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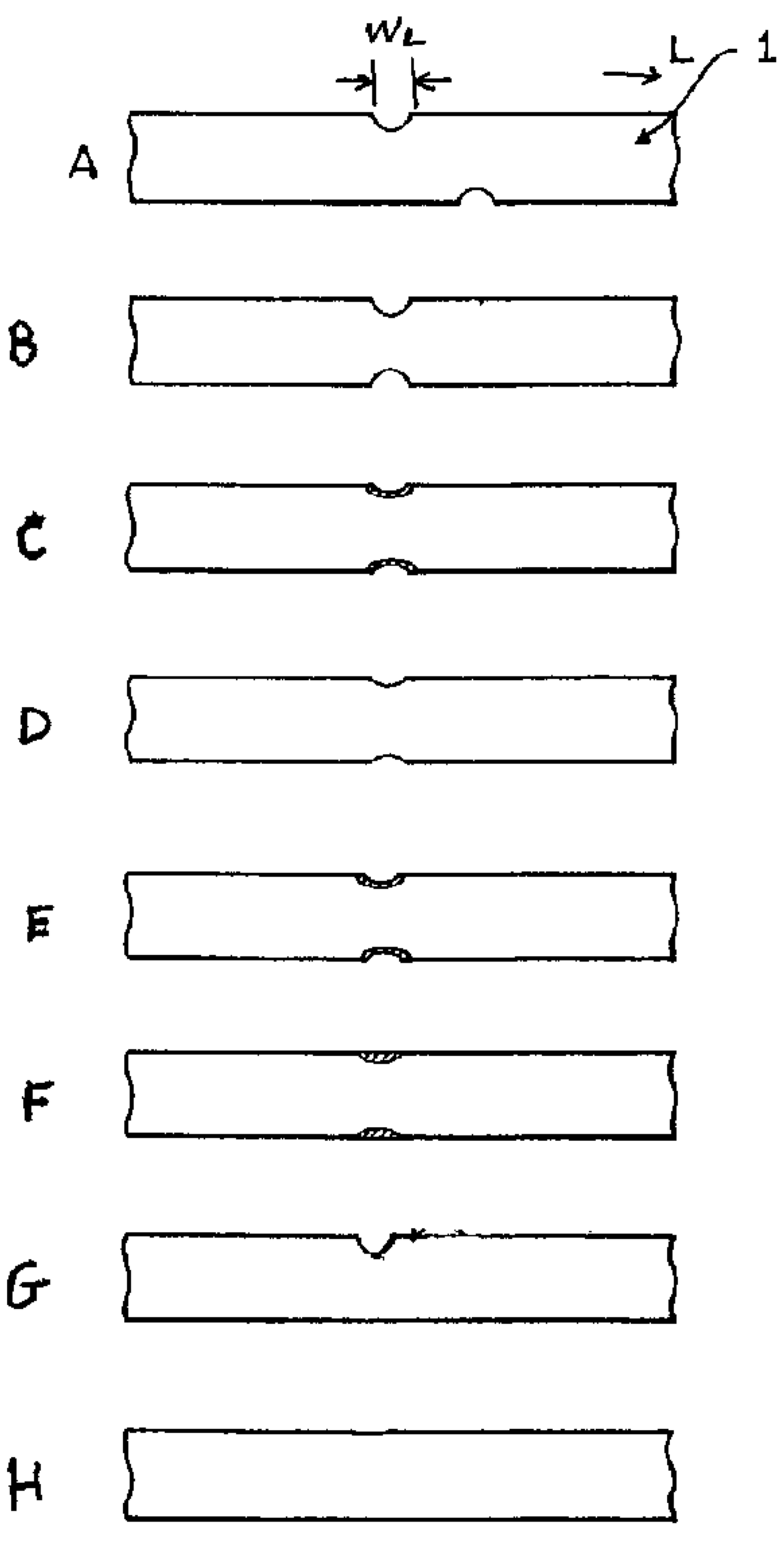
(54) Title: GRAIN-ORIENTED ELECTRICAL STEEL SHEET EXCELLENT IN MAGNETIC PROPERTIES, AND PRODUCTION METHOD THEREOF



(57) Abrégé/Abstract:
Similar linear or dotted line-like grooves and/or heat-affected layers that remain even after stress-relief annealing are formed on both surfaces of a grain-oriented electrical steel sheet at the exact same positions or slight deviate positions by laser irradiation. Deviation of the formation positions on both surfaces is smaller than the width of the grooves and/or the heat-affected layers in a rolling direction, and the groove depth of the grooves on both surfaces is not greater than 5% of the sheet thickness. The steel sheet can be applied to both a wound core and a stacked core, and has excellent magnetic properties capable of reducing the load on production setups.

Grain-Oriented Electrical Steel Sheet Excellent in Magnetic Properties, and Production Method Thereof

ABSTRACT OF THE DISCLOSURE

Similar linear or dotted line-like grooves and/or heat-affected layers that remain even after stress-relief annealing are formed on both surfaces of a grain-oriented electrical steel sheet at the exact same positions or slight deviate positions by laser irradiation. Deviation of the formation positions on both surfaces is smaller than the width of the grooves and/or the heat-affected layers in a rolling direction, and the groove depth of the grooves on both surfaces is not greater than 5% of the sheet thickness. The steel sheet can be applied to both a wound core and a stacked core, and has excellent magnetic properties capable of reducing the load on production setups.

Grain-Oriented Electrical Steel Sheet Excellent in Magnetic Properties, and Production Method Thereof

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a grain-oriented electrical steel sheet that retains a low iron loss and a high magnetic flux density even after stress-relief annealing and can be applied to both of a stacked core and a wound core, and a method of producing the same.

2. Description of the Related Art

One of the methods of producing a grain-oriented electrical steel sheet is described in Japanese Unexamined Patent Publication (Kokai) No. 58-26405. This method irradiates laser energy onto the surface of a steel sheet to form a 180° magnetic domain wall, finely divides the magnetic domains and thus lowers the iron loss. According to this method, the coating film on the surface of the steel sheet is evaporated by laser irradiation, a strain is imparted to the surface layer of the steel sheet by the reaction to evaporation, and a closure magnetic domain is formed in the proximity of the laser irradiated portion. The newly generated closure magnetic domain in this way increases the static magnetic energy but the magnetic domain is finely divided in such a manner as to minimize this increased static magnetic energy with the result that the iron loss can be improved. Due to the improvement of the iron loss by this domain fine dividing effect, the iron loss value can be lowered to a minimum value that is determined by the degree of crystal orientation of the material. Since this prior art method does not involve any physical deformation that would otherwise greatly impede the magnetic flux density, the method is almost free from a drop in the magnetic flux density after the laser irradiation.

For these reasons, the grain-oriented electrical steel sheet produced by this method exhibits an ideal magnetic properties.

Nonetheless, the strain that functions as the source of fine division of the magnetic domain disappears at around 500°C during heat-treatment and, at this time, the iron loss lowering effect also disappears.

In other words, the iron loss lowering effect in the grain-oriented electrical steel sheet produced by the prior art method cannot withstand stress-relief annealing, that is conducted at about 800°C in a production process for a wound iron core, and disappears.

For this reason, the grain-oriented electrical steel sheet produced by this method cannot be used for wound cores, but is used exclusively for stacked cores.

Therefore, methods have been proposed, as magnetic domain refinement technologies capable of withstanding stress-relief annealing which imparts portions having mutually different permeability values to the surface of the steel sheet in the direction of application of the magnetic field. Speaking more concretely, the methods that form linear or dotted line-like regions having mutually different permeability values in a direction substantially perpendicular to the rolling direction on the steel sheet surface, and various products produced by the methods, have been proposed. Among them, the magnetic domain refinement technology that forms the grooves on the surface layer of the steel sheet, and utilizes the difference of permeability between a base metal and air is an excellent technology, and this technology has already been put into industrial application. Incidentally, a method that mechanically pushes a gear type roll into the steel sheet (Japanese Examined Patent Publication (Kokoku) No. 63-44804), a method that employs chemical etching (U.S.P. No. 4,750,949) and a processing method that uses pulsed laser energy (Japanese Unexamined Patent Publication (Kokai)

No. 7-220913) have been proposed as the methods for forming the grooves.

In all of these grain-oriented electrical steel sheets that are produced by the prior art methods and have both a low iron loss and a resistance to disappear by annealing, the grooves are formed on only one of the surfaces of the steel sheets. In this case, the depth of the grooves must be from about 15 to 30 μm when the steel sheet thickness is 0.23 mm, in order to obtain a practically sufficient iron loss lowering effect, though the groove depth varies depending on the means employed for forming the grooves. In other words, a deep groove exceeding 5% of the sheet thickness must be formed. Because the iron loss lowering effect considerably changes with the change of the groove depth, the groove depth must be controlled carefully. Therefore, the conventional products are not yet free from the following problems in the product properties and in the production method.

First, the problems in the product properties will be explained. Because the deep groove that exceeds 15 μm, or 5% of the sheet thickness, is formed physically in the surface layer of the steel sheet, there exists a great hindrance to the magnetic flux density. In other words, the problem remains in that the magnetic flux density occurring in an arbitrary external magnetic flux drops greatly after the formation of the groove when compared with the magnetic flux density before the formation of the groove. Furthermore, because the iron loss lowering effect considerably changes with the change of the groove depth, variance in the iron loss characteristics of the products becomes great unless the groove depth is sufficiently controlled.

Next, the problems in the production method will be explained. In order to improve the iron loss by adding grooves, a groove having a depth of 15 to 30 μm is required, as described above. However, loads on the production method are great in order to form such a deep groove throughout the full width of the steel sheet which is more than 1 m wide, and various problems develop in the aspects of the costs of installation and operation, and the production rate. In the case of the mechanical method that pushes a gear type roll into the steel sheet, the force must be elevated in order to provide the steel sheet with a deep groove and, consequently, the setup becomes greater in scale. As the gear type roll is worn out, the groove depth becomes smaller, and another problem develops in that the gear type roll must be exchanged frequently. The chemical etching method requires a long etching time, and the processing speed is limited. To improve the etching rate, a longer etching tank becomes necessary. In the case of the laser method, too, the laser power must be increased for deep groove processing. In consequence, the setup becomes greater in size, and a plurality of large laser generators are necessary.

If the irradiation laser power is increased in the case of the laser method, the influence of heat is excessively applied to the peripheral portions of the irradiated portion, so that swell deformation occurs throughout the steel sheet. If such steel sheets are stacked to produce the stacked core, the iron loss increases or a space factor is deteriorated. Therefore, the steel sheet in which deep grooves are formed by the laser method involves still another problem in that the steel sheet cannot be used for the stacked core.

The laser method is an excellent technology because it can execute non-contact high speed processing, has s simple process and is excellent in controllability of the groove depth and positional accuracy of the groove formation positions. However, it involves the problem that when a deep groove is to be formed, it imparts an excessive heat influence onto the peripheral portions of the irradiated portion and invites the deformation of the steel sheet that would deteriorate the magnetic properties.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a grain-oriented electrical steel sheet excellent in magnetic properties, which has a domain refinement effect capable of withstanding stress-relief annealing that is to be executed in a production process of a wound core, can be applied to a wound core, can stably reduce the iron loss, is free from deterioration of a magnetic flux density, can restrict deformation, can be applied also to a stacked core and can reduce the load of production setups, and to provide also a method of producing the same.

The inventors have formed various grooves and/or heat-affected layers on a grain-oriented electrical steel sheet by the laser method, and have examined in detail the magnetic properties after the steel sheet is subjected to stress-relief annealing. As a result, the inventors have found that extremely excellent magnetic properties can be obtained in comparison with those of the conventional grain-oriented electrical steel sheet, by forming these grooves and/or the heat-affected layers on both surfaces of the steel sheet.

The present invention has been achieved on the basis of the finding described above, and the gist of the present invention resides in the following points.

In the present invention, linear or dotted line-like grooves and/or heat-affected layers, that remain even after stress-relief annealing, are formed on both surfaces of the steel sheet. Therefore, the iron loss is lowered to minimum. Because this iron loss lowering quantity hardly depends on the groove depth, the grain-oriented electrical steel sheet has a small variance in magnetic properties. Because the groove depth necessary for lowering the iron loss is minimized and because the groove depth need not be strictly controlled in the present invention, the grain-oriented electrical steel sheet does not add large loads to the production setups. In the present invention, the groove depth on both surfaces of the steel sheet is limited to 5% or less of the steel sheet. Therefore, the grain-oriented electrical steel sheet of the present invention is almost free from the drop of the magnetic flux density. In the present invention, the formation positions of the grooves and the heat-affected layers on both surfaces of the steel sheet form pairs, and their positional deviation is not greater than the width of the grooves and/or the heat-affected layers in the rolling direction. Therefore, the steel sheet can provide a large lowering effect of the iron loss and at the same time, is free from the swell deformation that is the problem in the steel sheet for the stacked core. In consequence, the steel sheet can be applied to both the stacked core and the wound core. Furthermore, because the present invention uses beams having high energy, particularly a continuous wave or a pulse laser, the present invention provides a production method for a grain-oriented electrical steel sheet capable of forming the grooves and/or the heat-affected layers on both surfaces of the steel sheet with high positional accuracy.

Incidentally, the heat-affected layer defined in the present invention as the dislocations and/or melted/re-solidified layers that are formed by the irradiation of the high energy beams such as laser, electron beams, and so forth, or the layer that has a permeability different from that of the steel sheet base metal and has a layer volume to such an extent as to be capable of providing a magnetic domain refinement effect to the steel sheet. This heat-affected layer can be easily confirmed by observing a section of the steel sheet through a microscope.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1(a) is a sectional view showing various sectional shapes of the grain-oriented electrical steel sheets, wherein steels A to F show the sectional shapes of the grain-oriented electrical steel sheets according to the present invention that have grooves and/or heat-affected layers on both surfaces thereof; a steel G shows the sectional shape of a grain-oriented electrical steel sheet which has a resistance to disappear by annealing according to the prior art and in which a groove is formed on one of the surfaces; and a steel H shows the sectional shape of a grain-oriented electrical steel sheet devoid of a resistance to disappear by annealing, in a which magnetic domain is finely divided by only the reaction of evaporation of a steel sheet film due to laser irradiation;

Fig. 1(b) is an enlarged view showing in magnification the grooves and the heat-affected layers in various sectional shapes shown in Fig. 1(a);

Fig. 2(a) is an explanatory view useful for explaining deviation of the groove formation positions on both surfaces of the grain-oriented electrical steel sheet according to the present invention;

Figs. 2(b) and 2(c) are explanatory views showing the results of measurement of the surface coarseness after stress-relief annealing is applied to the grain-oriented electrical steel sheet having the grooves and/or the heat-affected layers according to the present invention; and

Fig. 3(a) is an explanatory view showing the grain-oriented electrical steel sheet and useful for explaining its production method according to the present invention; and

Fig. 3(b) is an enlarged view showing a part (a portion of a white circle O in Fig. 3(a)) of a dotted line-like groove shown in Fig. 3(a).

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Initially, a production method of the grain-oriented electrical steel sheet according to the present invention will be explained.

The production method of the grain-oriented electrical steel sheet according to the present invention forms grooves, or grooves and heat-affected layers, or only the heat-affected layers, on both surfaces of the grain-oriented electrical steel sheet. These grooves and/or the heat-affected layers may be formed appropriately by high energy processing technologies using laser energy, electron beams, ion beams, plasma, and so forth. Among them, the technology that uses a laser (laser process) is most preferred as the production method of the grain-oriented electrical steel sheet according to the present invention from the aspects of beam irradiation positional accuracy, controllability of the formation of the groove/heat-affected layers and usability in atmospheric air, in comparison with methods using other energy beams.

Though the laser process is most appropriate, the grain-oriented electrical steel sheet according to the present invention includes within its scope those grain-oriented electrical steel sheets in which only the grooves devoid of the heat-affected layers are formed on both surfaces of the steel sheets. For this reason, an etching process not relying on heat or a gear type roll machining process may also be employed as the production method of the present invention. Incidentally, the object of the invention can be provided if only the grooves and/or heat-affected layers for a resistant to heat applied by annealing are formed on the surface layers of the final product. Therefore, the grooves and/or the heat-affected layers may be formed at any process steps of an ordinary production process of the grain-oriented electrical steel sheets.

Hereinafter, the grain-oriented electrical steel sheet according to the present invention will be explained where a laser is used as the energy beam source, by way of example.

If the power density of a laser is extremely high and its irradiation time is short when the laser energy is irradiated to the steel sheet, the steel sheet base metal at its irradiated portion is melted instantaneously, and almost all the irradiated portion evaporates, thereby forming a groove. At this time, heat-affected layers are slightly formed on the side surface and the bottom of the groove so formed. However, because the volume of this heat-affected layer is extremely small, the heat-affected layer does not exhibit by itself the magnetic domain refinement effect, though its permeability is different from that of the base metal. Therefore, this heat-affected layer is not included in the heat-affected layer that is defined in the present invention. Additionally, the groove formed thereby is essentially the same as the groove that is formed without relying heat at all such as by a etching process.

Next, if the irradiation time is prolonged or if the power density is lowered when the laser energy is irradiated to the steel sheet, the metal of the irradiated portion is not evaporated. In consequence, the amount of the components that are re-solidified from the melt state increases, the groove is formed and, at the same time, a heat-affected layer that has a thickness substantially equal to the groove depth and comprises a dislocations and/or melted/re-solidified layer is formed. Since the permeability of this heat-affected layer is different from the permeability of the base metal, it changes the magnetic field in the same way as the groove. In other words, this heat-affected layer has the domain refinement effect. Therefore, this heat-affected layer is included in the heat-affected layers defined in the present invention.

If the power density of the laser is further lowered when the laser energy is irradiated to the steel sheet, the metal of the irradiated portion does not reach the melting point, and the dislocations and/or melted/re-solidified layers devoid of a groove formation are formed. Even in such a case, the laser irradiated portion has a certain repeated heating-cooling cycle, and its permeability is therefore different from that of the base metal. As a result, this layer exhibits the domain refinement effect. For this reason, this layer is included in the heat-affected layers defined in the present invention.

As explained above, the present invention can provide a grain-oriented electrical steel sheet that has both a high magnetic flux density and a low iron loss, has extremely stable properties and can be applied to both of the stacked core and the wound core. In the present invention, the depth of the groove to be formed is small, and the groove depth need not be strictly controlled. Therefore, the load on production setups can be mitigated. When the high energy beam, particularly the laser beam, is used for the production method of the present invention, the optimum grooves and/or the heat-affected layers can be formed easily and with high accuracy.

Hereinafter, the present invention will be explained further in detail with reference to examples thereof. However, these examples are merely illustrative but in no way restrictive.

Example 1:

Fig. 3(a) is an explanatory view useful for explaining the grain-oriented electrical steel sheet 1 and the production method thereof according to the present invention. Pulse laser beams 4 outputted from a laser apparatus, not shown, and focused by a lens 5 form dotted line-like grooves and/or heat-affected layers with gaps PL = 6.5 mm in an L direction. Fig. 1(a) shows various sectional shapes of the grain-oriented electrical steel sheets having such grooves 2 and/or heat-affected layers 3 formed in this way, and Fig. 1(b) shows in enlargement the grooves 2 and/or the heat-affected layers 3 formed in this way. In the steel sheets A to G shown in Fig. 1(a), the diameter of the focused laser beam was 0.1 mm in the L direction and 0.3 mm in the C direction, these directions being shown in Fig. 3. The width of the dotted line-like grooves formed by such a beam was WL = 0.13 mm in the L direction and WC = 0.31 mm in the C direction, respectively. As shown in Fig. 3, the dotted line-like gap PC in the C direction was 0.30 mm. As shown in Fig. 3(b), therefore, the dotted line-like grooves in the C direction are adjacent to one another. Here, the depth of the groove is defined by the maximum value d of the depth as shown in Fig 1 (b). Deviation of the groove formation positions on both surfaces is defined by a value g shown in Fig. 2(a).

Table 1 shows the evaluation result of the magnetic properties of each steel sheet. Here, the iron loss value was an iron loss value W17/50 at 50 Hz and the maximum magnetic flux density 1.7T, and the magnetic flux density was a value B8 at a magnetizing force 0.8 A/m. The steel sheet was a 0.23 mm-thick grain-oriented electrical steel sheet having an insulating film on the surface thereof. For comparison, the magnetic properties of the steel sheet the iron loss of which was reduced by laser strain, and which was for exclusive use for a stacked core, were also shown in the table. The laser irradiation condition, and the conditions for the grooves, the heat-affected layers, etc, of each steel sheet were listed below. Incidentally, the existence of the grooves and the heat-affected layer was confirmed by inspecting the section of the steel sheet through a microscope.

Table 1

Steel sheet	Groove depth of one surface	Processed surface	Surface condition	Before laser irradiation		After laser irradiation		Iron loss change quantity	Flux density change quantity
				Iron loss W17/50 (W/kg)	Flux density B8 (T)	Iron loss W17/50 (W/kg)*	Flux density B8 (T)*	ΔW17/50 (W/kg)*	ΔB8 (Gauss)*
A	30 μm	both surfaces (g = 1.5 mm)	only groove	0.799	1.927	0.752	1.889	-0.047	-380
B	30 μm	both surfaces (g = 0.1 mm)	only groove	0.799	1.926	0.754	1.868	-0.045	-580
C	10 μm	both surfaces (g = 0.1 mm)	groove + heat-affected layer	0.799	1.925	0.748	1.922	-0.051	-30
D	5 μm	both surfaces (g = 0.1 mm)	only groove	0.800	1.925	0.752	1.924	-0.048	-10
E	5 μm	both surfaces (g = 0.1 mm)	groove + heat-affected layer	0.800	1.925	0.751	1.924	-0.049	-10
F	no groove	both surfaces (g = 0.1 mm)	only heat-affected layer	0.800	1.926	0.753	1.925	-0.047	-10
G (prior art)	30 μm	one surface	only groove	0.799	1.927	0.754	1.870	-0.045	-570
H (prior art)	no groove	one surface	only surface layer strain	0.799	1.925	0.750	1.924	-0.049	-10

* Values of steel sheets A to G represent the values after stress-relief annealing.

Steel sheet A:

Grooves having a depth of 30 μm were formed on both surfaces of the steel sheet by Q switch pulse CO_2 laser. The peak power density of the Q switch pulse CO_2 laser was about 10 to about 30 MW/mm^2, and the pulse time total width was 20 μs. The laser irradiated portion was evaporated almost fully by the high peak pulse processing. The heat-affected layer defined by the present invention did not exist at the irradiated portion, and only the grooves existed. The deviation g of the groove formation positions on both surfaces of the steel sheet was about 1.5 mm, and was greater than the width WL of the grooves in the L direction.

Steel sheet B:

Grooves having a depth of 30 μm were formed on both surfaces of the steel sheet by Q switch pulse CO_2 laser. Here, the peak power density of the Q switch pulse CO_2 laser was about 10 to about 30 MW/mm^2, and the pulse time total width was 20 μs. The laser irradiated portion was evaporated almost fully. The heat-affected layer defined by the present invention did not exist at the irradiated portion, and only the grooves existed. The deviation g of the groove formation positions on both surfaces of the steel sheet was about 0.1 mm, and was smaller than the width WL of the grooves in the L direction.

Steel sheet C:

Grooves having a depth of 10 μm were formed on both surfaces of the steel sheet by pulse modulated CO_2 laser. The peak power density of the pulse laser was 0.4 to 0.8 MW/mm^2, and the pulse time total width was 20 μs. Because of the decrease of the pulse peak power, the grooves and the heat-affected layers that were defined by the present invention existed in mixture at the irradiated portion. The deviation g of the groove formation positions on both surfaces of the steel sheet was 0.1 mm, and was smaller than the width WL of the grooves in the L direction.

Steel sheet D:

Grooves having a depth of 5 μm were formed on both surfaces of the steel sheet by Q switch pulse CO_2 laser. Here, the peak power density of the Q switch pulse CO_2 laser was about 10 to about 30 MW/mm^2, and the pulse time total width was 12 μs. Because of high peak pulse processing, the laser irradiated portion was evaporated almost fully. The heat-affected layer defined by the present invention did not exist at the irradiated portion, and only the grooves existed. The deviation g of the groove formation positions on both surfaces of the steel sheet was about 0.1 mm, and was smaller than the width WL of the grooves in the L direction.

Steel sheet E:

Grooves having a depth of 5 μm were formed on both surfaces of the steel sheet by pulse modulated CO_2 laser. Here, the peak power density of the pulse laser was 0.4 to 0.8 MW/mm^2 and the pulse time total width was 12 μs. Because of the decrease of the pulse peak power, the grooves and the heat-affected layer that was defined by the present invention existed in mixture at the irradiated portion. The deviation g of the groove formation positions on both surfaces of the steel sheets was 0.1 mm, and was smaller than the width WL of the grooves in the L direction.

Steel sheet F:

Only the heat-affected layers were formed on both surfaces of the steel sheet by pulse modulated CO_2 laser. Here, the peak power density of the pulse laser was 0.2 MW/mm^2, and the pulse time total width was 7 μs. Because of the further decrease of the pulse peak power, only the heat-affected layers defined by the present invention existed on the surface. The deviation g of the formation positions of the heat-affected layers on both surfaces of the steel sheet was 0.1 mm, and was smaller than the width WL of the heat-affected layers in the L direction.

Steel sheet G:

The steel sheet G was a conventional steel sheet, in which grooves having a depth of 30 μm were formed on only one of the surfaces of the steel sheet by Q switch pulse CO_2 laser. Here, the peak power density of the Q switch pulse CO_2 laser was about 10 to about 30 MW/mm^2, and the pulse time total width was 20 μs. The laser irradiated portion was evaporated almost fully due to the high peak pulse processing. The heat-affected layers that were defined by the present invention did not exist at the irradiated portion, and only the grooves existed.

Steel sheet H:

Only the film was evaporated from one of the surfaces of the steel sheet by Q switch pulse CO_2 laser. This was the steel sheet the iron loss of which was lowered by the laser strain. The peak power was 0.1 MW/mm^2, and the pulse time width was 4 μs. In only this steel sheet, the gap PC of the dotted line in the C direction was 0.5 mm, and the focused and irradiated beam was a circular beam having a diameter of 0.40 mm. Incidentally, stress-relief annealing was not applied to this steel sheet.

The result of the comparison of the magnetic properties of the steel sheets A to G revealed that the grain-oriented electrical steel sheets according to the present invention having the grooves and/or the heat-affected layers on both surfaces of the steel sheet exhibited the drop of the iron loss which was equal to, or greater than, that of the conventional grain-oriented electrical steel sheet having similar grooves on only one of the surfaces thereof. In other words, even when the comparison was made in terms of the total of the groove depths of both surfaces, the grain-oriented electrical steel sheets according to the present invention could provide the iron loss reducing effect, that was equivalent to, or higher than, the effect of the prior art, by the grooves shallower than the grooves of the steel sheet of the prior art having the grooves on only one of the surfaces thereof. It was found that in an extreme case, the formation of the grooves were almost unnecessary.

Therefore, it was obvious that the grain-oriented electrical steel sheet having the grooves and/or the heat-affected layers on both surfaces thereof according to the present invention was not a mere modification of the conventional grain-oriented electrical steel sheet having the grooves formed on one of the surfaces thereof so as to improve the iron loss, or the conventional grain-oriented electrical steel sheet not having the resistance to disappear by annealing, though the strain was imparted by the laser to the surfaces so as to reduce the iron loss.

The iron loss of the steel sheet H (prior art product), which was lowered by imparting the strain by the reaction of evaporation of the film due to the laser irradiation, was reduced to a value approximate to the limit that was determined by the degree of crystal orientation. In contrast, the grain-oriented electrical steel sheet having the grooves and/or the heat-affected layers on both surfaces thereof could provide an iron loss value equivalent to that of the former. When the iron loss drop quantities of the steels A to F were compared, it was found that the iron loss quantity remained substantially constant irrespective of the groove depth from the state where the groove hardly existed to the state where the groove depth was 30 μm.

When the change quantities of the magnetic flux density B8 were compared, it was found that in the steel sheets C to E, in which the grooves having a depth of not greater than 10 μm corresponding to 5% or less of the sheet thickness, were formed in accordance with the present invention, the B8 change quantity was not greater than 30 Gauss and the magnetic flux density B8 hardly changed. This was because the grooves that impeded the magnetic flux density were extremely shallow.

Therefore, the iron loss value could be stably lowered by the present invention irrespective of the depth of the grooves formed in the surface layer of the steel sheet. In other words, the grain-oriented electrical steel sheets almost devoid of the drop of the magnetic flux density could be obtained by forming the grooves to a depth of not greater than 5%.

Next, an explanation will be given of the effect brought forth when the grooves and/or the heat-affected layers are formed on both surfaces of the steel sheet at positions that form pairs. As described above, Fig. 2(a) is an explanatory view of the deviation g of the formation positions of the grooves formed on both surfaces of the steel sheet by the laser process and the width W_L of these grooves in the rolling direction. Figs. 2(b) and 2(c) show the measurement result of the surface coarseness of the steel sheets after stress-relief annealing, that is, the swell deformation quantity h. Symbol X in these drawings represents the groove positions. It can be seen from the drawings that the swell deformation quantity h hardly exists when the position deviation g is below the groove width W_L ($h = 5\ \mu m$ when $W_L (= 0.13\ mm) < g\ (= 0.30\ mm)$ in Fig. 2(b), whereas $h = 0\ \mu m$ when $W_L (= 0.13\ mm) > g\ (= 0.10\ mm)$ in Fig. 2(c)). This is because the deformation resulting from condensation of the base metal in the melt/resolidification process is balanced on both surfaces and, eventually, further deformation is restricted. When a stacked core is produced by stacking such steel sheets, deterioration of the iron loss properties and the magnetic flux density resulting from the deformation strain does not occur in the same way as when the steel sheet without grooves is stacked.

In the present invention, the deformation on the surface is corrected by the groove formation on both surfaces of the steel sheet. Therefore, there is the possibility that a local strain is imparted into the steel sheet. It is believed that this local stress-strain also exhibits the domain refinement effect.

Though this embodiment explains the case where the dotted line grooves are formed by a pulse laser, the same effect can be naturally obtained by a continuous groove, too.

CLAIMS

1. A grain-oriented electrical sheet comprising grooves, and grooves and heat-affected layers formed on both surfaces of a steel sheet, at a position such that a positional deviation of said grooves, and grooves and heat-affected layers when formed on both sides of the steel sheet is smaller than a width of said grooves, and grooves and heat-affected layers in a rolling direction, wherein a depth of said grooves formed on both surfaces of said steel sheet is less than 5% of a thickness of the steel sheet, wherein said grooves and grooves and heat-affected layers are formed using a high density energy beam.

2. The grain-oriented electrical sheet of claim 1, wherein said high density energy beam technique uses an energy source selected from the group consisting of a laser, electron beams, ion beams and plasma.

3. The grain-oriented electrical sheet according to any one of claims 1 and 2 applied to a stacked core and a wound core.

4. A method of producing a grain-oriented electrical sheet comprising the step of forming similar linear and dotted line-like grooves and heat-affected layers on both surfaces of a steel sheet at a position such that a deviation of formation positions of the grooves and the heat-affected layers is smaller that a width of the grooves and the heat-affected layers in a rolling direction, whereby the similar linear and dotted line-like grooves and heat-affected layers with a groove depth no greater than 5% of a thickness of the steel sheet are formed on both surfaces of the steel sheet, wherein said step of forming similar linear and dotted line-like grooves and heat-affected layers comprises using a high density energy beam.

5. The method according to claim 4, wherein said step of forming similar linear and dotted line-like grooves and heat-affected layers technique using a high density energy beam comprises using a source selected from the group consisting of a laser, electron beams, ion beams and plasma.

Fig. 1(a)

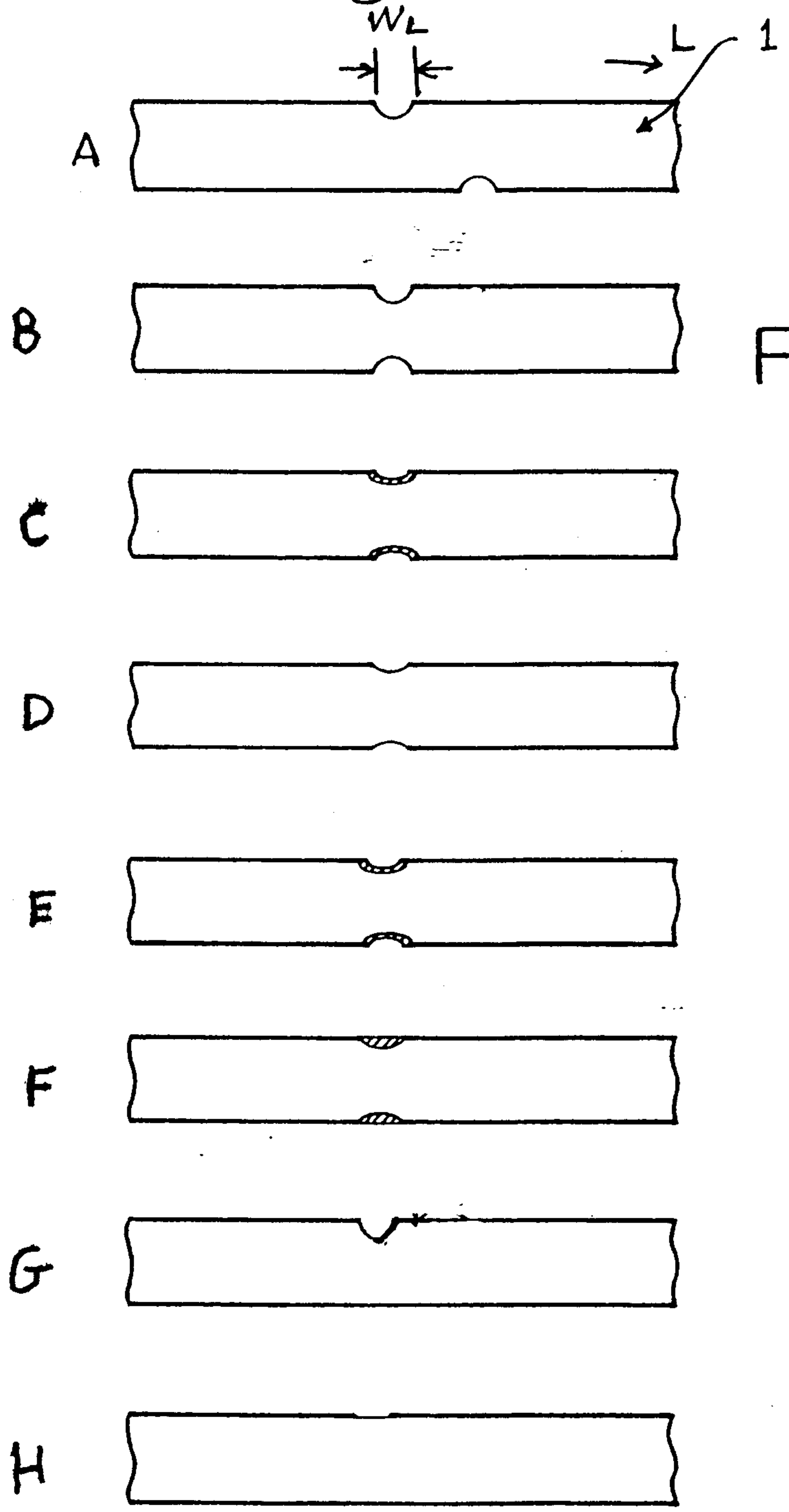


Fig. 1(b)

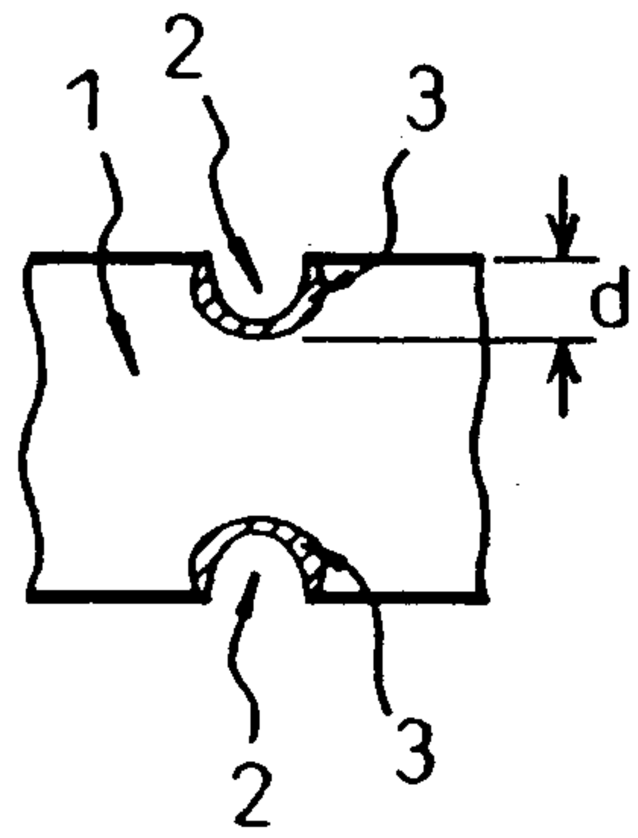


Fig.2(a)

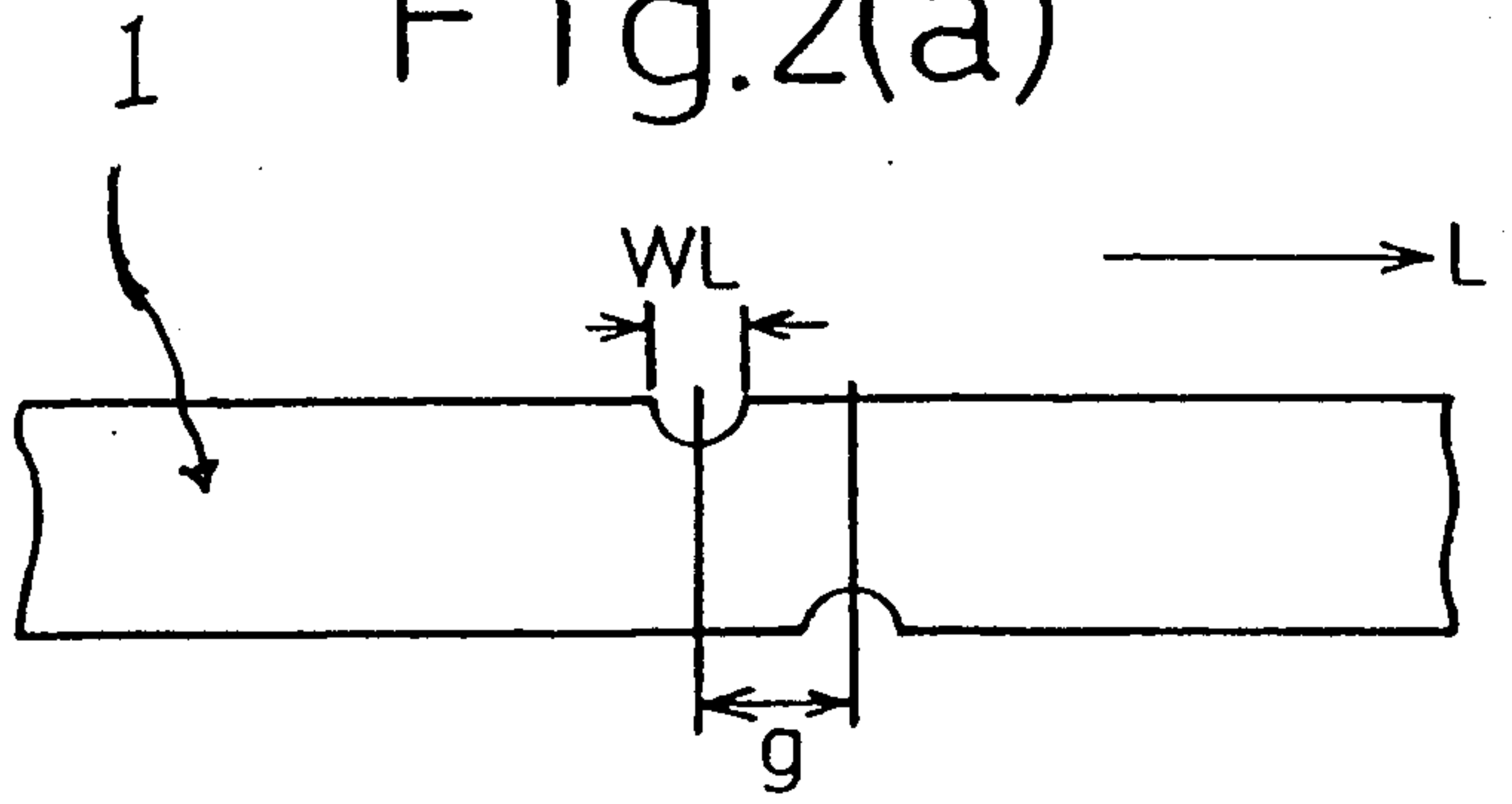


Fig.2(b)

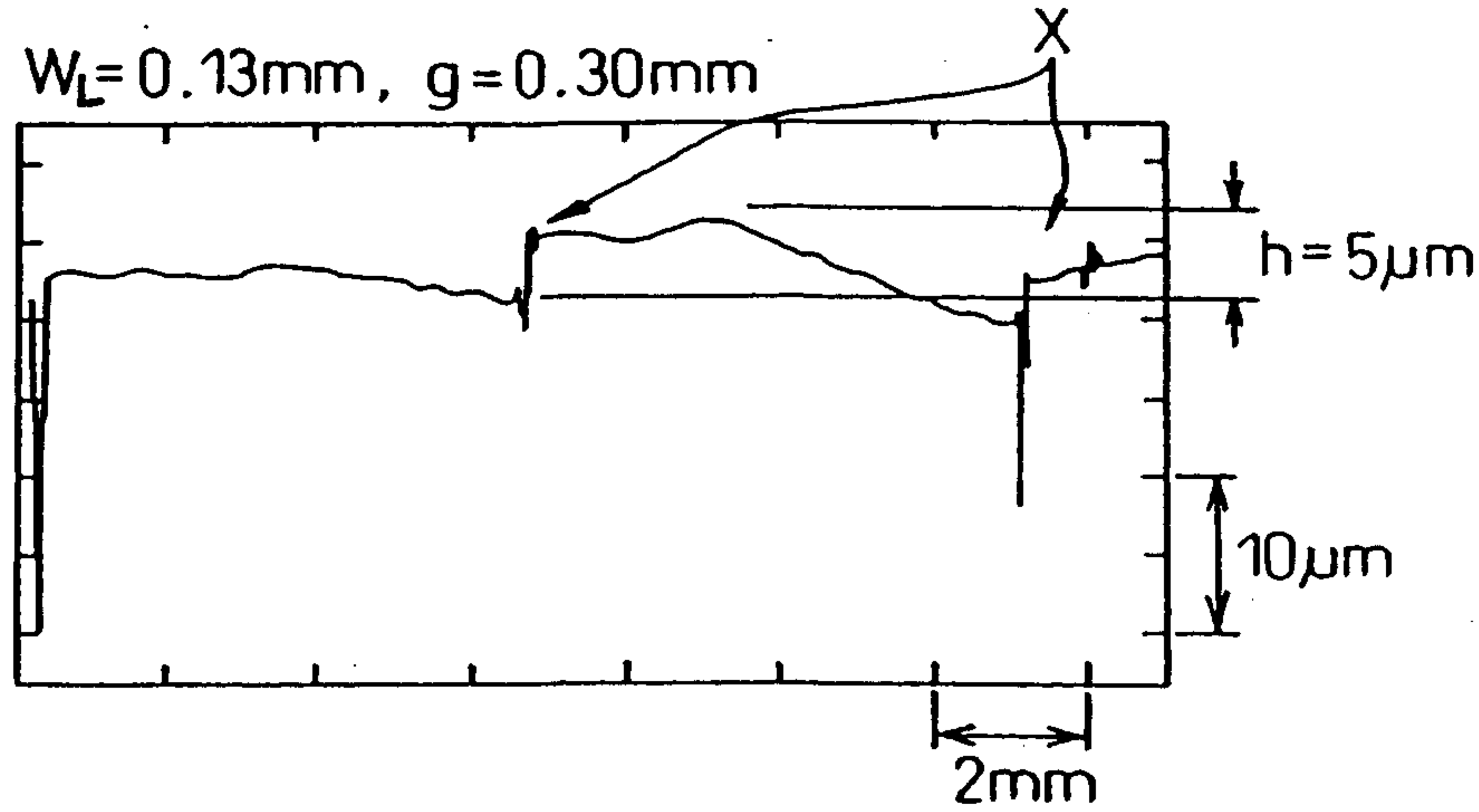


Fig.2(c)

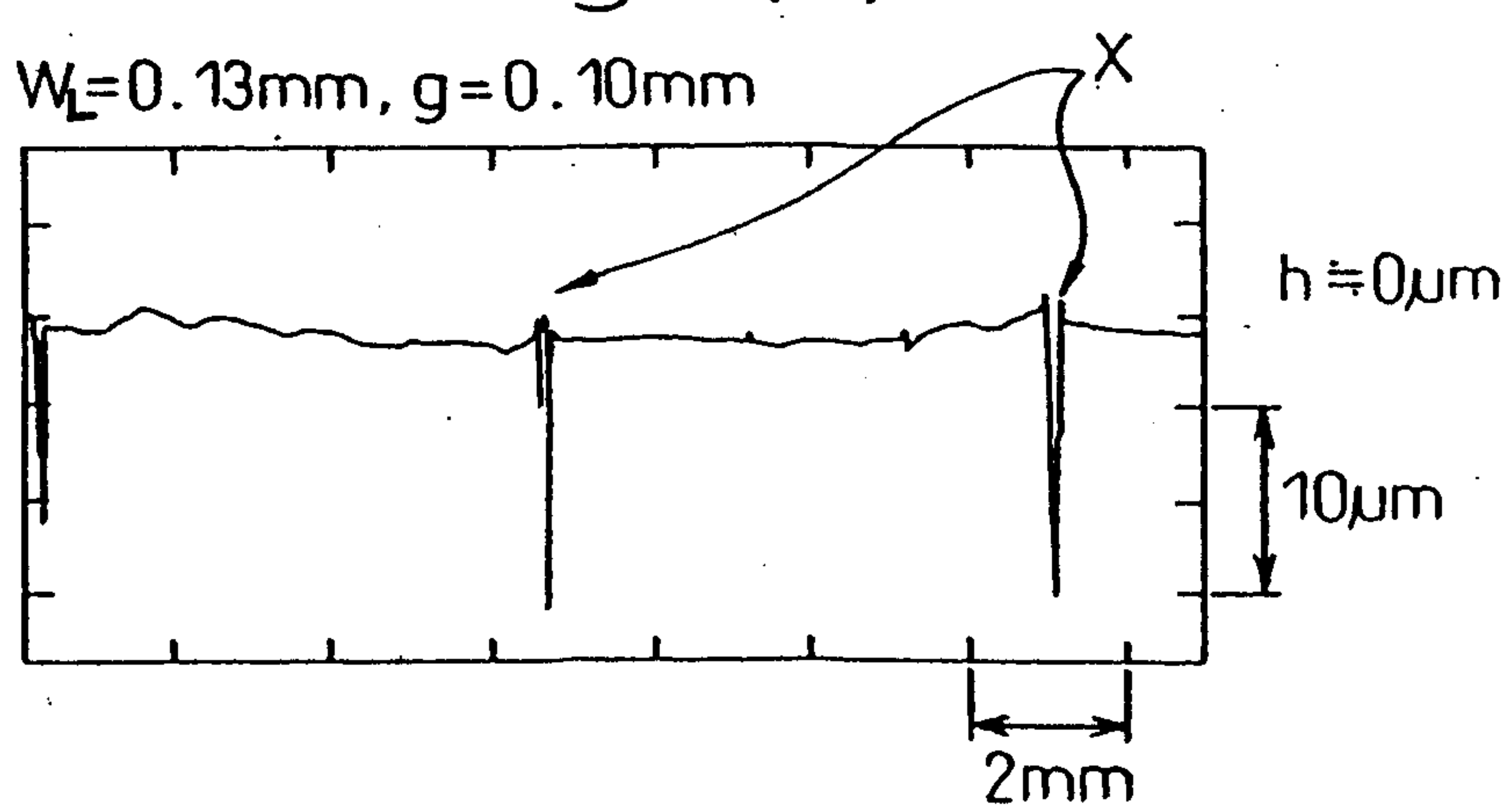


Fig.3(a)

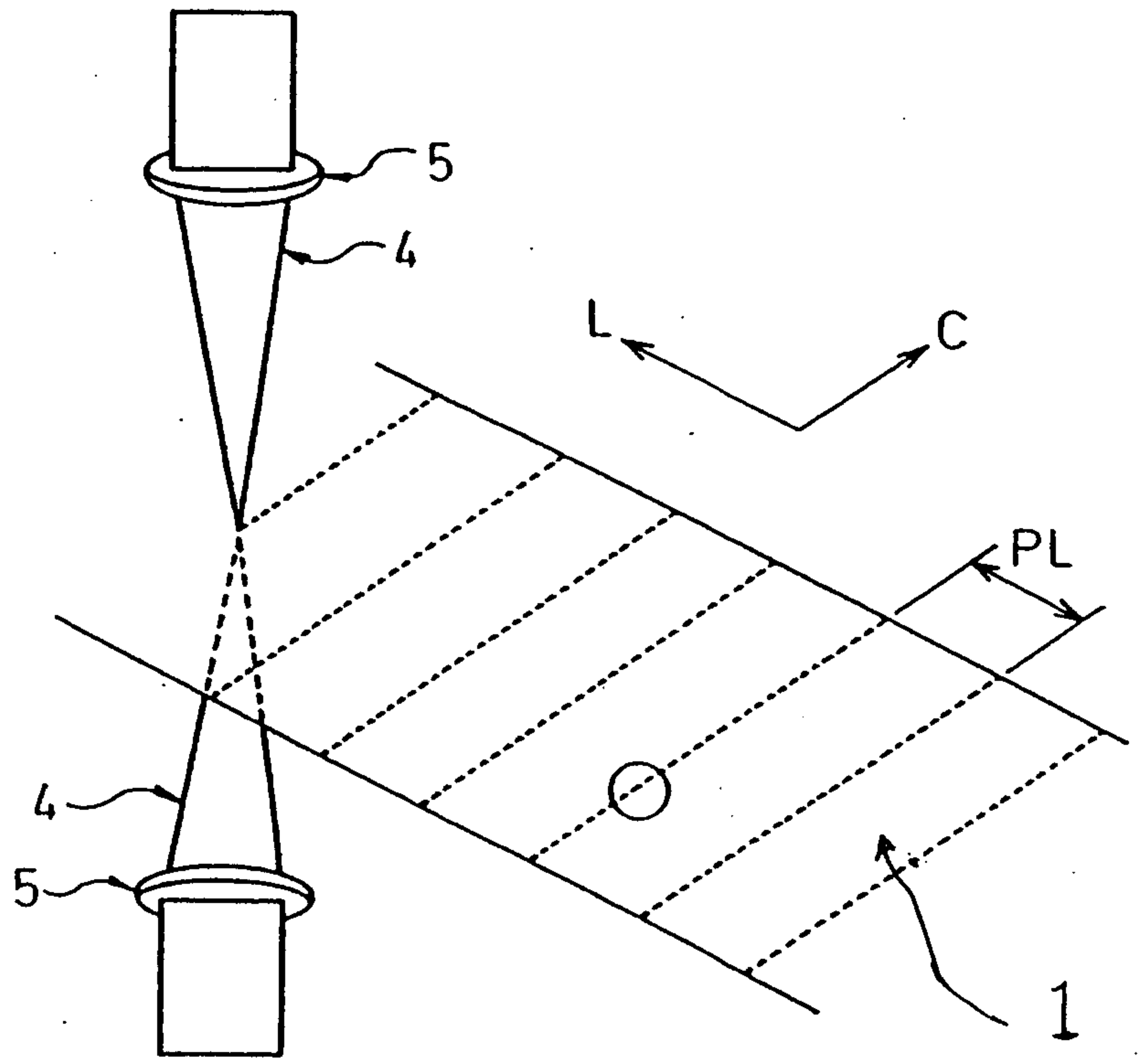
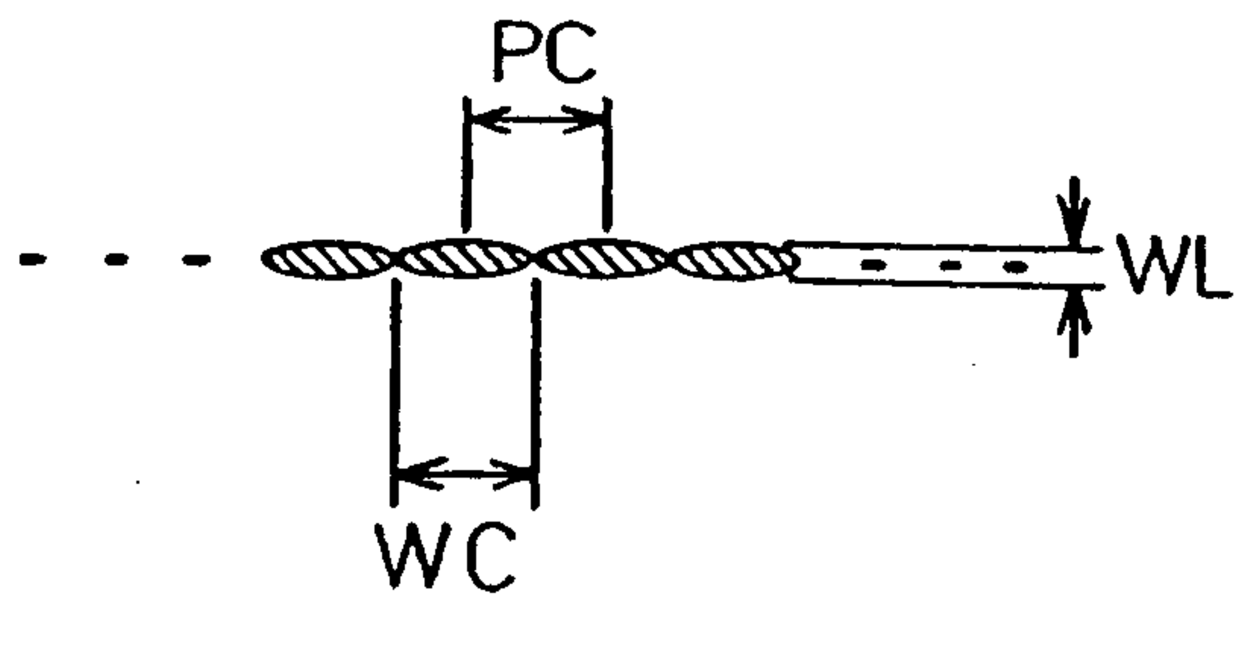
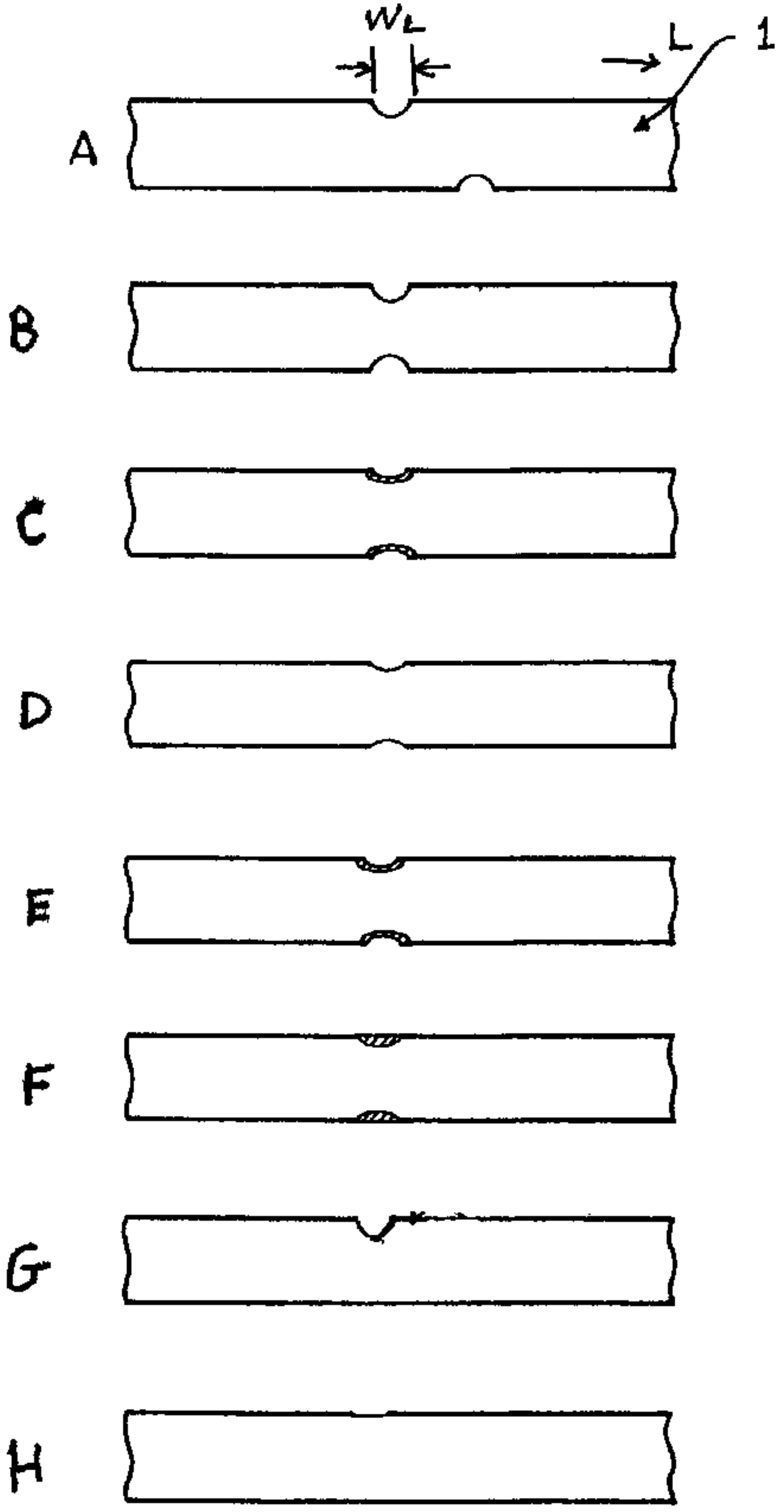


Fig.3(b)





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