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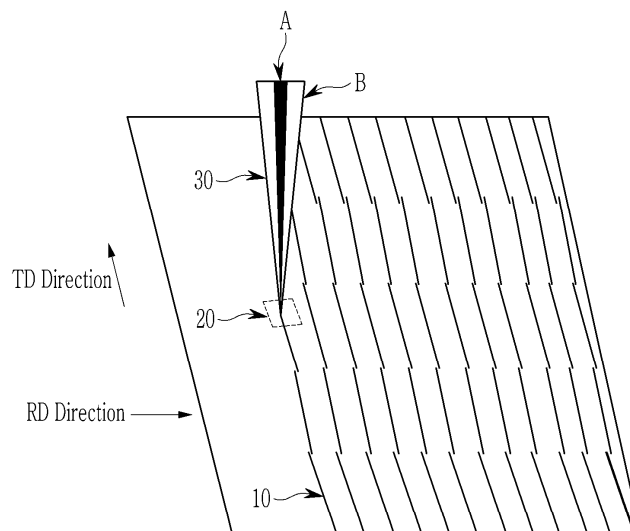
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Gyeongsangbuk-do 37859 (KR)(54) **GRAIN-ORIENTED ELECTRICAL STEEL SHEET AND METHOD FOR REFINING MAGNETIC DOMAINS THEREOF**

(57) A method for refining a magnetic domain of a grain-oriented electrical steel sheet includes forming a

groove by overlapping and irradiating beam spots of two or more lasers having different beam spot shapes.

FIG. 2

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Description**[Technical Field]**

[0001] An embodiment of the present disclosure relates to a grain-oriented electrical steel sheet and a method for refining a magnetic domain therein. More specifically, one embodiment of the present disclosure relates to a grain-oriented electrical steel sheet having excellent iron loss characteristics and a method for refining a magnetic domain thereof, by irradiating the surface of the steel sheet with two or more types of overlapping lasers to sufficiently secure a depth of a groove while at the same time drastically reducing molten by-products such as a hill-up sputter.

[Background Art]

[0002] A grain-oriented electrical steel sheet has an excellent magnetic characteristic to be generally used as an iron core material of a transformer. In manufacturing of the grain-oriented electrical steel sheet, a Goss texture recrystallized in an orientation of $\{110\} \langle 001 \rangle$ through a unique rolling and annealing process that only a manufacturing process of the electrical steel sheet has is formed throughout the steel sheet.

[0003] In order to cope with climate change, the world is strengthening calculation grade of greenhouse gas emission day by day. A factor affecting the calculation grade of the greenhouse gas emission in an iron core of the transformer is related to improvement of efficiency when the electrical steel sheet is used. In efficiency of the iron core of the transformer, an iron loss and a magnetic flux density (i.e., magnetic characteristics) of the electrical steel sheet are acting as important factors.

[0004] Because the magnetic flux density of the electrical steel sheet is higher as a degree to which a crystal axis that is easy to magnetize is gathered in a crystal structure that is crystal orientation is higher, the manufacturing process of the electrical steel sheet may significantly affect the magnetic flux density.

[0005] According to IEC60404-3 standard, for the iron loss of the electrical steel sheet, a W17/50 [W/kg] value measured when a magnetic field with a frequency of 50 Hz is applied at a maximum magnetic flux density of 1.7 T is called a guaranteed iron loss value of the core material, and this value is used as a measure of the iron loss of the electrical steel sheet. However, when the transformer is designed, a W15/50 [W/kg] value measured when a magnetic field with a frequency of 50 Hz is applied at a maximum magnetic flux density of 1.5 T that is lower than the maximum magnetic flux density of 1.7 T is also used. The lower the iron loss value, the better the efficiency of the transformer.

[0006] Therefore, the electric steel sheet with a high magnetic flux density and a low iron loss may be used as an iron core of the transformer with an excellent efficiency. The iron loss is evaluated as a more important indicator because a process technology for securing the high magnetic flux density through upward leveling of the manufacturing process of the electrical steel sheet has been developed to a level that may support an efficiency of the transformer.

[0007] The iron loss is divided into an eddy current loss and a hysteresis loss and the hysteresis loss tends to decrease if the magnetic flux density is high, so that the eddy current loss occupies an important position in controlling an overall iron loss in a grain-oriented electrical steel sheet. The eddy current loss among the iron loss is divided into a classical eddy current loss and an anomalous eddy current loss, and the classical eddy current loss is proportional to a thickness of the steel sheet so that the classical eddy current loss is decreased as the steel sheet is thinner. Therefore, controlling the anomalous eddy current loss is becoming an important technology for reducing the iron loss.

[0008] The eddy current loss among the iron loss may be reduced as a magnetic wall spacing of a 180° magnetic domain in a rolling direction becomes narrower, so that the iron loss is reduced by refining a magnetic domain of the electrical steel sheet.

[0009] Refining the magnetic domain in the electrical steel sheet means a process of separating the magnetic domain into multiple magnetic domains by applying a physical stimulus to a crystal grain with one magnetic characteristic.

[0010] A method for refining the magnetic domain may include laser irradiation, electron beam irradiation, plasma treatment, etching, roll pressing, or the like. Depending on whether an effect of refinement of the magnetic domain is maintained even after refinement treatment of the magnetic domain is performed and then stress relief annealing (SRA) is performed, refinement of the magnetic domain is divided into refinement of a permanent magnetic domain and refinement of a temporary magnetic domain.

[0011] Among the magnetic domain refinement technologies, the technology that can secure the magnetic domain refinement effect even after the stress relief annealing (SRA) is called as a permanent magnetic domain refinement technology. The permanent domain refinement technologies include a laser method for cold-rolled steel sheets or steel sheets that have completed secondary recrystallization, a groove transcription method using a rotating wedge-shaped knife roll, and an etching method that forms grooves through electrochemical etching in a solution. Since the groove transcription method is a groove forming method using a rotating knife roll, it is difficult to maintain roll durability due to changes in the applied load when the steel sheet thickness becomes thicker or thinner than a critical value, so it is difficult to precisely control the groove depth at high speeds. In addition, since the chemical etching method forms the grooves by an

anodic reaction of the steel sheet in a solvent, it is difficult to form the grooves at high speeds. When the laser method forms the groove by partially melting the steel sheet, it requires a high-power generator for a high-speed groove formation, and because the hill-up that occurs around the groove is removed by physical or chemical methods, it is necessary to use a brush after the groove formation or introduce a process of applying an oxide, etc. before the groove formation.

[Disclosure]

[Technical Problem]

[0012] In one embodiment of the present disclosure, a directional electrical steel sheet and a method for refining a magnetic domain thereof are provided. More specifically, in one embodiment of the present disclosure, by irradiating two or more types of overlapping lasers on the surface of the steel sheet to sufficiently secure the depth of a groove while at the same time drastically reducing molten by-products such as hill-up sputter, a grain-oriented electrical steel sheet having excellent iron loss characteristics and a method for refining a magnetic domain thereof are provided.

[Technical Solution]

[0013] A method for refining a magnetic domain of a grain-oriented electrical steel sheet includes forming a groove by overlapping and irradiating beam spots of two or more lasers having different beam spot shapes.

[0014] The laser may include a first laser and a second laser, and a first beam spot of the first laser beam and a second beam spot of the second laser beam may overlap by 10% or more.

[0015] The laser may include a first laser and a second laser, and an energy density of the first laser beam may be 1.1 to 4.0 times of an energy density of the second laser beam.

[0016] The first laser and the second laser may be selected from among a CO₂ laser, a fiber laser, a YAG laser, a ruby laser, a sapphire laser, a disk laser, a diode laser, or a UV laser.

[0017] The first laser and the second laser may each have an output of 10 to 2000 W.

[0018] The first laser and the second laser may have different wavelengths.

[0019] The interval between the time at which the first laser beam is irradiated and the time at which the second laser beam is irradiated may be 16 ms or less.

[0020] The groove may be in a form of a line extending in a direction intersecting a rolling direction.

[0021] The depth of the groove may be 5 to 15% of the thickness of the electrical steel sheet.

[0022] The longitudinal direction of the groove may form an angle of 75 to 105° with respect to the rolling direction.

[0023] The grooves may be formed intermittently in numbers of 2 to 10 along a vertical rolling direction of the electrical steel sheet.

[Advantageous Effects]

[0024] According to one embodiment of the present disclosure, by performing an optimal magnetic domain refinement using the overlapping laser, a magnetism may be further improved while at the same time sufficiently suppressing a generation of molten by-products such as a hill-up sputtering on the surface of a steel sheet.

[0025] According to one embodiment of the present disclosure, it is possible to easily increase the average output power by using the long-wavelength laser and secure the reliability of the processing line, and at the same time, by simultaneously irradiating the short-wavelength laser, the magnetic domains may be formed to a minimum, thereby effectively improving the magnetism.

[Description of the Drawings]

[0026]

FIG. 1 is a graph showing an optical absorption rate of a steel sheet according to a laser wavelength.

FIG. 2 is a schematic diagram illustrating a concept of a domain refinement for forming grooves by using an overlapping laser according to an embodiment of the present disclosure.

FIG. 3 is a schematic diagram showing a beam spot of an overlapping laser according to an embodiment of the present disclosure.

FIG. 4 is a schematic diagram showing a beam spot of an overlapping laser according to another embodiment of the present disclosure.

FIG. 5 is a schematic diagram showing a case where lasers are irradiated twice at a time interval rather than overlapping lasers according to one embodiment of the present disclosure.

[Mode for Invention]

[0027] Terms such as "first", "second", and "third" are used herein to describe various portions, components, regions, layers, and/or sections, but are not limited thereto. The terms are used only to distinguish one portion, component, region, layer, or section from another portion, component, region, layer, or section. Accordingly, a first portion, component, region, layer, or section described below may be referred to as a second portion, component, region, layer, or section within a scope that does not depart from a scope of the present disclosure.

[0028] A technical term used herein is intended only to refer to a specific embodiment, and is not intended to limit the present disclosure. Singular forms used herein also include plural forms unless phrases clearly indicate an opposite meaning. A term "include" used in the specification specifies a specific characteristic, region, integer, step, operation, element, and/or component, and does not exclude presence or addition of another characteristic, region, integer, step, operation, element, and/or component.

[0029] When it is said that a portion is "on" or "above" another portion, the portion may be disposed directly on or above the other portion, or another portion may be interposed therebetween. In contrast, when a portion is said to be "directly above" another portion, no other portion is interposed therebetween.

[0030] Although not otherwise defined, all terms used herein, including a technical term and a scientific term, have the same meanings as those generally understood by a person of ordinary skill in the art to which the present disclosure belongs. Terms defined in a dictionary commonly used are additionally interpreted to have a meaning consistent with the relevant technical literature and the presently disclosed contents, and are not interpreted in an ideal or very formal sense unless otherwise defined.

[0031] Hereinafter, an embodiment of the present disclosure will be described in detail so that a person of ordinary skill in the art to which the present disclosure belongs may easily implement the present disclosure. As those skilled in the art would realize, the described embodiments may be modified in various different ways, all without departing from the spirit or scope of the present disclosure.

[0032] In one embodiment of the present disclosure, the purpose is to provide excellent iron loss characteristics by irradiating the surface of the electrical steel sheet with an overlapping laser to sufficiently secure the depth of the groove while suppressing the formation of molten by-products such as a hill-up and a sputter existing on the surface of the steel sheet.

[0033] One embodiment of the present disclosure includes a step of forming a groove by overlapping and irradiating beam spots of two or more types of lasers having different beam spot shapes.

[0034] One of the preferred methods for improving an iron loss in a grain-oriented electrical steel sheet is to refine magnetic domains by forming grooves on the surface of the steel sheet by using a laser.

[0035] The process of refining the magnetic domain of the grain-oriented electrical steel sheet, as illustrated in Fig. 2, precedes and irradiates a laser in a direction crossing a rolling direction (a RD direction) to form a groove 10. The grooves may have a dot-like or continuous linear groove shape, and FIG. 2 illustrates a linear groove. Here, the linear groove or the groove on the line includes not only a solid line but also a dotted or broken line that continues intermittently, and also includes a zigzag shape when viewed microscopically but a straight line when viewed macroscopically, and includes all grooves that form a linear shape in practice.

[0036] The groove formation in the steel sheet by laser is achieved by melting and vaporizing a portion of the steel sheet by a laser irradiation, and the melted and vaporized portion remains in the shape of the groove.

[0037] At this time, the depth of the groove is proportional to an energy density (a power density) per unit time of the laser, and is also affected by the laser absorption rate of the steel sheet surface.

[0038] However, when the laser irradiation is performed, the depth of the groove increases as the total laser irradiation energy increases. However, if an energy exceeding the required amount is irradiated to the steel sheet, molten byproducts such as a hill-up and a sputter remain on the surface of the steel sheet, which have a negative effect on a magnetism and therefore need to be suppressed. Therefore, when irradiating with a laser, it is desirable to irradiate a large amount of the energy over a narrow area as much as possible, with a high energy absorption rate, for a short period of time.

[0039] Additionally, the interaction conditions between the laser beam and the steel sheet are affected by the characteristics of the laser and the absorption rate of the laser beam by the steel sheet. The absorption rate of the laser beam is affected by the surface roughness of the steel sheet, the temperature of the steel sheet, the absorption characteristics of the steel sheet surface, and the laser wavelength. However, when the manufacturing conditions of the steel sheet are constant over the entire surface, the surface roughness of the steel sheet, the temperature of the steel sheet, and the absorption characteristics of the steel sheet surface will be constant, and in this case, the absorption rate of the laser beam on the steel sheet will depend on the wavelength of the laser.

[0040] That is, when the manufacturing conditions of the steel sheet are constant, the laser absorption rate is affected by the wavelength of the laser. As shown in FIG. 1, the laser absorption rate of the steel sheet is approximately 35 to 40% when the wavelength is short (e.g., YAG or Fiber laser with $1.06\ \mu\text{m}$), while it is relatively low, approximately 5 to 10% when the wavelength is long (e.g., CO₂ laser with $10.6\ \mu\text{m}$).

[0041] In this way, in the process of refining the magnetic domains of the grain-oriented electrical steel sheet by using a laser, it is more efficient to use a short-wavelength laser than to use a long-wavelength laser to secure the stable iron loss characteristics.

[0042] Meanwhile, on the surface of the electrical steel sheet subject to a domain refinement treatment, an insulating film mainly composed of phosphate and silica with a thickness of several to several tens of micrometers is sometimes formed. These films show relatively low absorption of laser beams for short wavelength lasers (e.g., YAG or Fiber lasers of 1.06 μm), but high absorption for long wavelength lasers (e.g., CO₂ lasers of 10.6 μm). As a result, the thickness of the insulating film must be considered in long-wavelength lasers, but in short-wavelength lasers, the thickness of the insulating film needs to be considered less than in long-wavelength lasers.

[0043] As described above, short-wavelength lasers and long-wavelength lasers have different characteristics. Therefore, when using the short-wavelength lasers and the long-wavelength lasers simultaneously and superimposingly, the advantages of each laser applied to the domain refinement are preferentially exerted without side effects, thereby inducing a synergistic effect.

[0044] Here, using the lasers in an overlapping manner means using two or more lasers with different beam spot shapes to irradiate the surface of the steel sheet, and the spot of one laser beam formed on the surface of the steel sheet is partially or completely located within the spot of another laser beam. Therefore, in one embodiment of the present disclosure, the overlapping lasers having different wavelengths include not only those in which the spot of one laser beam is completely overlapped with the spot of another laser beam, but also those in which it is partially overlapped with the spot of another laser beam. Meanwhile, if there is a time interval for the irradiation time, the steel sheet surface cools rapidly during the interval, making it difficult to obtain the effect of overlapping laser irradiation. Accordingly, it is desirable to irradiate two or more lasers simultaneously, and specifically, the interval between the irradiation time of the first laser beam and the irradiation time of the second laser beam may be 16 ms or less. In FIG. 3, an example is shown in which the first laser beam 21 and the second laser beam 22 are partially overlapped and irradiated, and in FIG. 4, an example is shown in which the first laser beam 21 and the second laser beam 22 are completely overlapped and irradiated. As mentioned above, FIG. 5 is a case where the laser beams do not overlap at a specific point in time, and if the interval between the irradiation times to a specific location exceeds 16 ms, it is defined as not being irradiated by overlapping.

[0045] In one embodiment of the present disclosure, the beam spot means a beam spot on the surface of the steel sheet. In FIG. 3, the first beam spot of the first laser beam 21 and the second beam spot of the second laser beam 22 are schematically shown.

[0046] The first beam spot of the first laser beam and the second beam spot of the second laser beam overlap by 10% or more. 10% or more means the ratio of the width of the overlapping area OW to the width of the smaller laser beam among the width of the first laser beam B1W and the width of the second laser beam B2W. In FIG. 3, the width B1W of the first laser beam is small, and in this case, the overlap ratio may be calculated as OW/B1W.

[0047] The width of the laser beam is the length of the laser beam in the direction (a Y direction) perpendicular to the groove length direction (or a laser irradiation direction, a X direction). The length of the laser beam is the length of the laser beam in the groove length direction (or the laser irradiation direction, the X direction). In FIG. 3, the length B1L of the first laser beam and the length B2L of the second laser beam are indicated.

[0048] In FIG. 4, it is schematically shown that the first beam spot of the first laser beam 21 is disposed within the second beam spot of the second laser beam 22, and in this case, the overlap ratio is calculated as 100%.

[0049] Meanwhile, in one embodiment of the present disclosure, the groove has a shape in which the bell is turned upside down by the irradiation with the overlapping laser.

[0050] The first laser and the second laser may be selected from a CO₂ laser, a fiber laser, a YAG laser, a ruby laser, a sapphire laser, a disk laser, a diode laser, or a UV laser.

[0051] More specifically, the first laser A, which is the short-wavelength laser, may use a laser with a relatively short wavelength, such as an optical fiber (Er-Fiber, Yb-Fiber, Tm-Fiber) laser, a YAG (Nd:YAG, Yb:YAG) laser, a ruby laser, and a sapphire laser. In addition, a disk laser (1.03 μm), a diode laser (0.808 to 0.980 μm) or a UV laser (0.150 to 0.355 μm) may be used as the first laser.

[0052] Also, as the second laser, which is a long-wavelength laser, a laser with a relatively longer wavelength than a short-wavelength laser may be used. For example, a CO₂ laser is preferred as the second laser. However, if a UV laser (0.150 to 0.355 μm) is used as the first laser, which is a short-wavelength laser, any laser with a longer wavelength than the first laser can be used as the second laser. For example, in this case, when a UV laser (0.150 to 0.355 μm) is used as the first laser, a YAG laser may also be used as the second laser.

[0053] Hereinafter, a method for the domain refinement using an overlapping laser 30 will be described in more detail, taking as an example the case where a fiber laser is used as the first laser with a short wavelength and a CO₂ laser is used as the second laser with a long wavelength.

[0054] The fiber laser as the first laser uses the short wavelength laser with the relatively high laser absorption rate for the steel sheet, so it is possible to irradiate the incident energy capable of forming the groove to a narrow area for a shorter period of time. Additionally, the fiber laser used as the first laser may minimize the formation of molten byproducts because

its incident energy range is narrow. However, it is difficult to irradiate the sufficient energy to form the groove with only the first laser.

[0055] Meanwhile, as the second laser, the CO₂ laser may be used with an average output of several hundred W to several kilowatts or more depending on the sheet metal speed. Therefore, the CO₂ laser of the second laser is suitable for serving as a kind of preheating function. However, since the CO₂ laser, which is the second laser B, has a low laser absorption rate for the steel sheet, an excessive amount of the energy must be applied to form the groove using the CO₂ laser alone, and in this process, a large amount of molten byproducts are formed.

[0056] Accordingly, the fiber laser with the relatively short wavelength is used as the primary laser for groove formation, and the CO₂ laser with the relatively long wavelength is used as an auxiliary laser that serves as a kind of preheating.

[0057] In this case, a 180° magnetic domain (an opposite magnetic pole of a lancet magnetic domain) is formed in the surface direction by a magnetoelastic energy due to the magnetic domain refinement, and a 90° magnetic domain is formed to reduce the magnetoelastic energy in the plate thickness direction, thereby narrowing the gap between the magnetic domains and ultimately reducing an anomalous eddy current loss.

[0058] It is desirable that the position of the primary laser is located in an area where the beam intensity of the auxiliary laser cross-section is at least 25% of that of the auxiliary laser cross-section beam intensity. More preferably, the primary laser position needs to be located in an area having a value of 30% or more of the auxiliary laser cross-section beam intensity. When the primary laser position located on the final steel sheet surface is located in the area of 25% or more of the auxiliary laser cross-section beam intensity, the laser absorption rate of the primary laser may be maximized. That is, there is a disadvantage in that the laser absorption rate of the steel sheet surface by the primary laser cannot be significantly increased when located in an area of less than 25% of the beam intensity.

[0059] As described above, the method for refining the magnetic domain according to one embodiment of the present disclosure uses the fiber laser of the short-wavelength as the first laser and simultaneously uses the CO₂ laser of the long-wavelength as the second laser to form the groove 10 of the sufficient depth while minimizing the formation of molten byproducts.

[0060] At this time, the beam spot of the fiber laser, which is the first short-wavelength laser irradiated on the surface of the steel sheet, is preferably in a shape close to a circle, and the diameter BW1 and BL1 may be 5 to 500 μm. In addition, the beam spot of the fiber laser may be used with the width BW1 of 5 to 500 μm and the length BL1 that is less than or greater than the beam spot of the CO₂ laser, which is the second laser.

[0061] When the beam width BW1 of the optical fiber, which is the first laser, is reduced to less than 5 μm, the energy density is concentrated in a narrow area, which may cause a magnetic flux density and core loss inferiority, and there is a problem that the optical system structure becomes complicated. Also, when the beam width BW1 of the optical fiber, which is the first laser, increases to 500 μm or more, the groove width in the longitudinal direction of the steel sheet increases, and a large number of melting byproducts such as hill-up and sputter are formed, which may result in a decrease in the magnetic flux density. More specifically, the width and length of the beam spot may be 10 to 100 μm.

[0062] Meanwhile, the beam spot of the CO₂ laser, which is the second long-wavelength laser irradiated onto the surface of the steel sheet, is preferably an ellipse with the beam width (B2W) of 100 to 400 μm and a beam length (B2L) of 0.4 to 20 mm. Additionally, the beam spot of a long-wavelength CO₂ laser may be used as a circle with a radius of 100 μm or more.

[0063] It is not desirable to form the CO₂ beam width B2W of the second laser within 100 μm because the mirror optical system becomes complicated like a fiber laser, and if it increases to more than 400 μm, a large number of melting byproducts such as hill-up and sputtering may be formed, which may result in a decrease in the magnetic flux density.

[0064] The reason for limiting the size of the beam spot of the CO₂ laser, which is the long-wavelength second laser, is to consider the range within which the effect of the laser beam acting on the steel sheet is maintained when scanning the surface of the steel sheet moving at high speed with a high-speed laser.

[0065] The case of using the lasers in the overlapping manner according to one embodiment of the present disclosure will be described in more detail.

[0066] As shown in FIG. 3 and FIG. 4, using the first laser beam 21 and the second laser beam 22 to overlap on the final steel sheet surface means that the beam spot of the first laser beam 21 and the beam spot of the second laser beam 22 are controlled to overlap. That is, the laser beam spots 20 irradiated on the surface of the steel sheet are said to be "overlapping" when the first laser beam 21 is completely positioned anywhere within the range of the second laser beam 22 with the large beam spot when viewed in a plan view, as in FIG. 4, and further, as in FIG. 3, it means that the beams are "overlapping" including the first laser beam 21 being partially positioned within the range of the second laser beam 22. Furthermore, if the laser beams do not overlap at a specific point in time, as in FIG. 5, they are considered as a non-overlapping. However, if the interval between the time at which the first laser beam is irradiated and the time at which the second laser beam is irradiated for a specific location is 16 ms or less, it is considered that they are irradiated simultaneously. Beyond this time range, the surface of the steel sheet cools rapidly, making it difficult to sufficiently obtain the effect of the overlapping laser irradiation. The time interval refers to the time from when the second laser (or the first laser) is irradiated until the first laser (or the second laser) advances and the width OW of the overlapping region

becomes maximum. In the case of FIG. 5, the laser beams are not overlapped for a specific point in time, but if the first laser beam 21 moves to a dotted circle within 16 ms and overlaps and irradiates the location irradiated by the second laser beam 22, it is considered that the irradiations are performed in an overlap manner.

[0067] In one embodiment of the present disclosure, a laser beam oscillation mode is preferably a continuous wave laser that continuously generates a laser light for both the first laser and the second laser, but a pulse laser may also be used.

[0068] The energy density of the first laser beam may be 1.1 to 4.0 times of the energy density of the second laser beam. As mentioned above, the energy density of the first laser beam is high, so that a high energy may be applied to a narrow area, thereby forming the deep groove with less melting by-products. Additionally, the energy density of the second laser beam is relatively small, so that the absorption rate of the first laser beam may be increased by applying a low energy to a large area.

[0069] Also, the quality of the laser beam used is preferably a Gaussian mode of TEM 00 for both the first and second lasers, but a multi-mode (a multi transverse mode) of TEM mn may also be used.

[0070] However, since the overlapping laser beams 20 of the different wavelengths irradiated on the surface of the steel sheet according to one embodiment of the present disclosure may form the depth of the grooves deep while minimizing the formation of the grooves in the longitudinal direction of the steel sheet, the beam shape or the beam quality of each laser is not specifically limited.

[0071] The first laser and the second laser may each have an output power of 10 to 2000 W. More specifically, the output of the first laser may be 1000 to 2000 W, and the output of the second laser may be 100 to 700 W. The output range of each laser indicates a laser output condition when the steel sheet is advanced at the speed of 10 to 30 mpm. The output value of the laser may be optimally controlled according to the steel sheet advancement speed, and the output value may also go beyond the above range depending on the steel sheet advancement speed.

[0072] When the laser beam (30) in which the first laser and the second laser are overlapped as described above is irradiated onto the surface of the steel sheet, the interval (i.e., the interval between the grooves in the rolling direction of the steel sheet) may be 2 to 10 mm, the angle between the rolling direction and the laser propagation direction (the groove length direction, the X direction) may be 75 to 105°, and the scanning speed is preferably 0.1 to 300 m/sec.

[0073] The electrical steel sheet used at this time may be a cold-rolled sheet, a steel sheet after a primary recrystallization annealing, or a steel sheet after a secondary recrystallization annealing.

[0074] Also, if the irradiation interval of the overlapping laser beam 20 irradiated on the surface of the steel sheet is too narrow, less than 2 mm, the effect of the heat affected zone becomes large, and the magnetic flux density and the iron loss become inferior, and if the irradiation interval is 10 mm or more, the thermal shock effect for securing the magnetic domain refinement effect is reduced, making it difficult to achieve the effect.

[0075] In addition, when irradiating the overlapping laser beam 20 to the surface of the steel sheet, the irradiation may be performed in a direction perpendicular or inclined to the steel sheet rolling direction, and the angle between the rolling direction and the laser propagation direction (the groove length direction, the X direction) may be 75 to 105°. Outside this angular range, the required domain refinement effect may not be achieved.

[0076] And, since the scanning speed of the overlapping laser should be the same as the steel sheet progress speed, the scanning speed should be faster as the progress speed increases, so 0.1 to 300 m/sec is preferable, and this speed means the value exemplified under the condition of 15 mpm.

[0077] Meanwhile, it means that the first laser beam and the second laser beam are simultaneously superimposed and irradiated as in FIG. 3 and FIG. 4, and the irradiated and superimposed with the time interval as in FIG. 5 is excluded. Simultaneously irradiating means that the interval between the time at which the first laser beam is irradiated and the time at which the second laser beam is irradiated for a specific location is 16 ms or less. Beyond this time range, the surface of the steel sheet cools rapidly, making it difficult to sufficiently obtain the effect of the overlapping laser irradiation. The time interval refers to the time from when the second laser (or the first laser) is irradiated until the first laser (or the second laser) advances and the width OW of the overlapping region becomes maximum.

[0078] The groove may be in the form of the line extending in a direction intersecting the rolling direction.

[0079] The depth of the groove may be 5 to 15% of the thickness of the electrical steel sheet.

[0080] The longitudinal direction of the groove may form an angle of 75 to 105° with respect to the rolling direction.

[0081] The grooves may be formed intermittently in the number of 2 to 10 along the vertical rolling direction of the electrical steel sheet. Meanwhile, when forming the grooves by irradiating the overlapping laser on the surface of the electrical steel sheet according to one embodiment of the present disclosure, it is preferable that the W17/50 iron loss improvement rate of the steel sheet be 5.0% or more. More specifically, it over 9% is desirable.

[0082] Hereinafter, a method for manufacturing the grain-oriented electrical steel sheet according to one embodiment of the present disclosure will be described in detail.

[Manufacturing of cold rolled steel sheets]

[0083] To manufacture the grain-oriented electrical steel sheet, first, a slab of an electrical steel sheet substrate is

manufactured.

[0084] The chemical composition and metal structure of the slab are not specifically limited as long as the magnetization axis is aligned in a certain direction and functions as the electrical steel sheet. Only, as an example, the chemical composition of the slab is as follows.

[0085] As a mass %, C: 0.08% or less (excluding 0%), Si: 1.0 to 6.5%, Mn: 0.005 to 3.0%, (sum of any one or more of Nb, V, Ti): 0.070% or less, (sum of any one or more of Cr, Sn, Sb): 2.5% or less, Al: 2.0% or less (excluding 0%), (sum of any one or more of P, S): 0.100% or less (excluding 0%), (sum of Cu and Sn): 1.0% or less, rare earth elements and other impurities totaling 0.2% or less, the remainder being Fe.

(C: 0.08% or less (excluding 0%))

[0086] Carbon (C) may be an element that is inevitably mixed into steel, but carbon (C) may be controlled to an appropriate content because it deteriorates a magnetic characteristic due to magnetic aging. If a content of C within the steel sheet is too low, phase transformation may not occur sufficiently during a manufacturing process thereof. Thus, a microstructure of the steel sheet may be made non-uniform so that a secondary recrystallization structure becomes unstable. If the content of C within the steel sheet is too high, carbide may become coarse and an amount of precipitation thereof may be excessive during the manufacturing process. Thus, a degree of integration of a Goss texture may be reduced due to insufficient decarbonization so that a secondary recrystallization texture is damaged. Therefore, the content of C of the steel sheet may be 0.08% or less or 0.001 to 0.040%.

(Si: 1.0 to 6.5 %)

[0087] Silicon (Si) may be a basic composition of the grain-oriented electrical steel, and may play a role in increasing resistivity of the steel sheet to reduce an iron loss. If a content of Si is less than 1.0%, the resistivity may be decreased so that an eddy current loss is increased. Thus, an iron loss characteristic may be deteriorated so that an effect of Si addition is not expected. If the content of Si is 6.5% or more, brittleness of the steel sheet may be increased and toughness of the steel sheet may be decreased so that breakage of the sheet occurs during a rolling process, and nitride may not be sufficiently formed during the manufacturing process so that sufficient grain inhibition necessary for secondary recrystallization is not secured in a final high-temperature annealing process. Therefore, it is preferable that the content of Si may be 1.0 to 6.5%.

(Mn: 0.005 ~ 3.0%)

[0088] Manganese (Mn) may have an effect of reducing a total iron loss by increasing resistivity to reduce an eddy current loss, and manganese (Mn) may be an important element that reacts with S in a fired steel state to form Mn-based sulfide and reacts with nitrogen introduced by nitriding with Si to form a precipitate of (Al, Si, Mn) N so that it inhibits growth of a primary recrystallized grain to cause secondary recrystallization and affects surface quality of a final product. If too little Mn is included, the surface quality of the final product may be deteriorated. If too much Mn is included, an austenite phase fraction may be very increased so that the Goss texture is damaged, a magnetic flux density may be reduced, and an oxide layer may be formed too excessively during decarbonization annealing so that decarbonization is hindered. Therefore, Mn is preferably 0.005 to 3.0%.

(at least one of Nb, V, and Ti: 0.05% or less)

[0089] Niobium (Nb), vanadium (V), and titanium (Ti) may be elements that react with C and N during the manufacturing process to form a precipitate. If too much at least one of Nb, V, and Ti is added, the at least one of Nb, V, and Ti may remain in the steel sheet even after secondary recrystallization annealing so that a magnetic characteristic of the steel sheet is reduced. Therefore, at least one element selected from Nb, V, and Ti may be controlled so that a content of the at least one element is 0.05% or less.

(at least one of Cr, Sn, and Sb: 2.5% or less)

[0090] Chromium (Cr) may be added for a purpose of reducing an iron loss by promoting formation of the Goss texture, and Sn may be added for a purpose of suppressing grain growth to ultimately improve a magnetic flux density. Antimony (Sb) may have an effect of inhibiting growth of a grain to stabilize secondary recrystallization by segregating at a grain boundary. Because all of the three elements that are Cr, Sn, and Sb are correlated with formation of a secondary recrystallized structure, a total of Sn, Sb, and Cr may be controlled so that a content of the total of Sn, Sb, and Cr is 2.5% or less.

(Al: 2.0% or less (excluding 0%))

[0091] In addition to Al-based nitride precipitated during the manufacturing process, aluminum (Al) may be coupled with N introduced by nitriding treatment during a primary recrystallization process and Al, Si, and Mn present in a solid solution state in steel to form (Al, Si, Mn)N and AlN-type nitride, so that aluminum (Al) serves as a strong grain growth inhibitor. If too much Al is included, a precipitate may become non-uniform so that formation of secondary recrystallization becomes unstable. Thus, a magnetic characteristic of the steel sheet may be reduced so that Al is added in an amount of 2.0% or less.

(at least one of P and S: 0.1% or less (excluding 0%))

[0092] Phosphorus (P) may be segregated at a grain boundary to hinder a movement of the grain boundary and simultaneously serve as an auxiliary role inhibiting growth of a grain, and if too much S is added, S may make formation of secondary recrystallization unstable. P and S may be elements that are inevitably added during a process of manufacturing the electrical steel sheet, and may be controlled so that a content of P and S is 0.1% or less.

(Cu and Sn: 0.1% or less)

[0093] Copper (Cu) may play a role of improving the texture by being partially dissolved within a grain, and if a content of Cu and Sn is excessive, Cu and Sn may be controlled so that the content of Cu and Sn is 0.1% or less because Cu and Sn are segregated in a grain boundary to form a liquid phase at a high temperature.

(Total of rare earth element and other impurity: 0.2% or less)

[0094] The grain-oriented electrical steel sheet according to an embodiment of the present disclosure may include the rare earth element such as cerium (Ce) or praseodymium (Pr) and the other impurity, and a total amount of the rare earth element and the impurity may be 0.2% or less. The rare earth element and the impurity may refer to an impurity that is intentionally introduced or inevitably mixed in steelmaking and a manufacturing process of the grain-oriented electrical steel sheet. Because the inevitable impurity is widely known, a detailed description thereof is omitted. An embodiment of the present disclosure does not exclude addition of an element in addition to the above-described alloy component, and may be variously included within a range that does not impair the technical idea of the present disclosure. If the additional element is included, the additional element may replace the balance of iron (Fe).

[0095] Next, the slab may be manufactured by a continuous casting method, the manufactured slab may be heated by a usual method to be hot-rolled, and hot-rolled sheet annealing may be performed on the hot-rolled slab selectively as necessary to be cold-rolled so that the steel sheet having the above composition is manufactured in a thickness range of 0.1 to 0.5 mm. The cold rolling may be performed by one cold rolling or two or more cold rolling with intermediate annealing interposed therebetween.

[primary recrystallization annealing]

[0096] The primary recrystallization annealing may be performed on the cold-rolled steel sheet described above through a simultaneous decarbonitriding or post-decarbonization nitrification process. In the primary recrystallization annealing by simultaneous decarbonitriding, a structure of the cold rolling deformed during the annealing process may include recrystallization so that decarbonization annealing is performed on the structure of the cold rolling. To this end, the primary recrystallization annealing may be performed in a mixed gas atmosphere in which nitrogen, hydrogen, and water are mixed. In the nitriding after decarbonization, a nitrification treatment in which a nitrogen ion is introduced into the steel sheet may be performed using an ammonia gas after decarbonization.

[0097] If the simultaneous decarbonitriding is performed, in the primary recrystallization annealing for the cold-rolled steel sheet loaded into a furnace, a dew point temperature of an atmospheric gas may be set to 40 to 70°C in a 700 to 900°C section and a $\text{Fe}_2\text{SiO}_4/\text{SiO}_2$ ratio of a surface thereof may be controlled to 0.5 to 3.0 to form an oxide layer on a surface of the electric steel sheet.

[secondary recrystallization annealing]

[0098] Then, an annealing separation agent based on MgO may be applied to a surface of the electrical steel sheet and then a temperature may be raised to 1,000°C or higher to cause secondary recrystallization by long-term soak annealing so that it forms a texture of a Goss orientation in which a {110} surface of the steel sheet is parallel to a rolling surface and a <001> direction is parallel to a rolling direction. Through the final high-temperature annealing process, a glass film layer

including forsterite may be formed on a surface of the steel sheet and the secondary recrystallization may be formed inside the steel sheet.

[formation of insulating film]

[0099] A steel sheet on which the secondary recrystallization occurs may be coated with a single or composite insulating coating liquid of colloidal silica and metal phosphate and then may be annealed to form an insulating film layer on a surface of the electric steel sheet on which the glass film layer is formed.

[0100] A method for forming the insulating film layer may be used without particular limitation, and for example, the insulating film layer may be formed by applying an insulating coating liquid including phosphate. A coating liquid including colloidal silica and metal phosphate may be used as the insulating coating liquid. In this case, the metal phosphate may be Al phosphate, Mg phosphate, or a combination thereof, and a content of Al, Mg, or a combination thereof compared with a weight of the insulating coating liquid may be 15 wt% or more.

[groove formation and refinement treatment of magnetic domain]

[0101] Since the methods for forming the groove and refining the magnetic domain have been described above, detailed descriptions are omitted. The magnetic domain refinement treatment may be performed during the aforementioned process, after cold rolling, after primary recrystallization annealing, after secondary recrystallization annealing, or after insulating film formation. More specifically, it may be performed after cold rolling and before the first recrystallization annealing.

[0102] Below, the present disclosure is described in more detail through specific examples. However, these examples are only for illustrating the present disclosure, and the present disclosure is not limited thereto.

Experimental Example 1

[0103] A cold-rolled steel sheets with a thickness of 0.20 mm is manufactured using a slab having a composition shown in Table 1 below and hot-rolled and cold-rolled. In Table 1, an element % may mean weight %.

(Table 1)

C (%)	Si (%)	Mn (%)	Cr (%)	Sn (%)	Sb (%)	Al (%)	Balance
0.05	3.518	0.103	0.113	0.0699	0.019	0.003	Fe

[0104] At a plate moving speed of 0.83 m/s, a fiber laser was used as a main laser and a CO₂ laser was used as an auxiliary laser. The beam size of the fiber laser finally formed on the steel sheet was 10 μm in the width (a rolling direction) to form an elliptical beam, and the CO₂ laser formed an elliptical beam with the width of 150 μm. By aligning the centers of the laser beams and irradiating the laser in the width direction of the steel sheet simultaneously, linear grooves with an average depth of 20 μm were formed at 3mm intervals.

[0105] The steel sheet formed with the grooves by the laser irradiation was subjected to a decarburization, a MgO application, a high-temperature annealing, and a flattening annealing to form a surface insulation coating layer. Afterwards, the magnetism of the steel sheet was measured using a single sheet tester (SST) after a stress relief annealing heat treatment, and the original plate was subjected to the decarburization, the high-temperature annealing, and the flattening annealing targeting the cold-rolled plate closest to the groove formation area to form the surface insulating coating layer, and then a stress relief annealing heat treatment was performed, and the magnetism was measured using the single sheet tester to measure the core loss and magnetic flux density of the original plate.

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(Table 2)

	First laser		Second laser	Groove no-formation		Groove formation		Iron loss improvement (%)	Electric insulation (mA)
	Oscillation mode / beam quality	Output (W)	output(W)	$W_{17/50}$ (W/kg)	B_8 (T)	$W_{17/50}$ (W/kg)	B_8 (T)		
Embodiment 1	Continuous wave	1200	800	0.73	1.913	0.63	1.911	13.7	8
Embodiment 2	Pulse wave (15kHz)	1200	800	0.73	1.913	0.62	1.911	15.1	9
Embodiment 3	Gaussian (M2=1.05)	1200	800	0.73	1.914	0.62	1.910	15.1	10
Embodiment 4	Multi-mode (M2=12.2)	1200	800	0.73	1.913	0.63	1.911	13.7	10

[0106] As shown in Table 2, when the first and second lasers were superimposed, no appropriate iron loss improvement could be obtained.

Experimental Example 2

[0107] The same procedure as Example 1 was followed, but the laser irradiation interval was changed to 2.5 mm, and the beam overlap ratio was changed as shown in Table 3 below. In Comparative Example 4, the second laser was applied after a one second interval following the first laser irradiation.

(Table 3)

	First laser	Second laser	Overlapping rate (%)	Groove no-formation		Groove formation		Iron loss improvement rate (%)	Electric insulation (mA)
	Output (W)	Output (W)		$W_{17/50}$ (W/kg)	$W_{17/50}$ (W/kg)	$W_{17/50}$ (W/kg)	B_8 (T)		
Embodiment 5	1200	800	25	0.73	1.914	0.69	1.913	5.5	10
Embodiment 6	1200	800	30	0.73	1.914	0.68	1.913	6.8	9
Embodiment 7	1200	800	50	0.73	1.915	0.65	1.912	11.0	11
Embodiment 8	1200	800	100	0.73	1.915	0.63	1.911	13.7	8
Comparative Example 1	1200	-	-	0.73	1.923	0.74	1.925	-1.4	67
Comparative Example 2	-	800	-	0.73	1.920	0.76	1.900	-4.1	350

(continued)

	First laser	Second laser	Overlapping rate (%)	Groove no-formation		Groove formation		Iron loss improvement rate (%)	Electric insulation (mA)
	Output (W)	Output (W)		$W_{17/50}$ (W/kg)	$W_{17/50}$ (W/kg)	$W_{17/50}$ (W/kg)	B_8 (T)		
Comparative Example 3	-	2000	-	0.73	1.920	0.78	1.875	-6.8	670
Comparative Example 4	1200	800	-	0.73	1.920	0.74	1.923	-1.4	75

[0108] As shown in Table 3, it may be confirmed that when the first and second lasers are superimposed, the improvement in the iron loss may be achieved. On the other hand, when a single laser is used or the laser is irradiated over a long period of time, it may be confirmed that the iron loss actually deteriorates and the insulation is inferior.

[0109] The present disclosure is not limited to the embodiments, may be manufactured in various different forms, and a person of ordinary skill in the art to which the present disclosure belongs will be able to understand that the present disclosure may be implemented in other specific forms without changing the technical idea or essential feature of the present disclosure. Therefore, it should be understood that the embodiments described above are illustrative and not limited in all respects.

[Explanation of symbols]

100: grain-oriented electrical steel sheet, 10: groove,
 20: laser beam spot, 21: first laser beam spot
 22: second laser beam spot

Claims

1. A method for refining a magnetic domain of a grain-oriented electrical steel sheet, comprising forming a groove by overlapping and irradiating beam spots of two or more lasers having different beam spot shapes.
2. The method for refining the magnetic domain of the grain-oriented electrical steel sheet of claim 1, wherein: the laser includes a first laser and a second laser, and a first beam spot of the first laser beam and a second beam spot of the second laser beam overlap by 10% or more.
3. The method for refining the magnetic domain of the grain-oriented electrical steel sheet of claim 1, wherein: the laser includes a first laser and a second laser, and an energy density of the first laser beam is 1.1 to 4.0 times of an energy density of the second laser beam.
4. The method for refining the magnetic domain of the grain-oriented electrical steel sheet of claim 1, wherein: the laser includes a first laser and a second laser, and the first laser and the second laser are selected from among a CO₂ laser, a fiber laser, a YAG laser, a ruby laser, a sapphire laser, a disk laser, a diode laser, or a UV laser.
5. The method for refining the magnetic domain of the grain-oriented electrical steel sheet of claim 1, wherein: the laser includes a first laser and a second laser, and the first laser and the second laser each have an output of 10 to 2000 W.
6. The method for refining the magnetic domain of the grain-oriented electrical steel sheet of claim 1, wherein: the laser includes a first laser and a second laser, and the first laser and the second laser have different wavelengths.
7. The method for refining the magnetic domain of the grain-oriented electrical steel sheet of claim 1, wherein: the laser includes a first laser and a second laser, and, at the overlapping irradiation, the interval between the time at which the first laser beam is irradiated and the time at which the second laser beam is irradiated is 16 ms or less.

FIG. 1

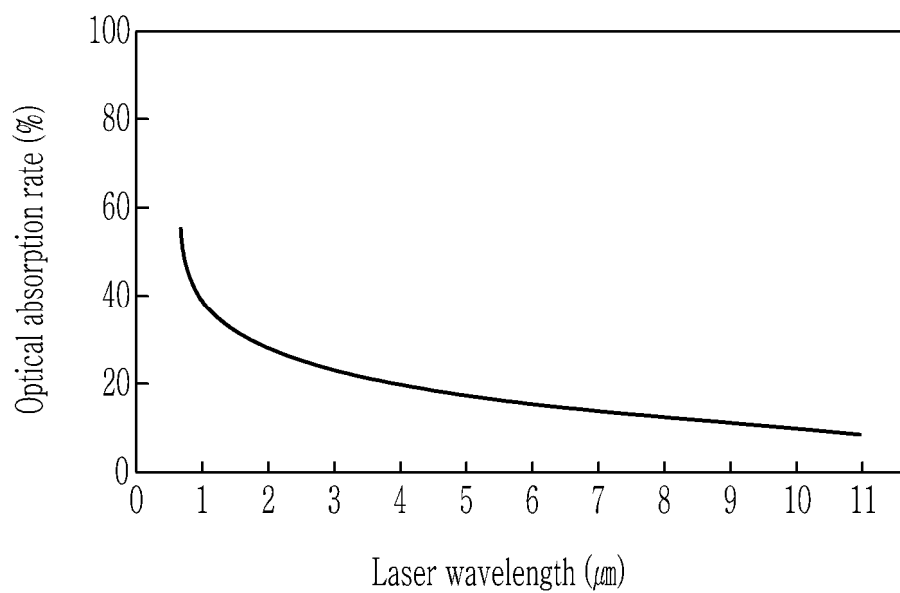


FIG. 2

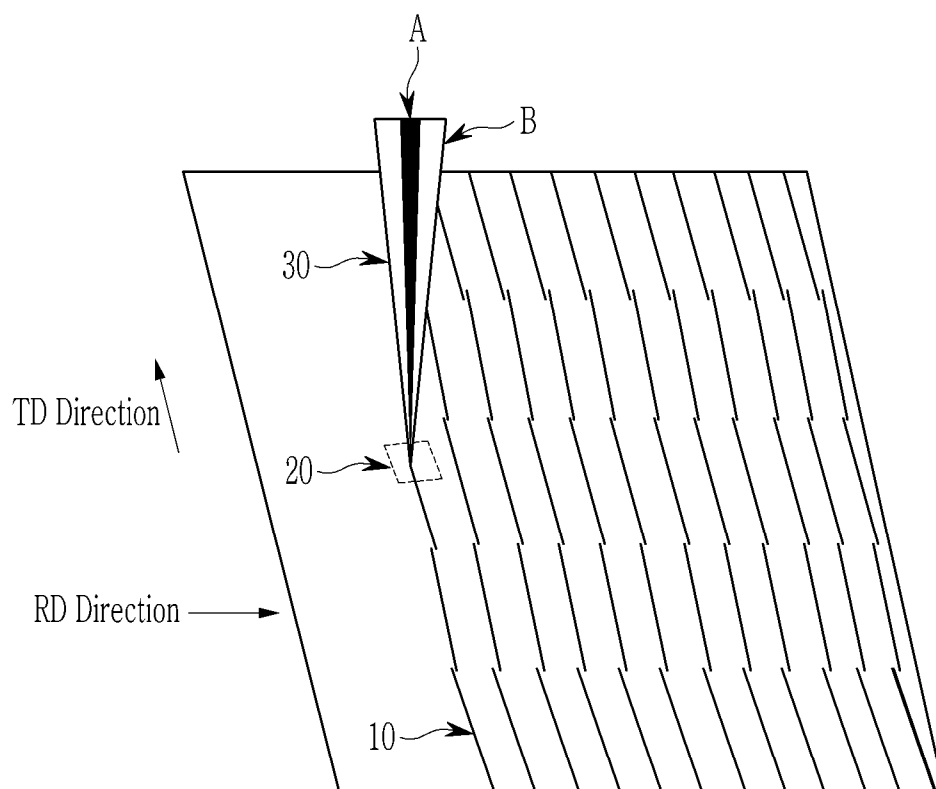


FIG. 3

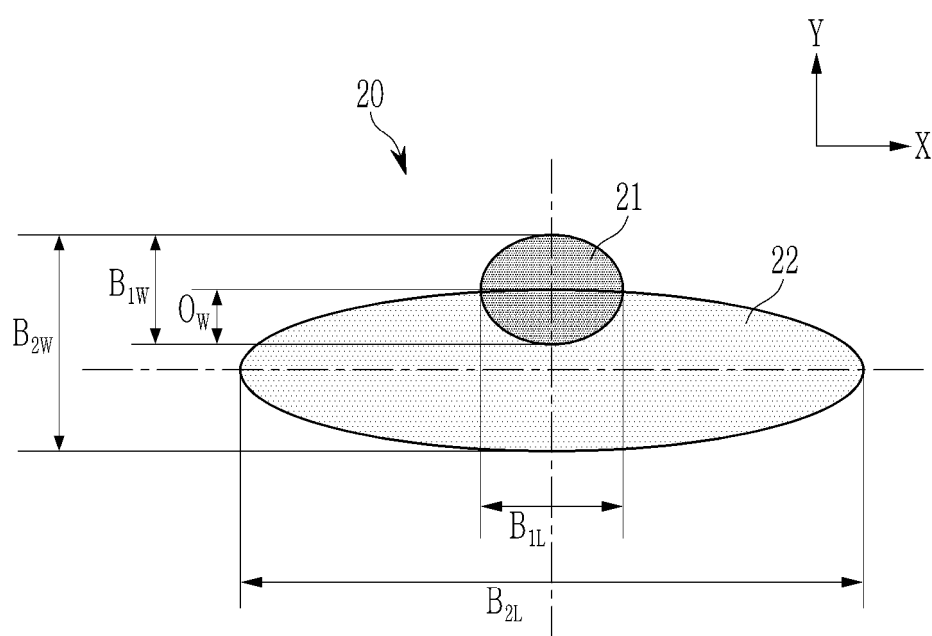


FIG. 4

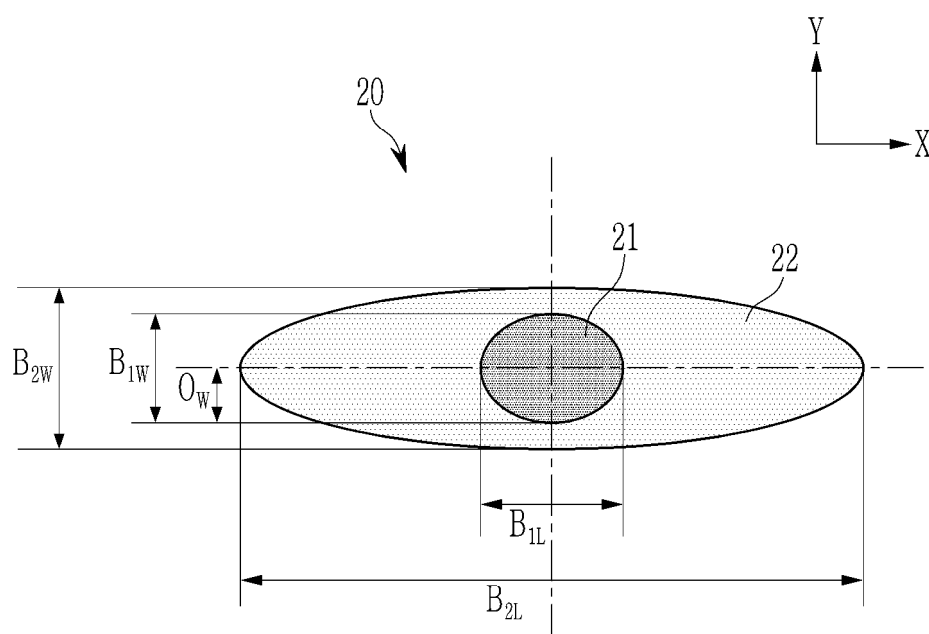
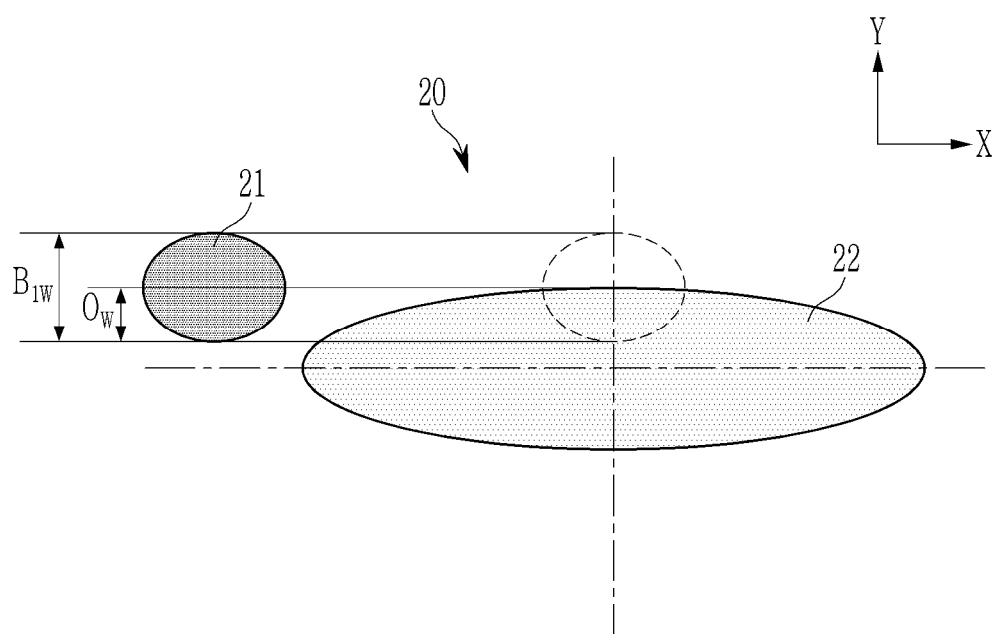


FIG. 5



INTERNATIONAL SEARCH REPORT

International application No.

PCT/KR2023/021089

A. CLASSIFICATION OF SUBJECT MATTER

C21D 8/12(2006.01)i; C21D 10/00(2006.01)i; C22C 38/02(2006.01)i; H01F 1/147(2006.01)i

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)

C21D 8/12(2006.01); B23K 26/00(2006.01); C21D 10/00(2006.01); C21D 6/00(2006.01); C22C 38/00(2006.01); H01F 1/147(2006.01); H01F 1/16(2006.01)

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

Korean utility models and applications for utility models: IPC as above

Japanese utility models and applications for utility models: IPC as above

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

eKOMPASS (KIPO internal) & keywords: 방향성(grain-oriented), 전기강판(magnetic steel plate), 레이저(laser), 그루브(groove), 철손(iron loss), 자구 미세화(domain refinement), 파장(wavelength)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	KR 10-2023-0038271 A (JFE STEEL CORPORATION) 17 March 2023 (2023-03-17) See paragraphs [0012], [0027], [0029] and [0031], claim 1 and table 1.	1-7
A	US 2015-0318091 A1 (NIPPON STEEL & SUMITOMO METAL CORPORATION) 05 November 2015 (2015-11-05) See paragraph [0086] and figure 7.	1-7
A	KR 10-2013-0128731 A (POSCO) 27 November 2013 (2013-11-27) See paragraph [0052] and figure 2.	1-7
A	WO 2016-171130 A1 (NIPPON STEEL & SUMITOMO METAL CORPORATION) 27 October 2016 (2016-10-27) See claim 1 and figure 3.	1-7
A	JP 2012-031516 A (JFE STEEL CORP.) 16 February 2012 (2012-02-16) See paragraphs [0022]-[0023].	1-7

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

* Special categories of cited documents:

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“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

28 May 2024

Date of mailing of the international search report

28 May 2024

Name and mailing address of the ISA/KR

Korean Intellectual Property Office
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Authorized officer

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/KR2023/021089

5	Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
10	KR 10-2023-0038271 A	17 March 2023	CN 115917020 A EP 4206339 A1 EP 4206339 A4 JP 7367779 B2 JP WO2022-045264 A1 US 2023-0307160 A1 WO 2022-045264 A1	04 April 2023 05 July 2023 21 February 2024 24 October 2023 03 March 2022 28 September 2023 03 March 2022
15	US 2015-0318091 A1	05 November 2015	BR 112015009485 A2 BR 112015009485 B1 CN 104755637 A CN 104755637 B EP 2918689 A1 EP 2918689 A4 EP 2918689 B1 IN 3147DEN2015 A JP 6044642 B2 JP WO2014-073599 A1 KR 10-1641032 B1 KR 10-2015-0065860 A PL 2918689 T3 RU 2015116262 A RU 2621092 C2 US 9607744 B2 WO 2014-073599 A1	04 July 2017 14 January 2020 01 July 2015 15 March 2017 16 September 2015 13 July 2016 01 January 2020 02 October 2015 14 December 2016 08 September 2016 19 July 2016 15 June 2015 27 July 2020 27 December 2016 31 May 2017 28 March 2017 15 May 2014
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55				

Form PCT/ISA/210 (patent family annex) (July 2022)