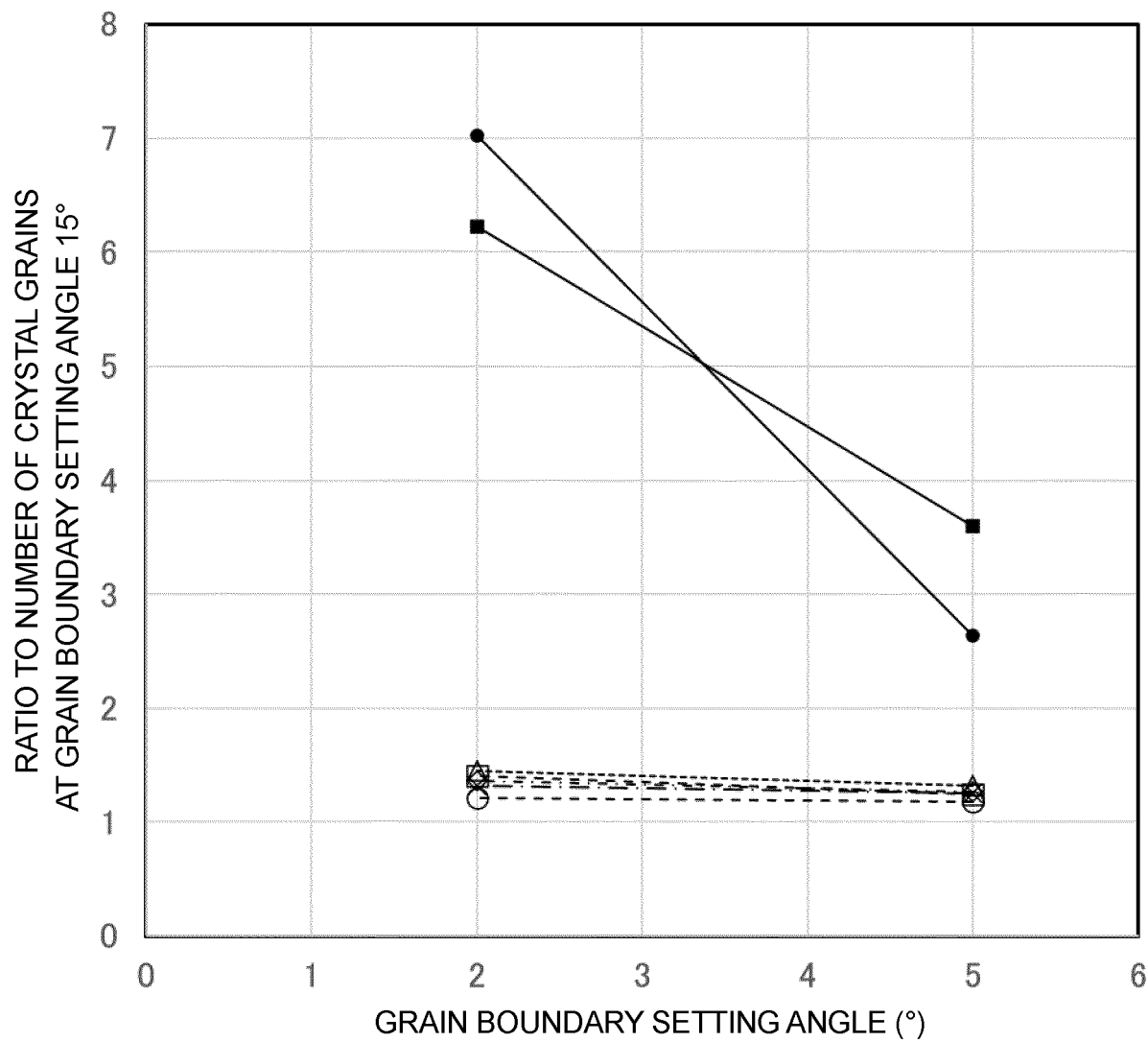
FIG.30

FIG.31

- SWRH-62A, ϕ 2.11, CONVENTIONAL PRODUCT-565°C
- SWRH-62A, ϕ 1.06, CONVENTIONAL PRODUCT-600°C
- SWRH-62A, ϕ 2.11, DEVELOPED PRODUCT-565°C
- SWRH-62A, ϕ 1.06, DEVELOPED PRODUCT-600°C
- ◇- SWRH-62A, ϕ 2.11, DEVELOPED PRODUCT-450°C
- △-- SWRH-62A, ϕ 2.11, DEVELOPED PRODUCT-425°C
- ×- SWRH-62A, ϕ 1.06, DEVELOPED PRODUCT-475°C

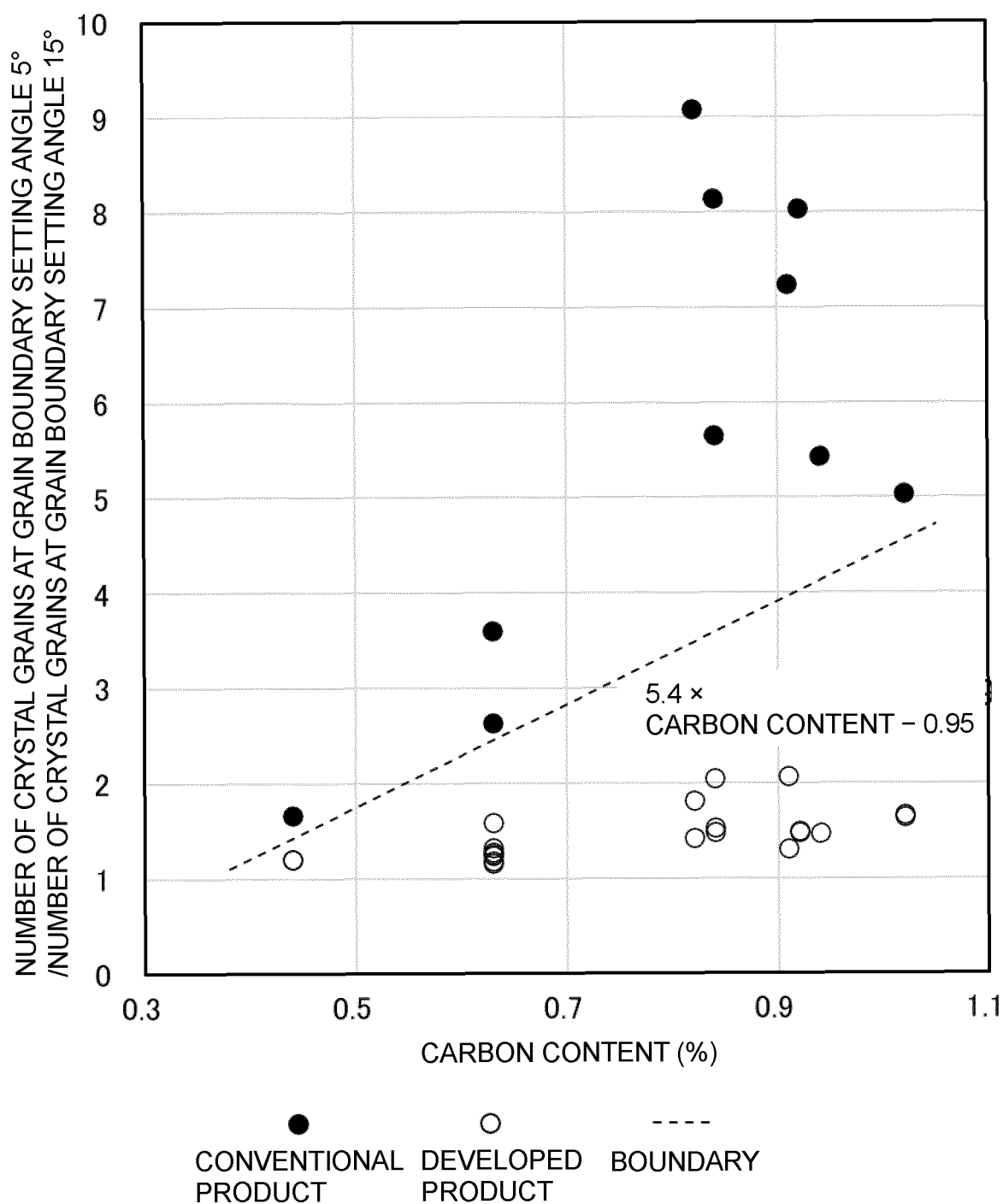
FIG.32

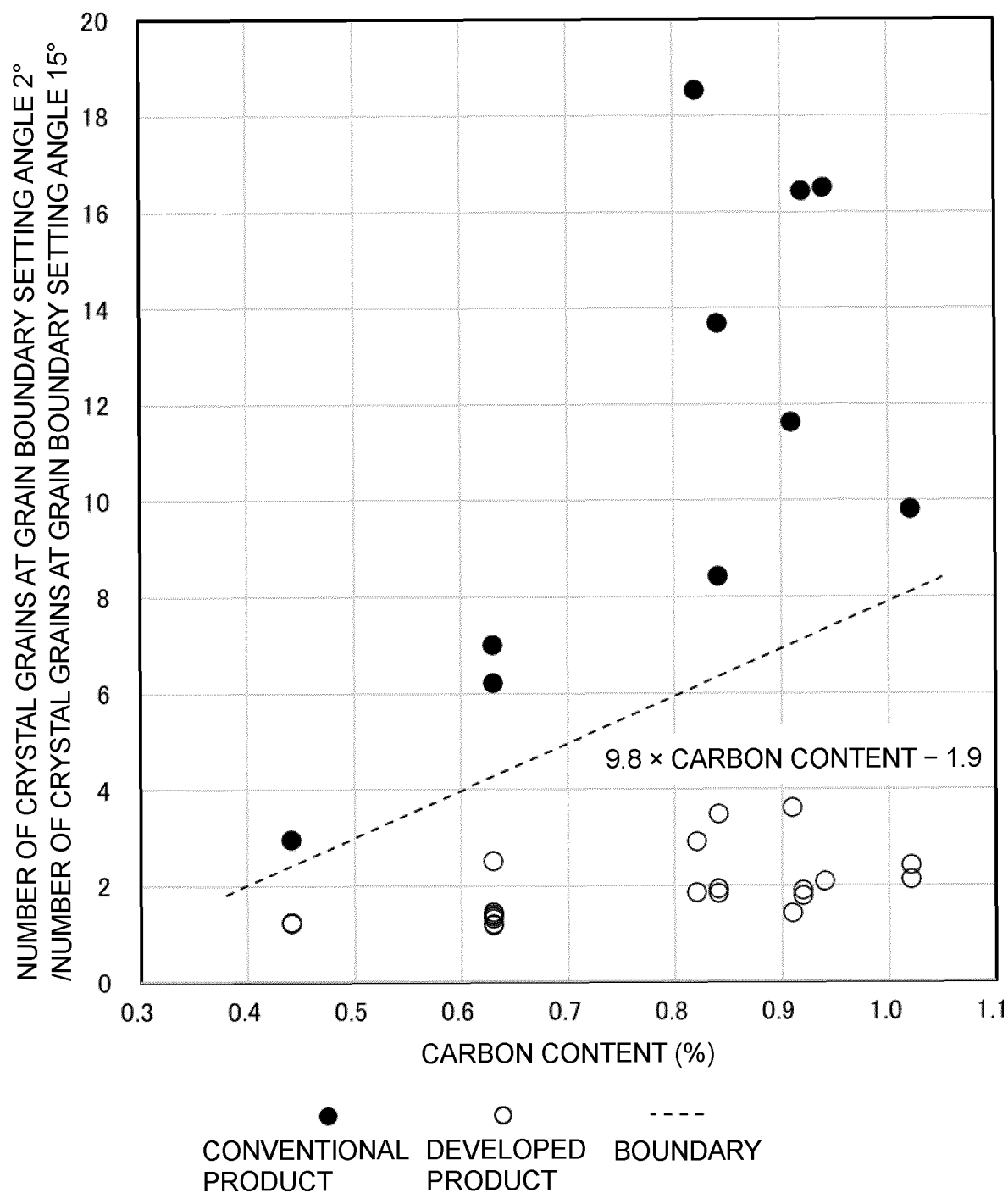
FIG.33

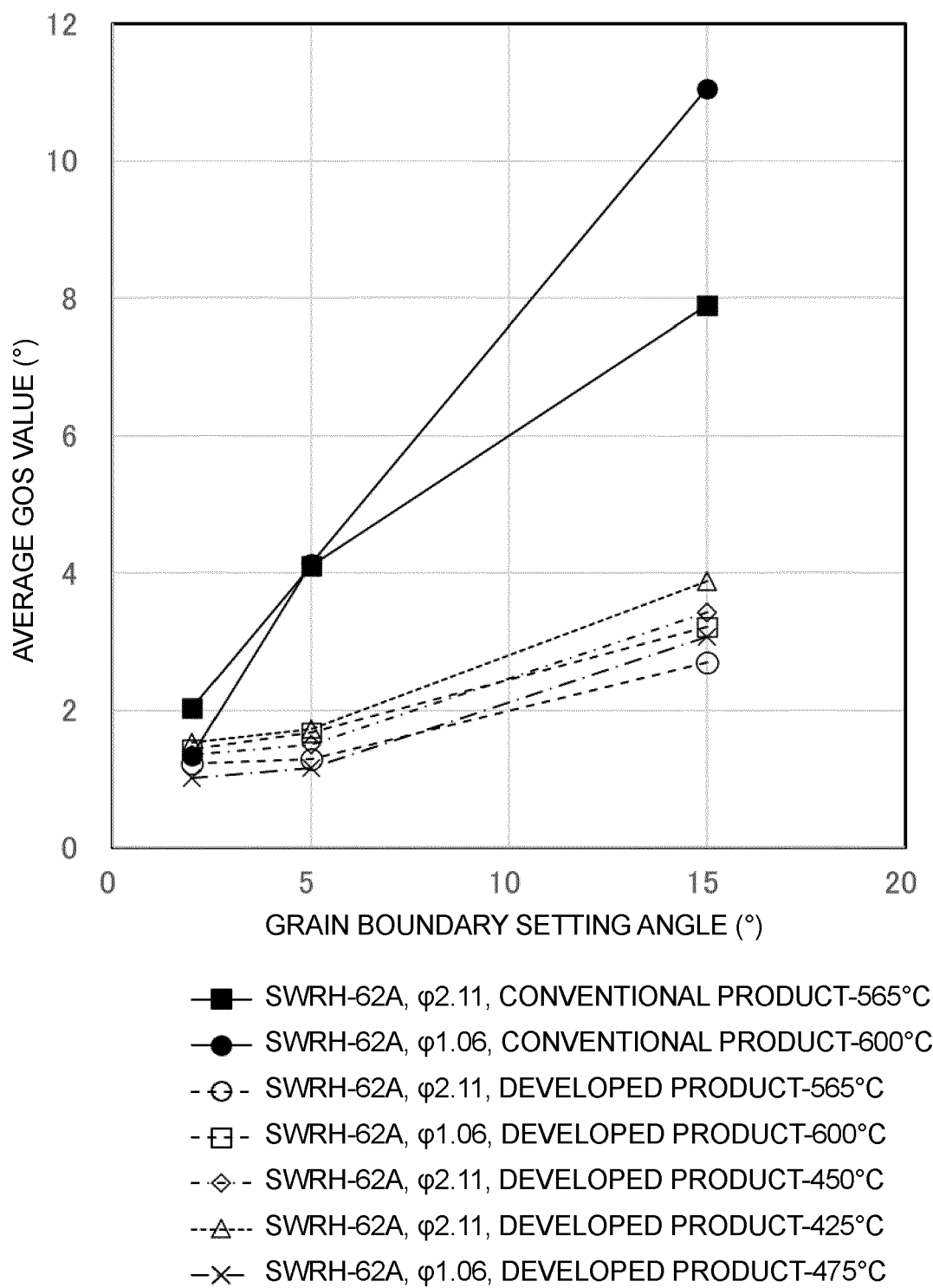
FIG.34

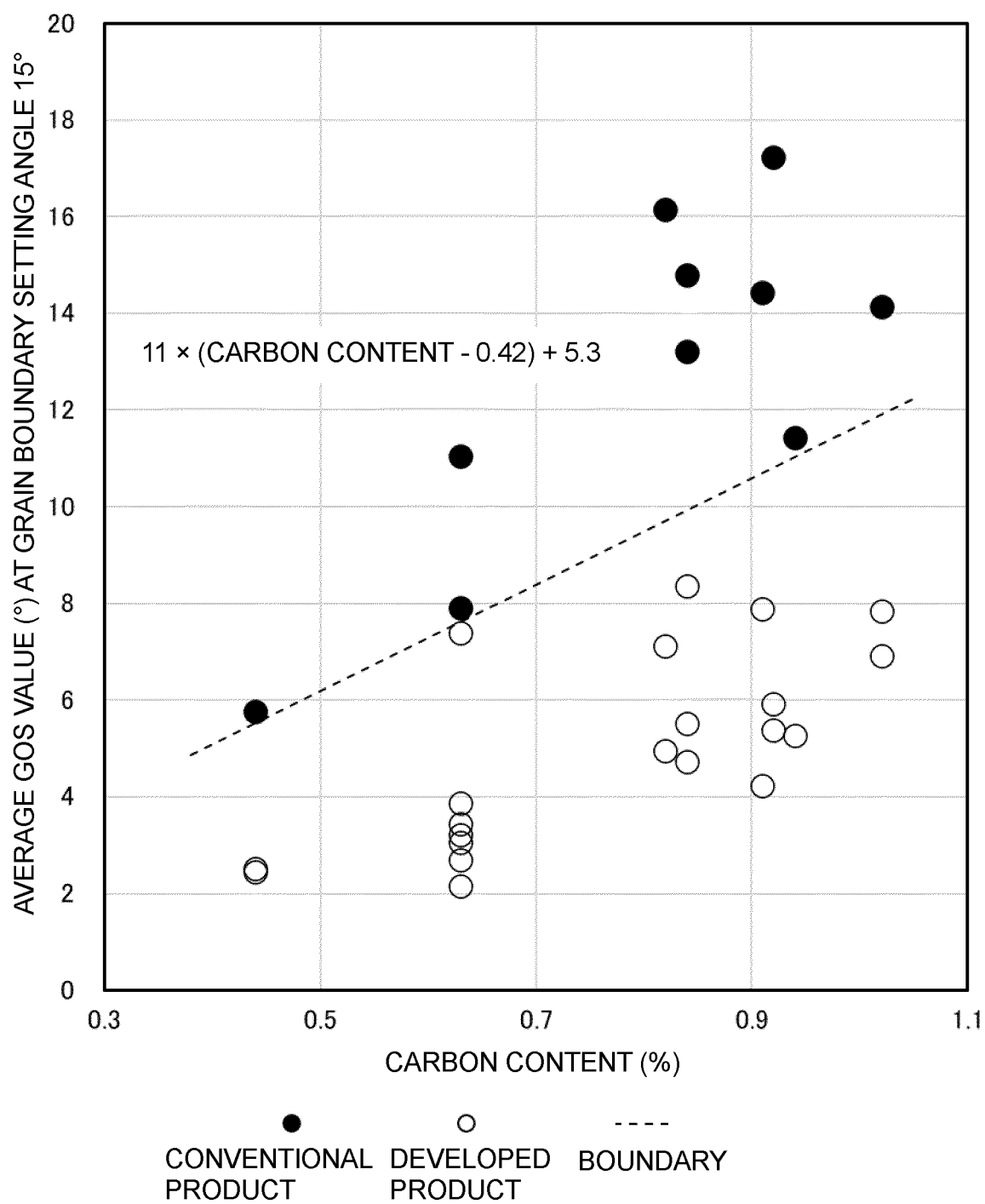
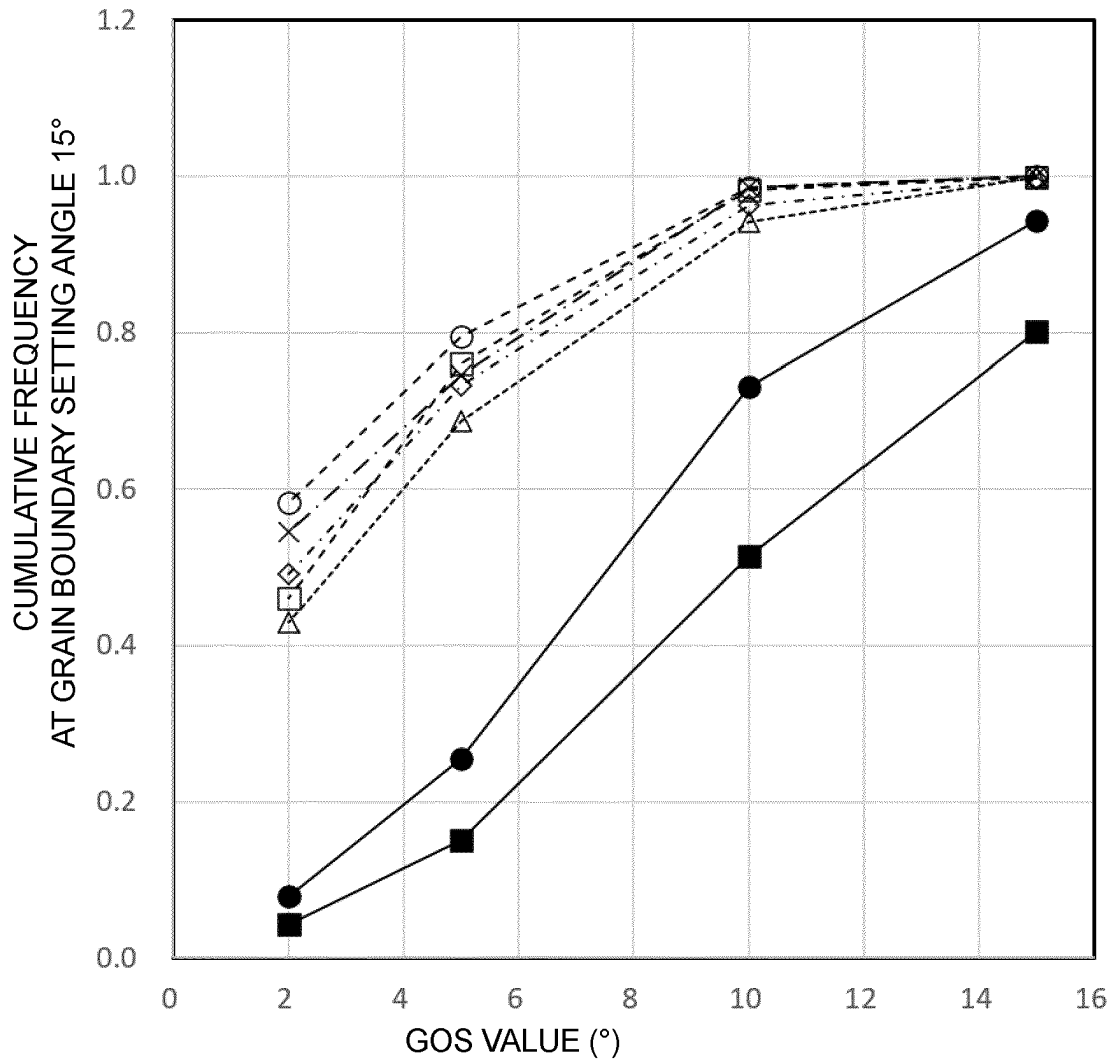
FIG.35

FIG.36

- SWRH-62A, ϕ 2.11, CONVENTIONAL PRODUCT-565°C
- SWRH-62A, ϕ 1.06, CONVENTIONAL PRODUCT-600°C
- SWRH-62A, ϕ 2.11, DEVELOPED PRODUCT-565°C
- SWRH-62A, ϕ 1.06, DEVELOPED PRODUCT-600°C
- ◇- SWRH-62A, ϕ 2.11, DEVELOPED PRODUCT-450°C
- △-- SWRH-62A, ϕ 2.11, DEVELOPED PRODUCT-425°C
- ×- SWRH-62A, ϕ 1.06, DEVELOPED PRODUCT-475°C

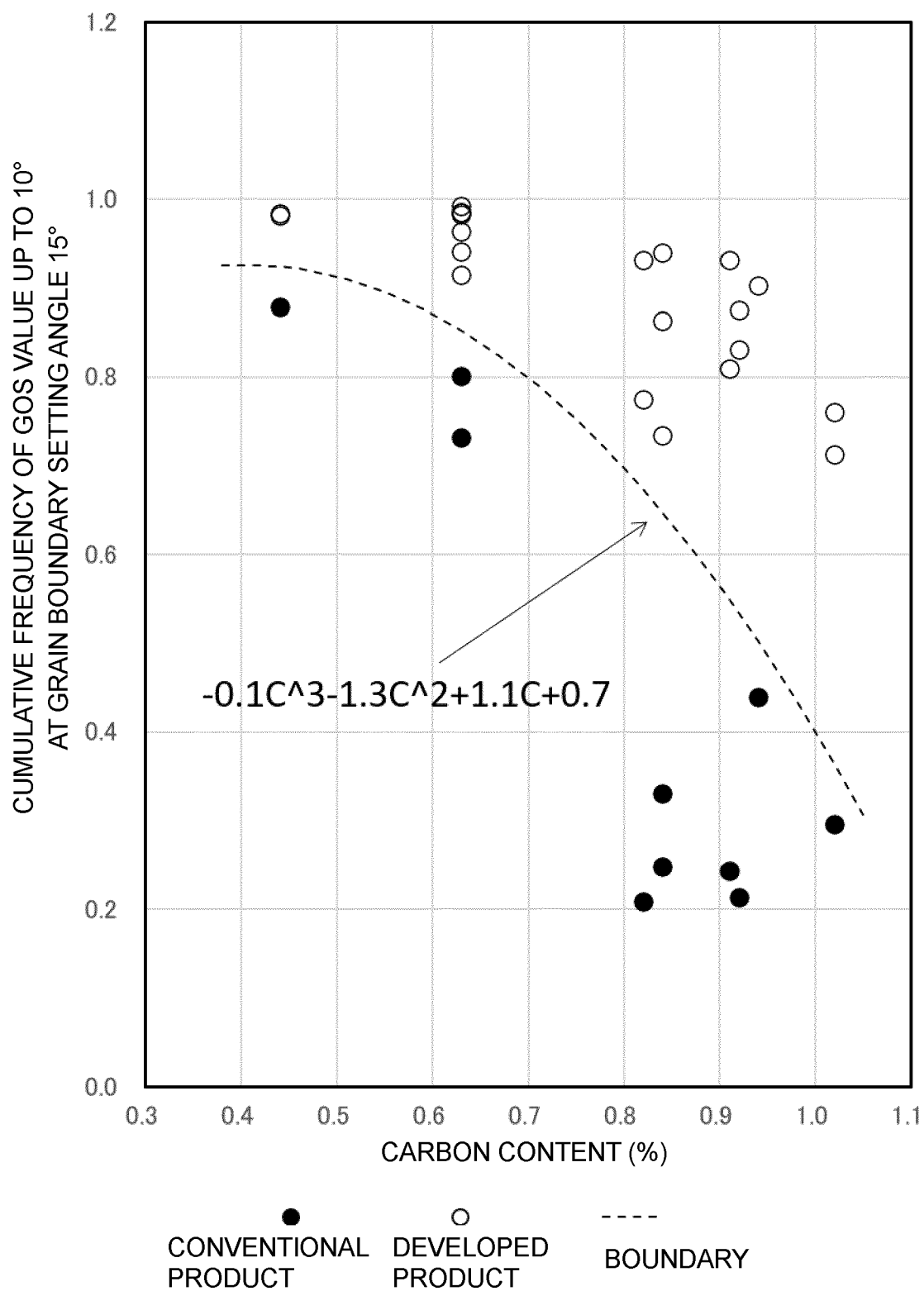
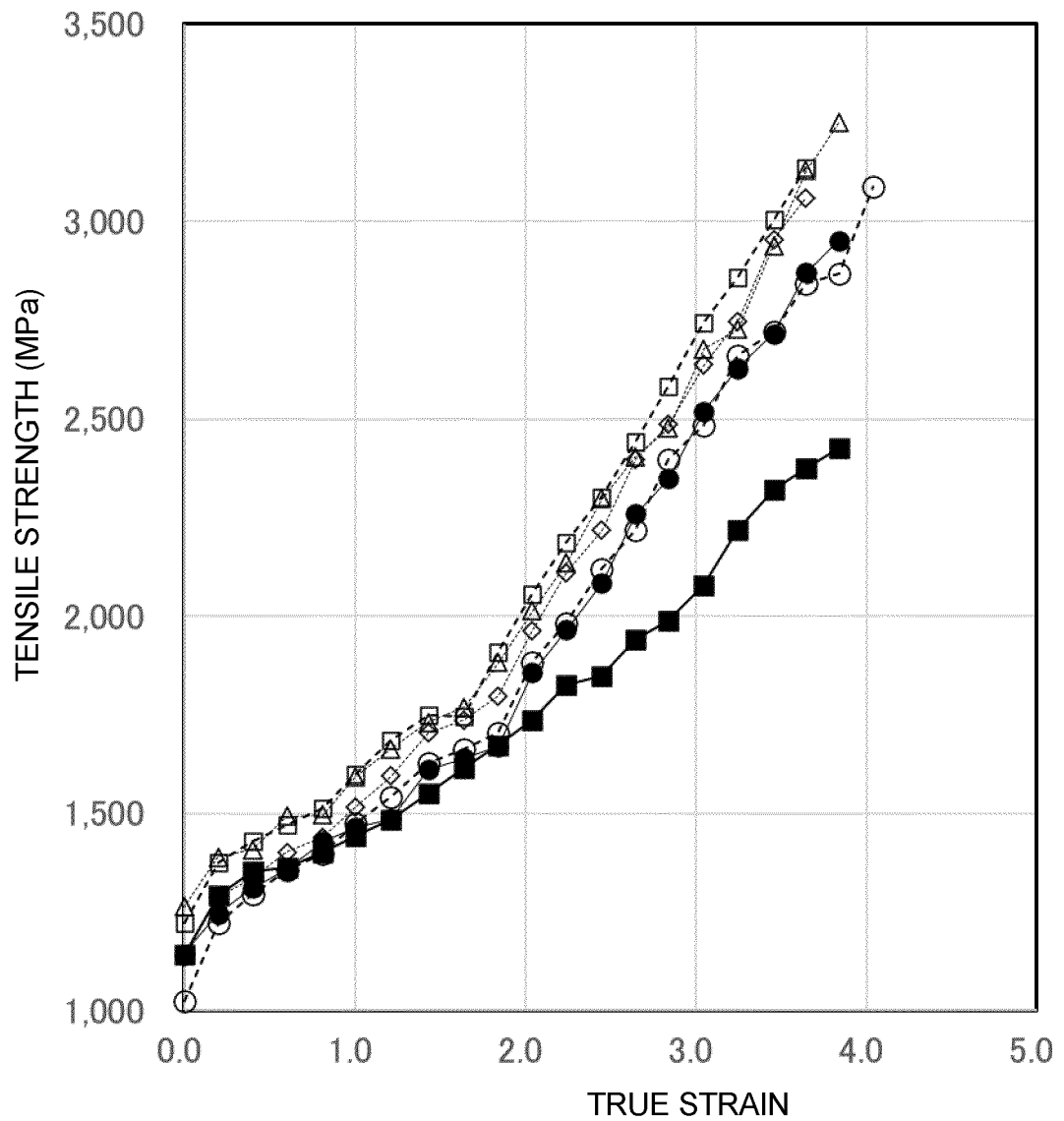
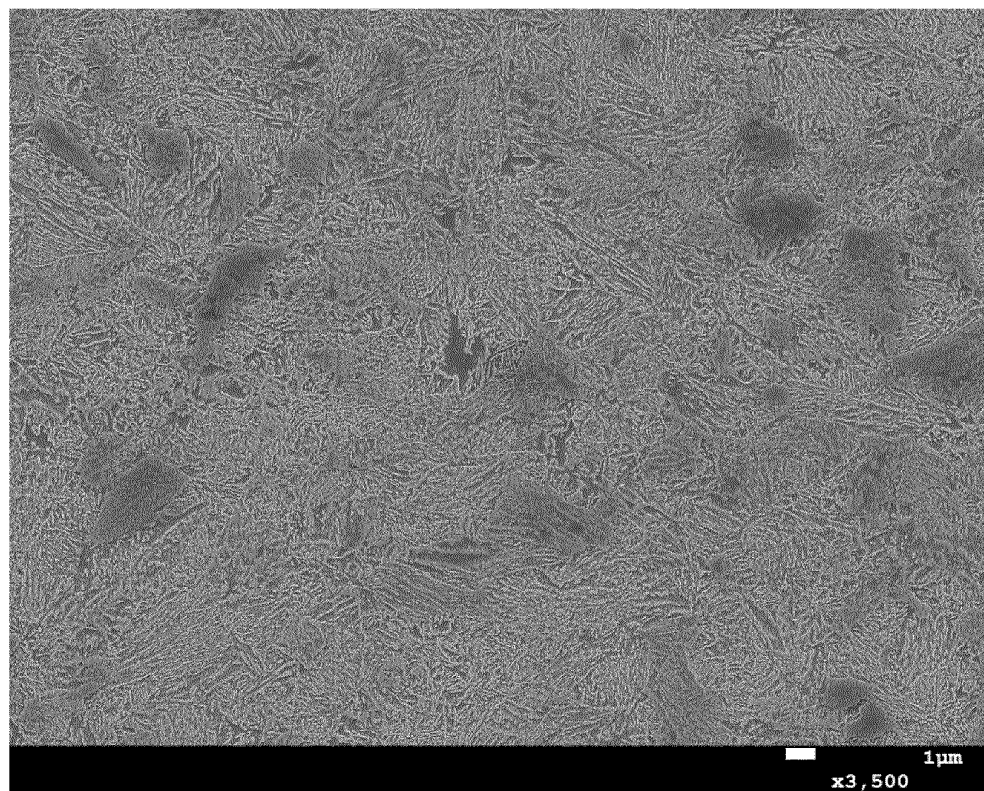
FIG.37

FIG.38

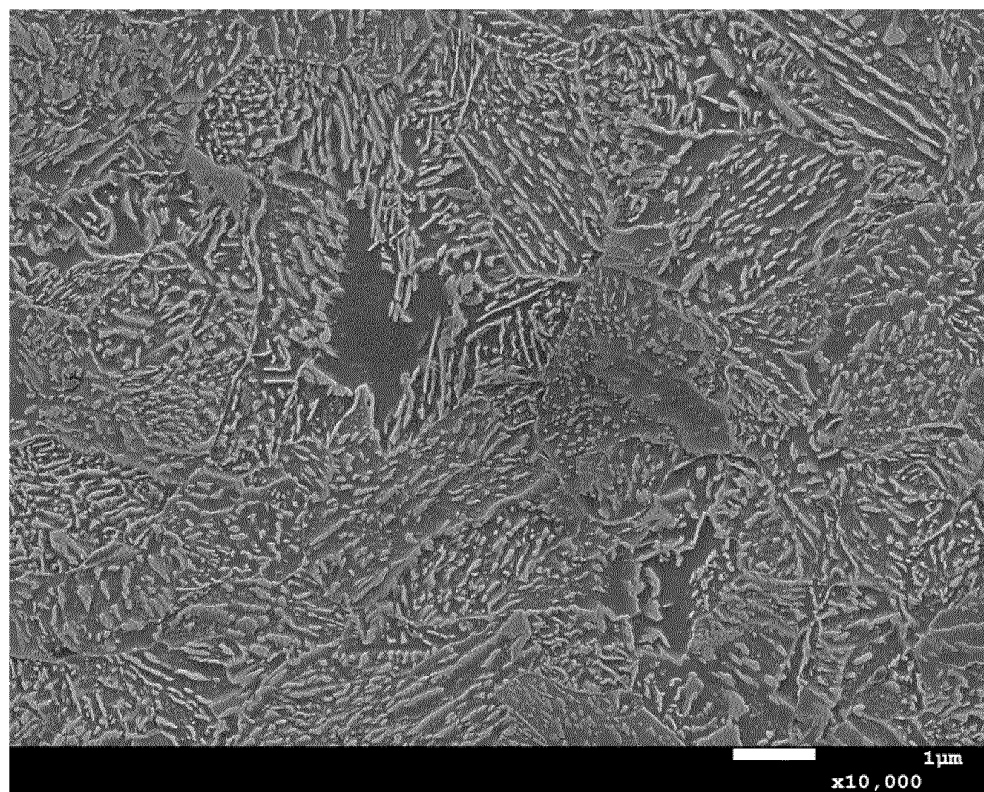
- SWRH-62A, $\phi 2.11$, CONVENTIONAL PRODUCT-565°C
- SWRH-62A, $\phi 2.11$, CONVENTIONAL PRODUCT-450°C
- SWRH-62A, $\phi 2.11$, DEVELOPED PRODUCT-565°C
- SWRH-62A, $\phi 2.11$, DEVELOPED PRODUCT-450°C
- ◇--- SWRH-62A, $\phi 2.11$, DEVELOPED PRODUCT-425°C NO. 1
- △--- SWRH-62A, $\phi 2.11$, DEVELOPED PRODUCT-425°C NO. 2

FIG.39A



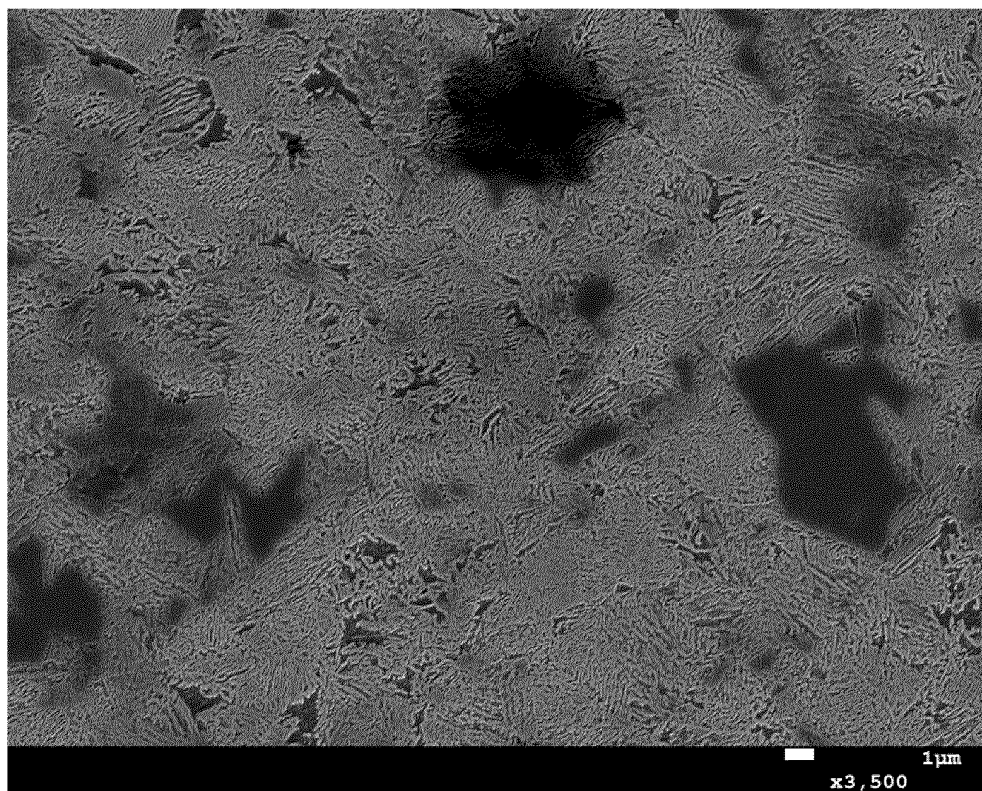
DEVELOPED PRODUCT-LEAD FURNACE TEMPERATURE 425°C NO. 1,
SWRH62A: SEM IMAGE

FIG.39B



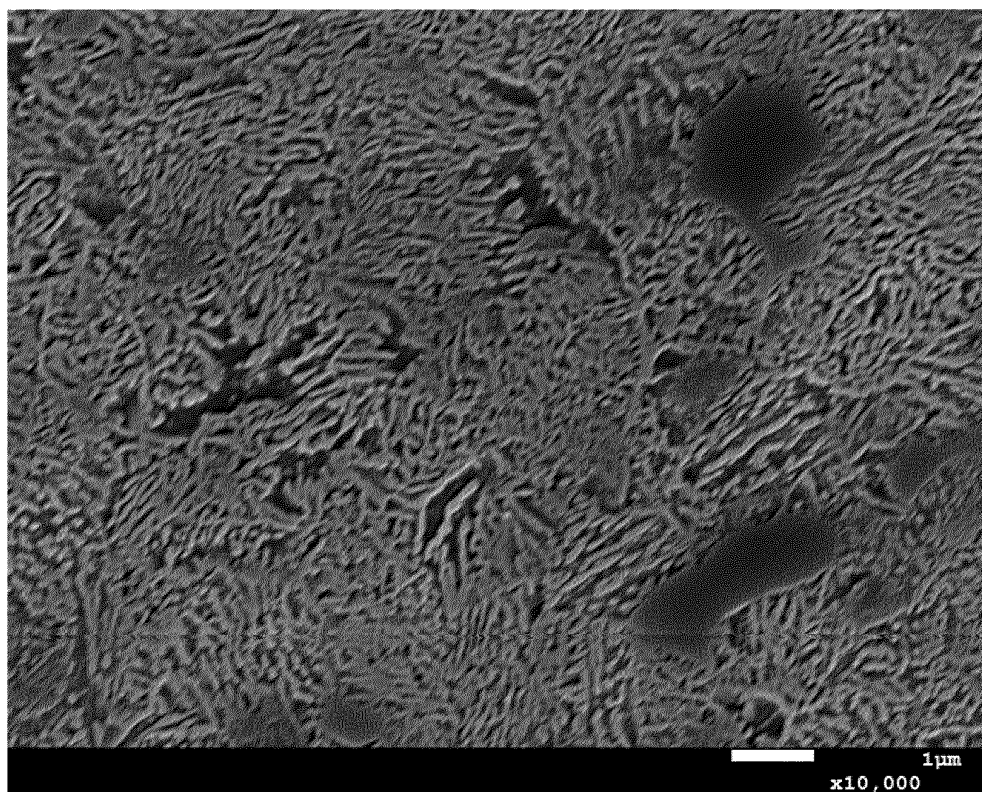
DEVELOPED PRODUCT-LEAD FURNACE TEMPERATURE 425°C NO. 1,
SWRH62A: SEM IMAGE

FIG.40A



DEVELOPED PRODUCT-LEAD FURNACE TEMPERATURE 425°C NO. 2,
SWRH62A: SEM IMAGE

FIG.40B



DEVELOPED PRODUCT-LEAD FURNACE TEMPERATURE 425°C NO. 2,
SWRH62A: SEM IMAGE

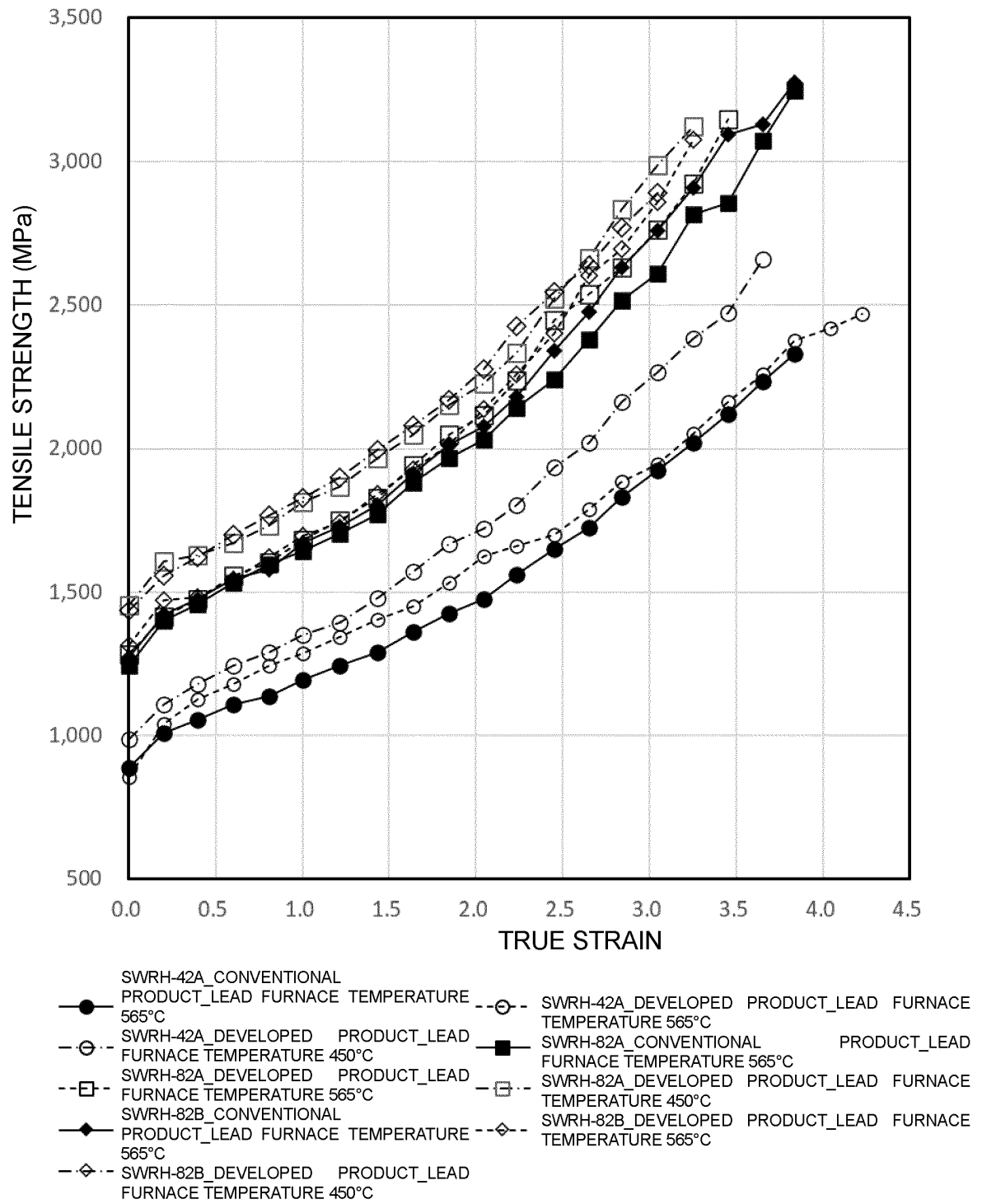
FIG.41

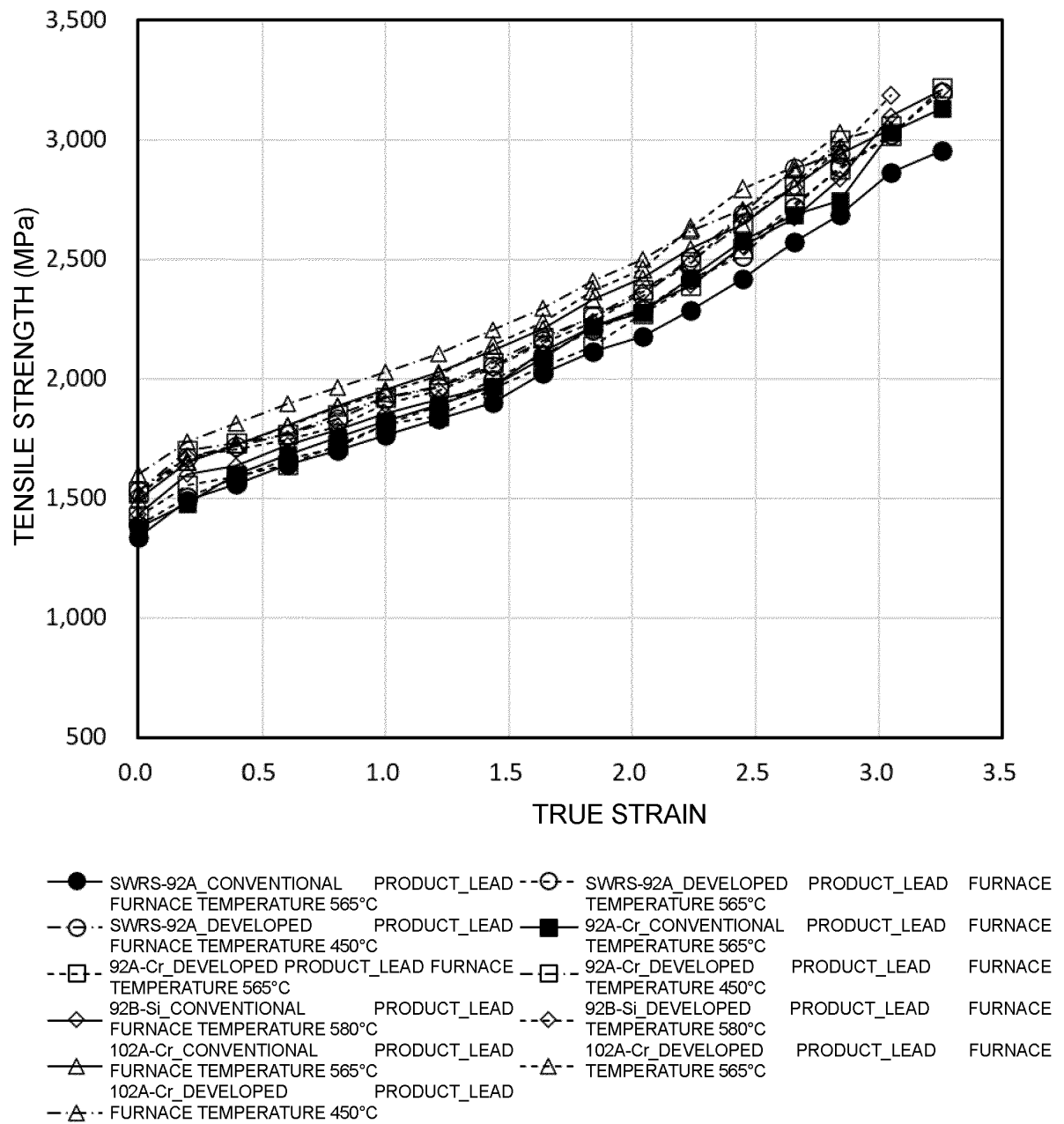
FIG.42

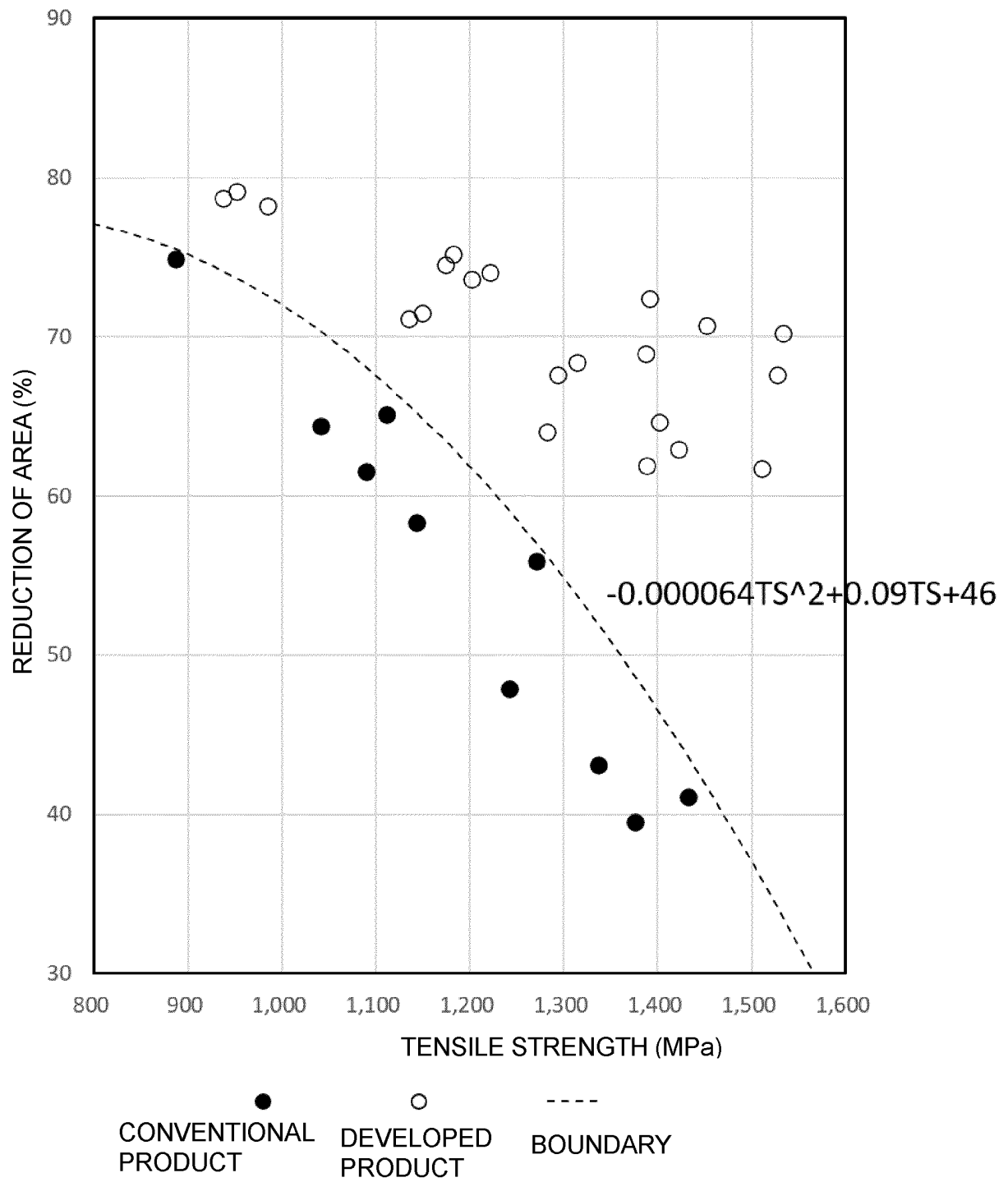
FIG.43

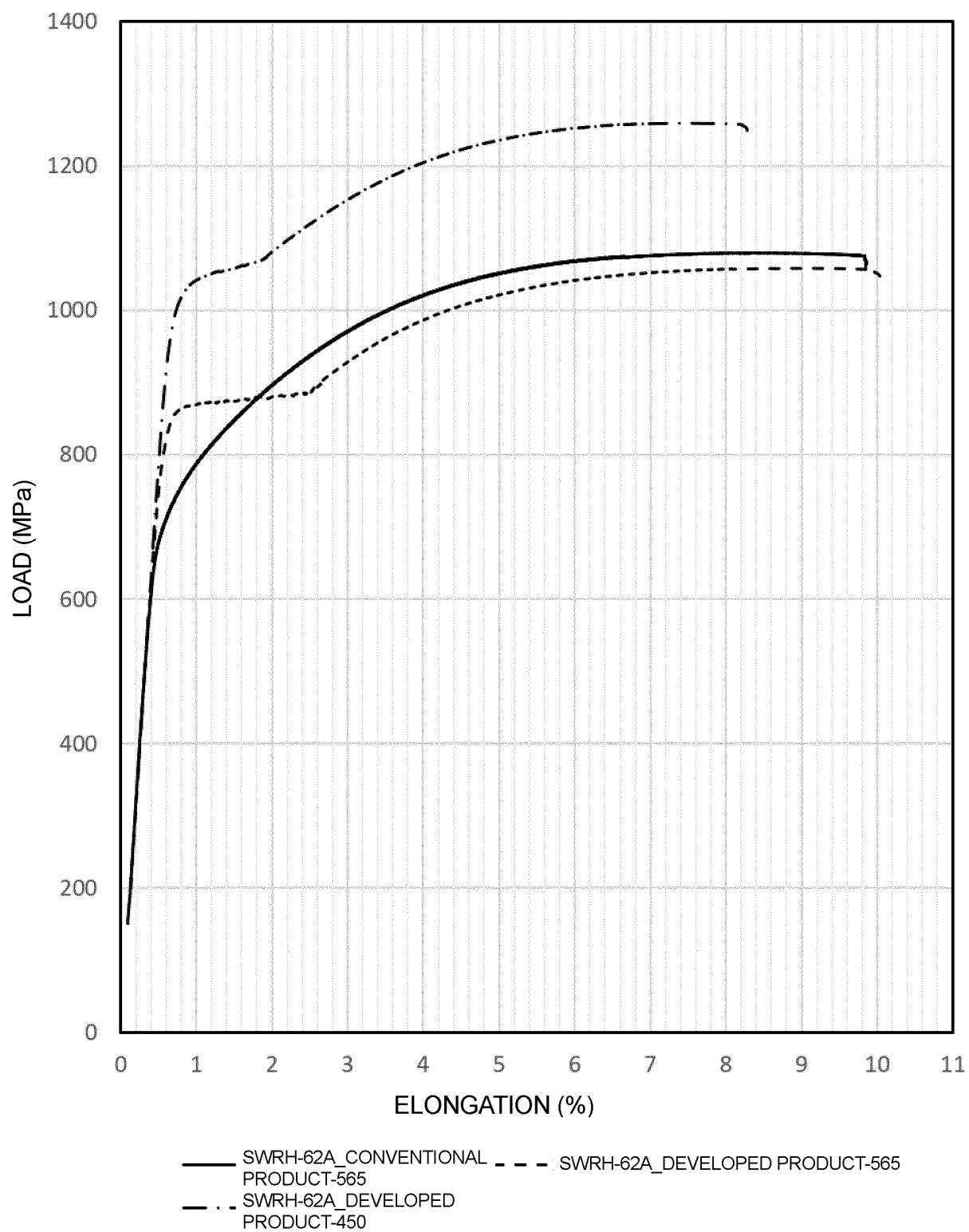
FIG.44

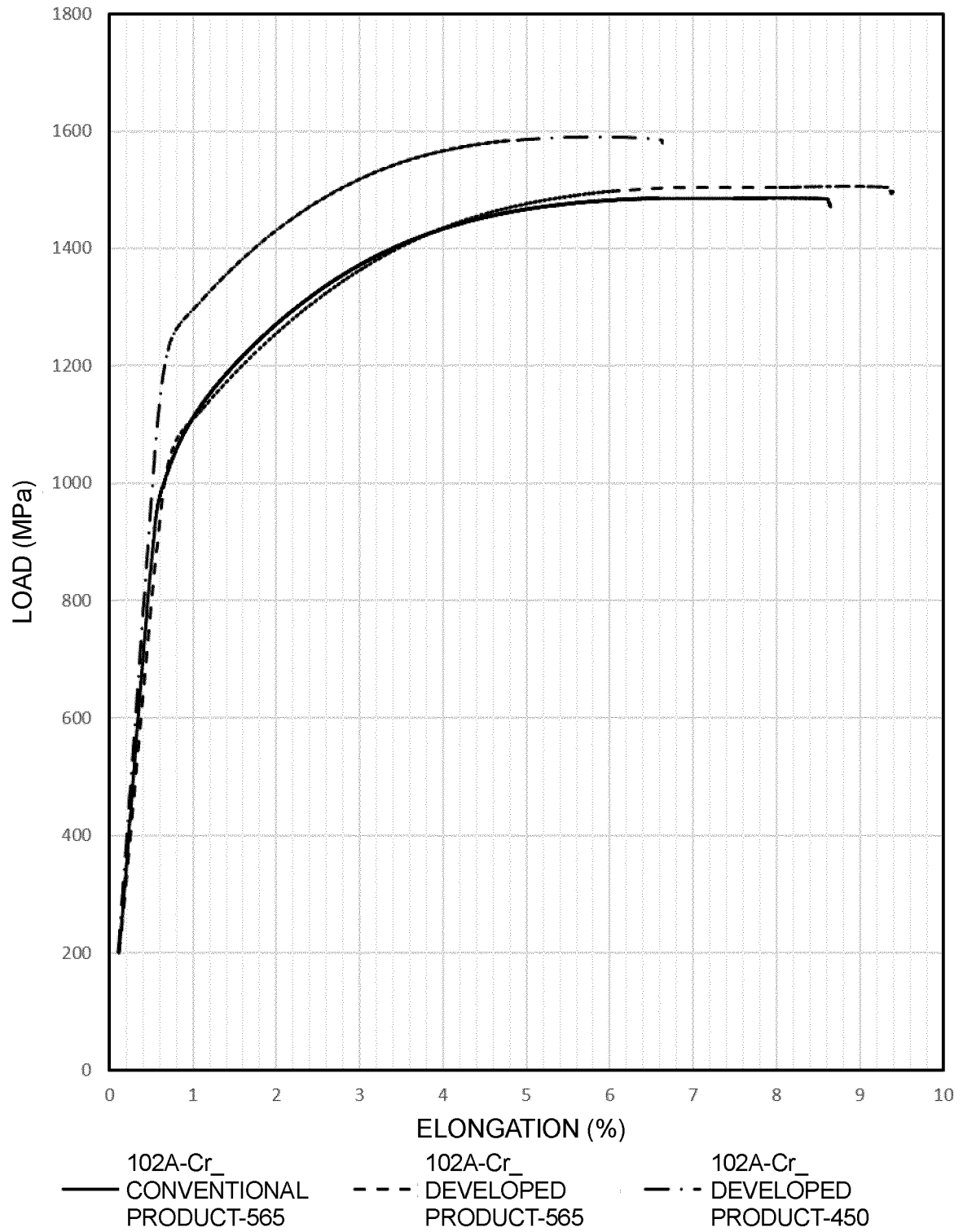
FIG. 45

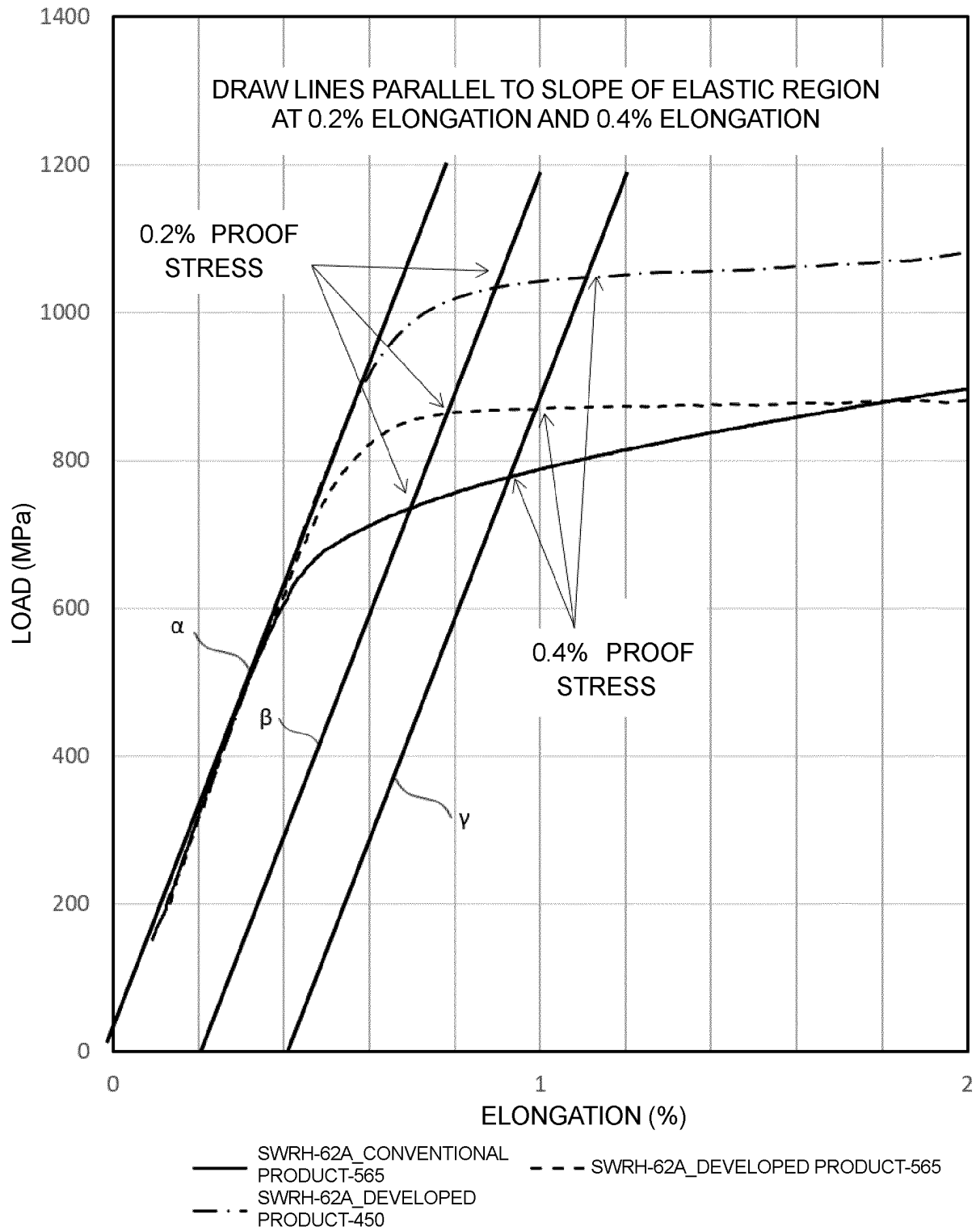
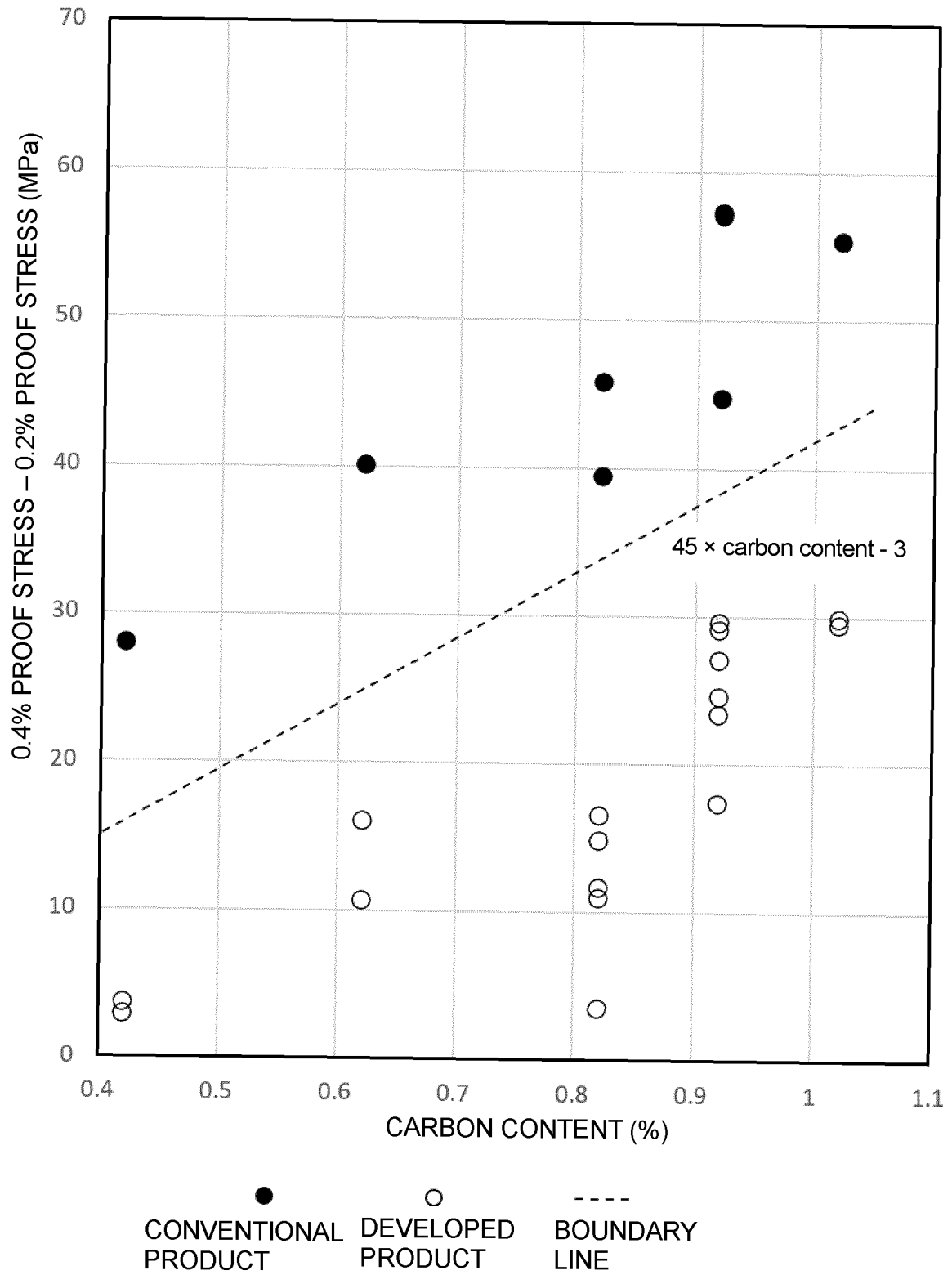
FIG.46

FIG.47

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2022/017584

A. CLASSIFICATION OF SUBJECT MATTER

C21D 9/52(2006.01)i; *C22C 38/00*(2006.01)i; *C22C 38/18*(2006.01)i; *C21D 1/40*(2006.01)i; *C21D 1/42*(2006.01)i;
C21D 1/48(2006.01)i

FI: C22C38/00 301Y; C22C38/18; C21D9/52 103Z; C21D1/40 A; C21D1/42 Z; C21D1/48

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C21D9/52; C22C38/00-38/60; C21D1/40; C21D1/42; C21D1/48

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

Published examined utility model applications of Japan 1922-1996
 Published unexamined utility model applications of Japan 1971-2022
 Registered utility model specifications of Japan 1996-2022
 Published registered utility model applications of Japan 1994-2022

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 6-322480 A (SUMITOMO METAL INDUSTRIES, LTD.) 22 November 1994 (1994-11-22) claims, paragraphs [0001]-[0074], fig. 1-3	1-11
A		12-13
X	WO 2020/032785 A1 (POSCO) 13 February 2020 (2020-02-13) claims, paragraphs [0096]-[0121], fig. 3(a)	1-11
A		12-13
X	JP 2008-7856 A (NIPPON STEEL CORP) 17 January 2008 (2008-01-17) claims, paragraphs [0007]-[0039], table 1, 3-4, 7-9, 12-13, table 2, no. 6-7, 10-12, 15-17	1-11
X	JP 2017-504721 A (ARCELORMITTAL WIRE FRANCE) 09 February 2017 (2017-02-09) claims	12-13
A	JP 10-183242 A (SUMITOMO METAL INDUSTRIES, LTD.) 14 July 1998 (1998-07-14) entire text, all drawings	13

☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:

“A” document defining the general state of the art which is not considered to be of particular relevance

“E” earlier application or patent but published on or after the international filing date

“L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

“O” document referring to an oral disclosure, use, exhibition or other means

“P” document published prior to the international filing date but later than the priority date claimed

“T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

“X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

“Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

“&” document member of the same patent family

Date of the actual completion of the international search

30 June 2022

Date of mailing of the international search report

12 July 2022

Name and mailing address of the ISA/JP

Japan Patent Office (ISA/JP)
 3-4-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8915
 Japan

Authorized officer

Telephone No.

Form PCT/ISA/210 (second sheet) (January 2015)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2022/017584

C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2018/012625 A1 (NIPPON STEEL & SUMITOMO METAL CORPORATION) 18 January 2018 (2018-01-18) claims, paragraphs [0050]-[0064]	1-13
A	JP 2016-56438 A (NIPPON STEEL & SUMITOMO METAL CORPORATION) 21 April 2016 (2016-04-21) claims, paragraphs [0056]-[0071], fig. 1-2	1-13

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2022/017584

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

The common matter shared by the inventions in claims 1-13 is a "heat-treated steel material comprising, in terms of mass%, 0.38-1.05% of C, 0.0-1.0% of Mn, 0.0-0.50% of Cr, and 0.0-1.5% of Si, with the remainder consisting of Fe and inevitable impurities", and said matter is known in JP 6-322480 A (claims, paragraphs [0001]-[0074], and fig. 1-3), WO 2020/032785 A1 (claims, paragraphs [0096]-[0121], and fig. 3(a)), JP 2008-7856 A (claims, paragraphs [0007]-[0039], 3, 4, 7-9, 12, and 13 in table 1, and no. 6, 7, 10-12, and 15-17 in table 2), WO 2018/012625 A1 (claims and paragraphs [0050]-[0064]), and JP 2016-56438 A (claims, paragraphs [0056]-[0071], and fig. 1 and 2) and is thus not a special technical feature (STF) that makes a contribution over the prior art.

The inventions in claims 1 and 2 are common in that "the average crystal grain size at a grain boundary setting angle of 15° is at most $10 \times C + 7$ (μm) (C is a carbon content (%))", and are thus classified as invention 1.

The invention in claim 3 has the feature in which "(the number of crystal grains at a grain boundary setting angle of 5°)/(the number of crystal grains at a grain boundary setting angle of 15°) is at most $5.4 \times C - 0.95$ (C is a carbon content (%))" and is also not a subordinate concept of invention 1, and is thus classified as invention 2.

The invention in claim 4 has the feature in which "(the number of crystal grains at a grain boundary setting angle of 2°)/(the number of crystal grains at a grain boundary setting angle of 15°) is at most $9.8 \times C - 0.19$ (C is a carbon content (%))" and is also not a subordinate concept of either invention 1 or invention 2, and is thus classified as invention 3.

The invention in claim 5 has the feature in which "the GOS value at a grain boundary setting angle of 15° is at most $11 \times (C - 0.42) + 5.3$ (C is a carbon content (%))" and is also not a subordinate concept of any of inventions 1-3, and is thus classified as invention 4.

The invention in claim 6 has the feature in which "the cumulative frequency in the GOS value range of 0-10° at a grain boundary setting angle of 15° is $-0.1C^3 - 1.3C^2 + 1.1C + 0.7$ (C is a carbon content (%))" and is also not a subordinate concept of any of inventions 1-4, and is thus classified as invention 5.

The invention in claim 7 has the feature in which "when a structure is observed through a backscattered electron image (BSE), the area ratio of branched, bent, and curved iron carbides in the lamellar structure of ferrite and an iron carbide is at least 9% in the visual field" and is also not a subordinate concept of any of inventions 1-5, and is thus classified as invention 6.

The invention in claim 8 has the feature in which "when a structure is observed with an electron scanning microscope (SEM), in the lamellar structure of ferrite and an iron carbide, spherical protrusions are observed on the surface of the iron carbide" and is also not a subordinate concept of any of inventions 1-6, and is thus classified as invention 7.

The invention in claim 9 has the feature in which "when a structure is observed with an electron scanning microscope (SEM), in the lamellar structure of ferrite and an iron carbide, protrusions and recesses are formed on the surface of the iron carbide, and rod-shaped or plate-shaped isotropic iron carbides, which are formed into a three-dimensional comb or mesh form, are generated" and is also not a subordinate concept of any of inventions 1-7, and is thus classified as invention 8.

The invention in claim 10 has the feature in which "when the tensile strength is TS (MPa), the aperture is at least $-0.000064TS^2 + 0.09TS + 46$ (%)" and is also not a subordinate concept of any of inventions 1-8, and is thus classified as invention 9.

The invention in claim 11 has the feature in which "the proof stress difference, which is obtained by subtracting the 0.2% proof stress obtained in an S-S curve from the 0.4% proof stress obtained in the S-S curve, is at most $45 \times C - 3$ (MPa) (C is a carbon content (%))" and is also not a subordinate concept of any of inventions 1-9, and is thus classified as invention 10.

The invention in claim 12 has the feature of a "method for heat-treating a steel material, the method comprising: a step for directly heating a steel material by causing the steel material itself to generate heat; and a step for cooling the steel material by passing the heated steel material through a bathtub in which a cooling medium capable of performing isothermal transformation is stored, wherein the heating step has the largest temperature gradient at the final stage of heating, and the heated steel material is made to enter the cooling medium immediately after the steel material reaches a predetermined maximum heating temperature at the final stage of heating in the heating step" and is also not a subordinate concept of any of inventions 1-10, and is thus classified as invention 11.

The invention in claim 13 has the feature of a "method for heat-treating a steel material, wherein the steel material is heated from room temperature to at least 820°C in a few seconds, and the heated steel material is cooled to at most 620°C in a few seconds without maintaining the maximum heating temperature" and is also not a subordinate concept of any of inventions 1-11, and is thus classified as invention 12.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2022/017584

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☒ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

- Remark on Protest**
- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
 - ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
 - ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/JP2022/017584

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
JP 6-322480 A	22 November 1994	US 5458699 A claims, column 1, line 1 to column 13, line 34, fig. 1-3 EP 624658 A1	
WO 2020/032785 A1	13 February 2020	JP 2021-533271 A claims, paragraphs [0033]-[004 4], fig. 3(a) CN 112703266 A KR 10-2065264 B1	
JP 2008-7856 A	17 January 2008	(Family: none)	
JP 2017-504721 A	09 February 2017	US 2020/0032367 A1 claims US 2016/0319392 A1 WO 2015/097354 A1 WO 2015/097349 A1 EP 3087207 B1 KR 10-2016-0090357 A CN 105849288 A	
JP 10-183242 A	14 July 1998	(Family: none)	
WO 2018/012625 A1	18 January 2018	US 2020/0370142 A1 claims, paragraphs [0105]-[012 6] EP 3486345 A1 KR 10-2018-0132925 A CN 109196132 A	
JP 2016-56438 A	21 April 2016	(Family: none)	

Form PCT/ISA/210 (patent family annex) (January 2015)

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP 3599551 B [0006]