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(54) METALLIC MATERIAL AS A SOLID SOLUTION HAVING A BODY-CENTERED CUBIC (BCC) STRUCTURE, AN ORIENTATION OF CRYSTAL AXIS <001> OF WHICH IS CONTROLLED, AND METHOD OF MANUFACTURING THE SAME

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C21D 8/00 (2006.01)

(52) **U.S. Cl.** **148/559**; 148/400

(57) **ABSTRACT**

An orientation of crystal axis <001> of the metallic material as a solid solution having a structure of body-centered cubic (BCC) is arranged along a work surface of the metallic material by hot rolling process in a temperature range of structuring the metallic material to be BCC single phase solid solution. For example, Fe-Si alloy as the metallic material is heated in the temperature range for BCC single phase solid solution, and processed so as to arrange the orientation of crystal axis <001> along the work surface by pressing the BCC single phase solid solution in a strain rate to maintain work condition for controlling motion of dislocation by atmosphere of solute atom generated in BCC single solid solution and migrating grain boundary by strain energy stored in a crystal grain as driving force.

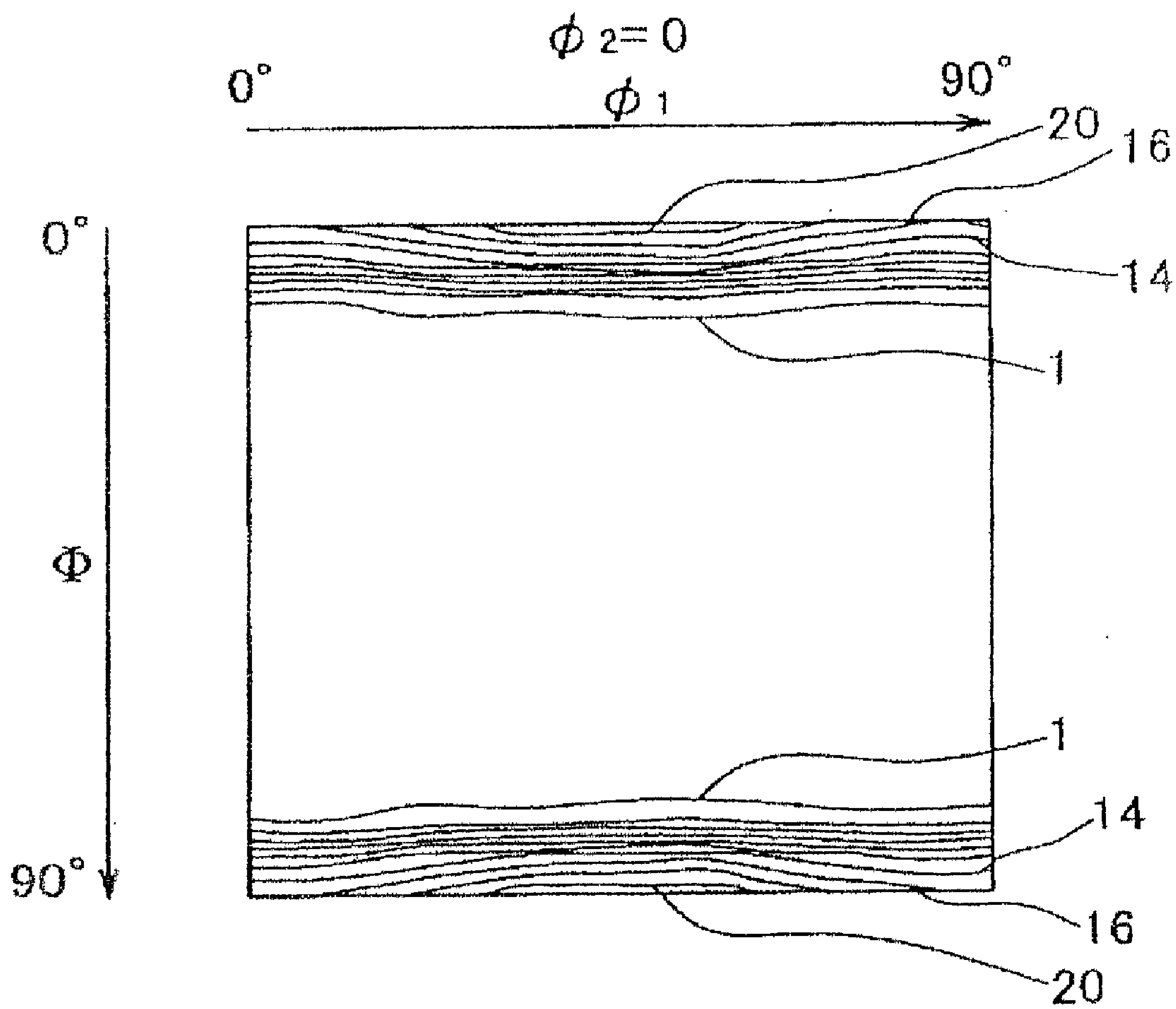


FIG. 1

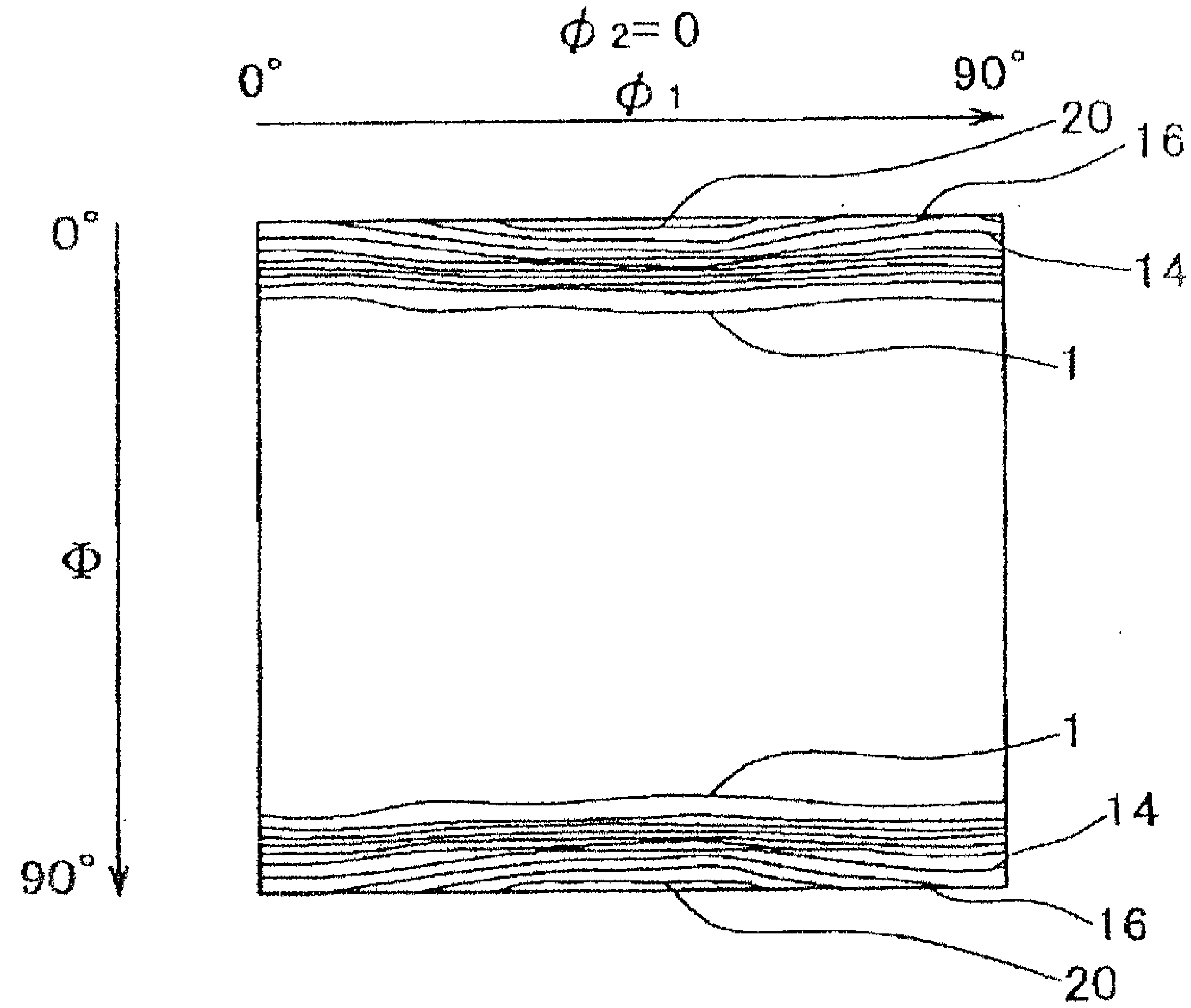

φ 2=0
0°
φ 1
90°
20
16
14
1
0°
Φ
90°
1
14
16
20

FIG. 2

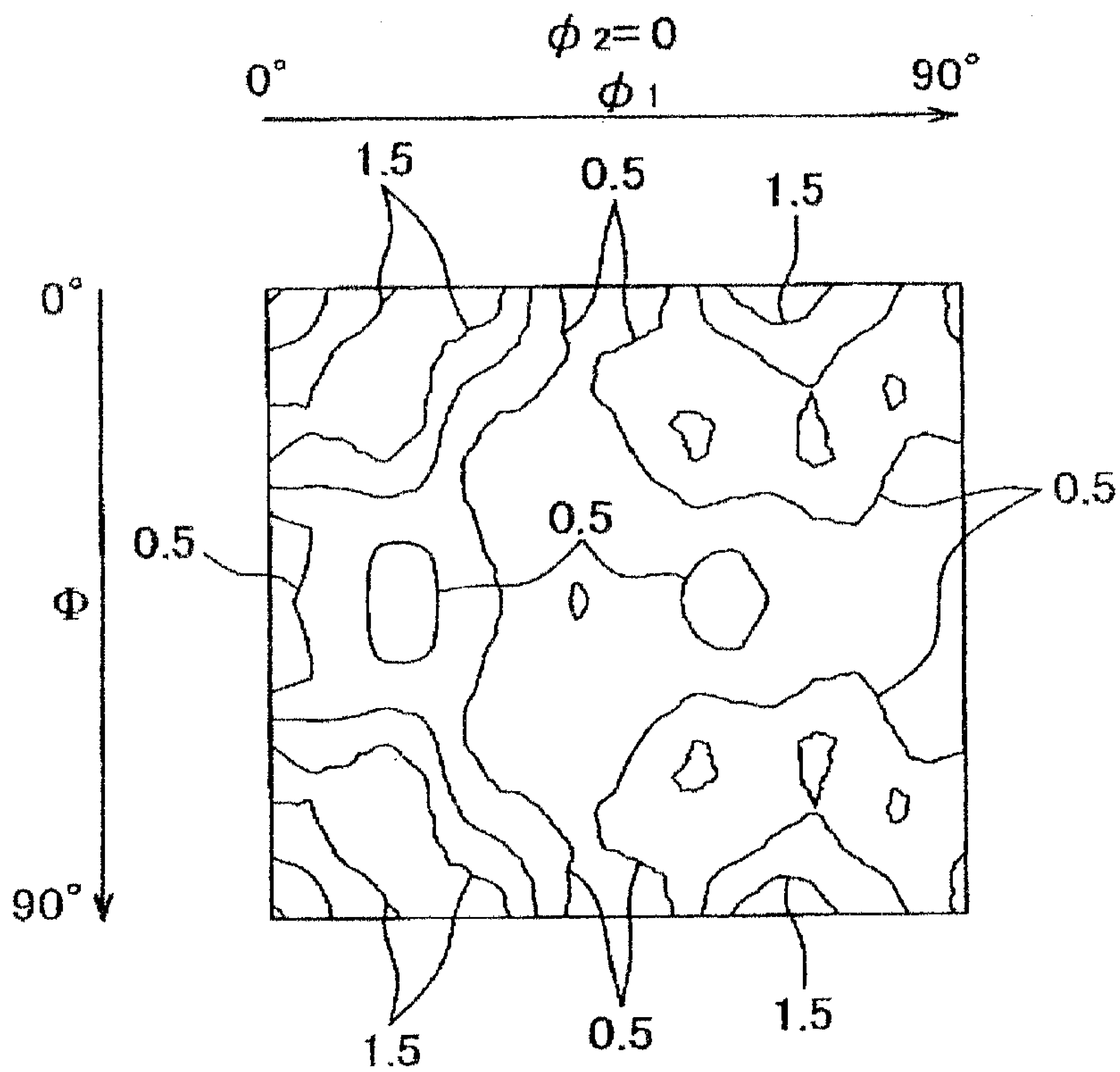

φ 2=0
0°
φ 1
90°
1.5
0.5
1.5
0°
0.5
0.5
0.5
Φ
90°
1.5
0.5
1.5

FIG. 3

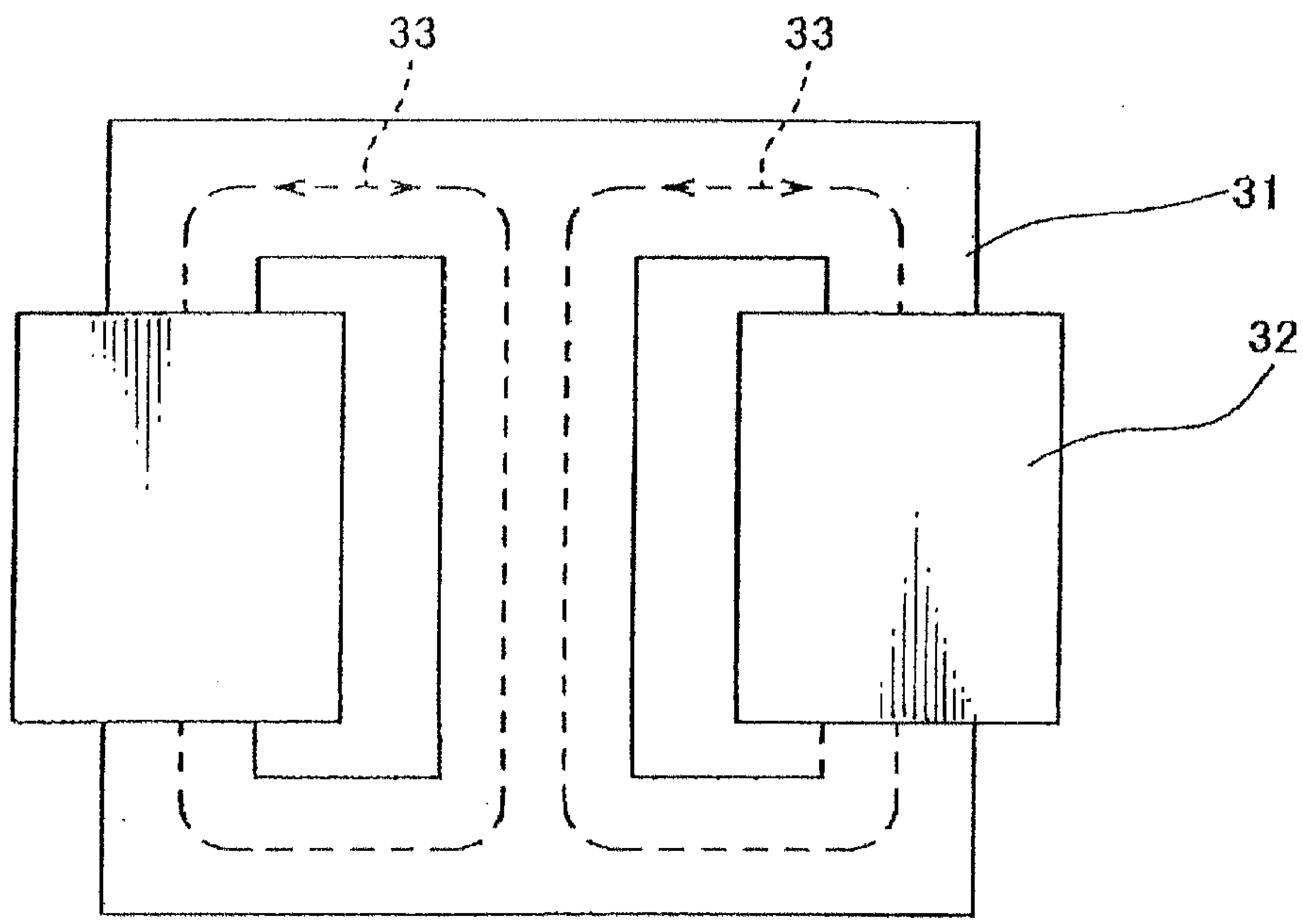


FIG. 4

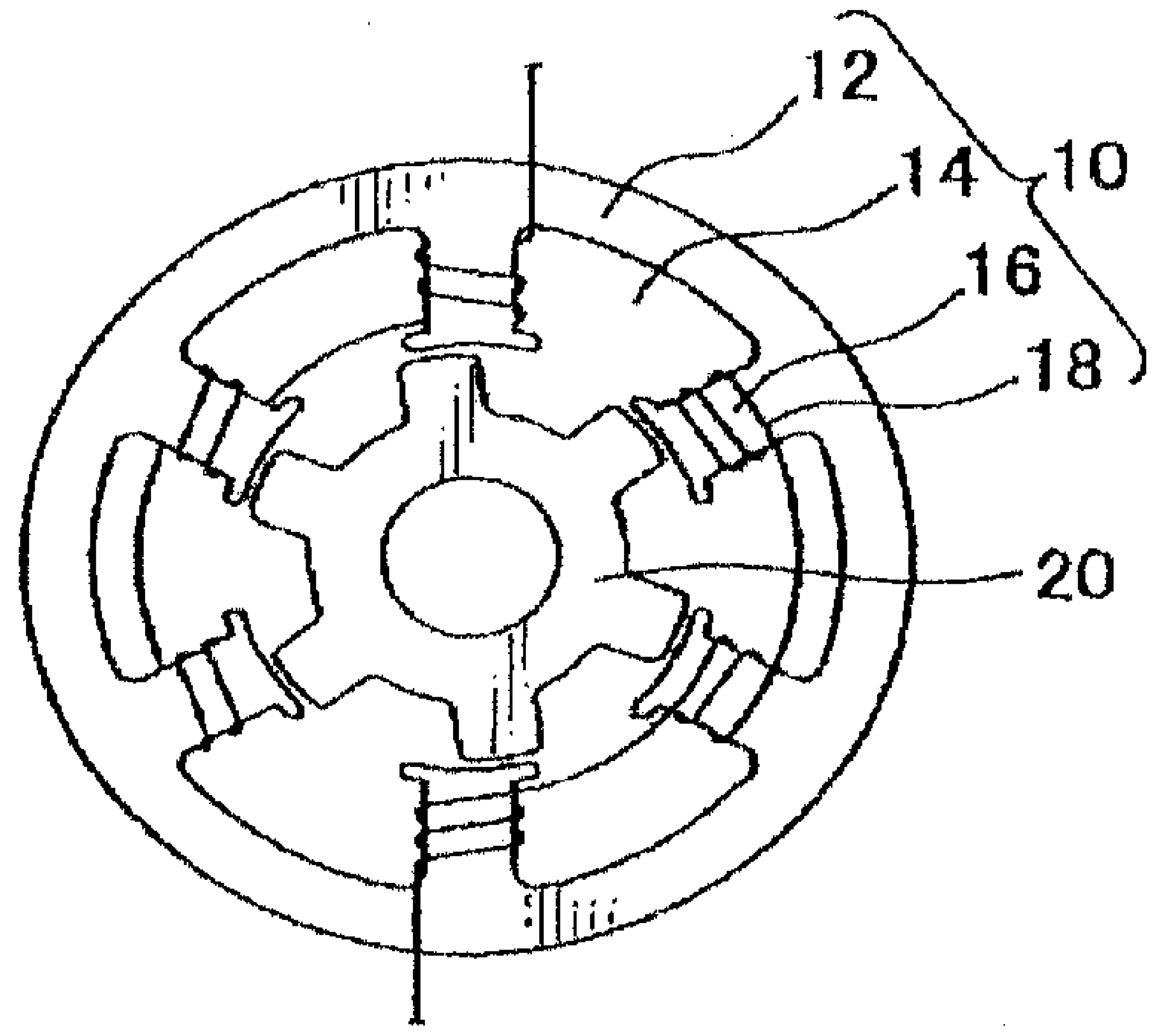


FIG. 5

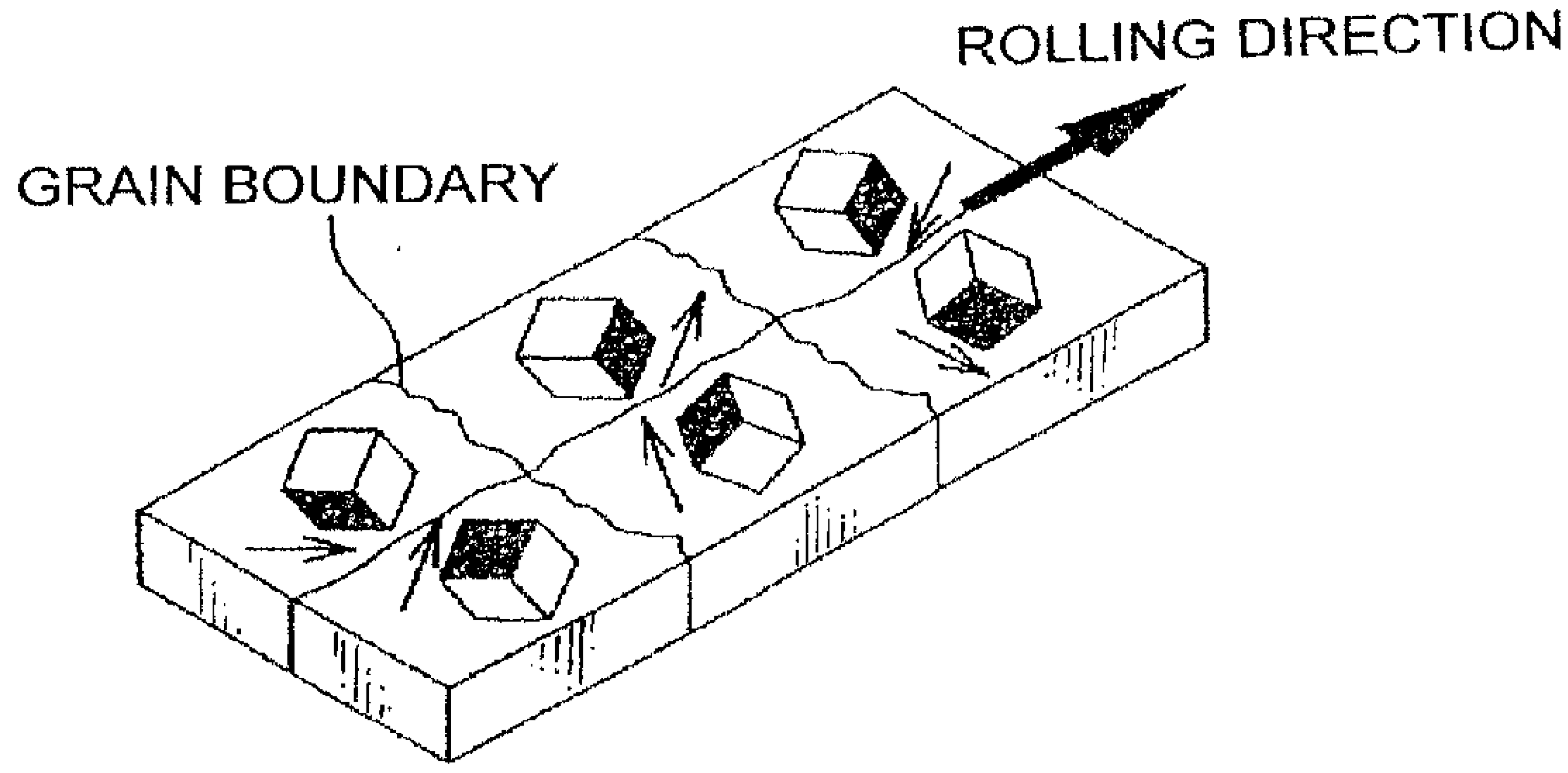


FIG. 6

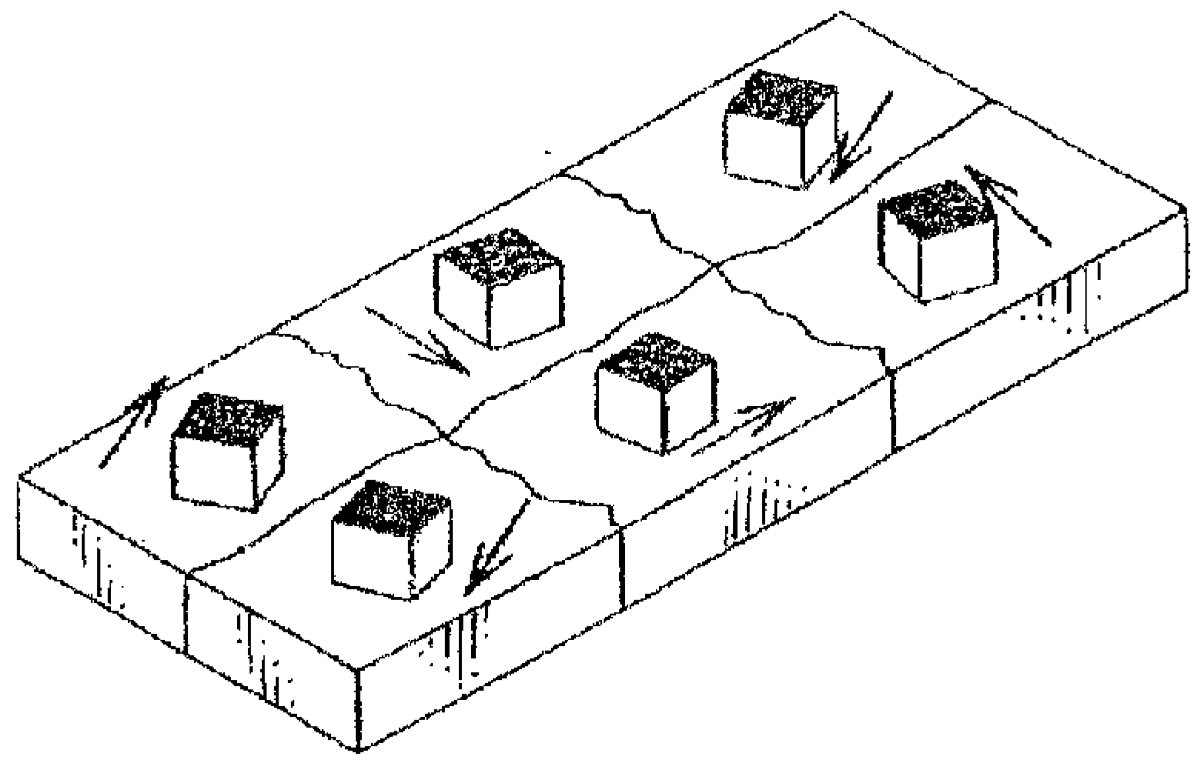


FIG. 7A

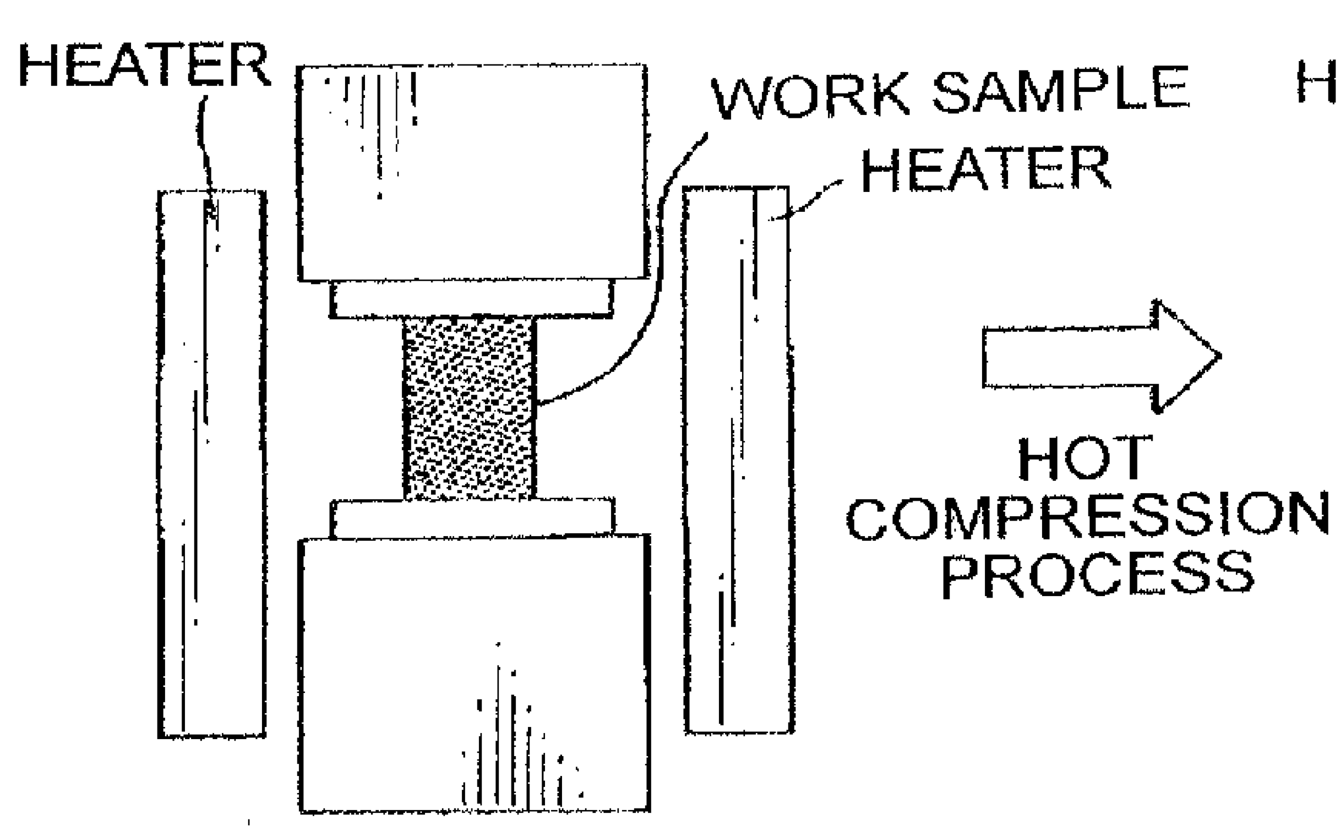


FIG. 7B

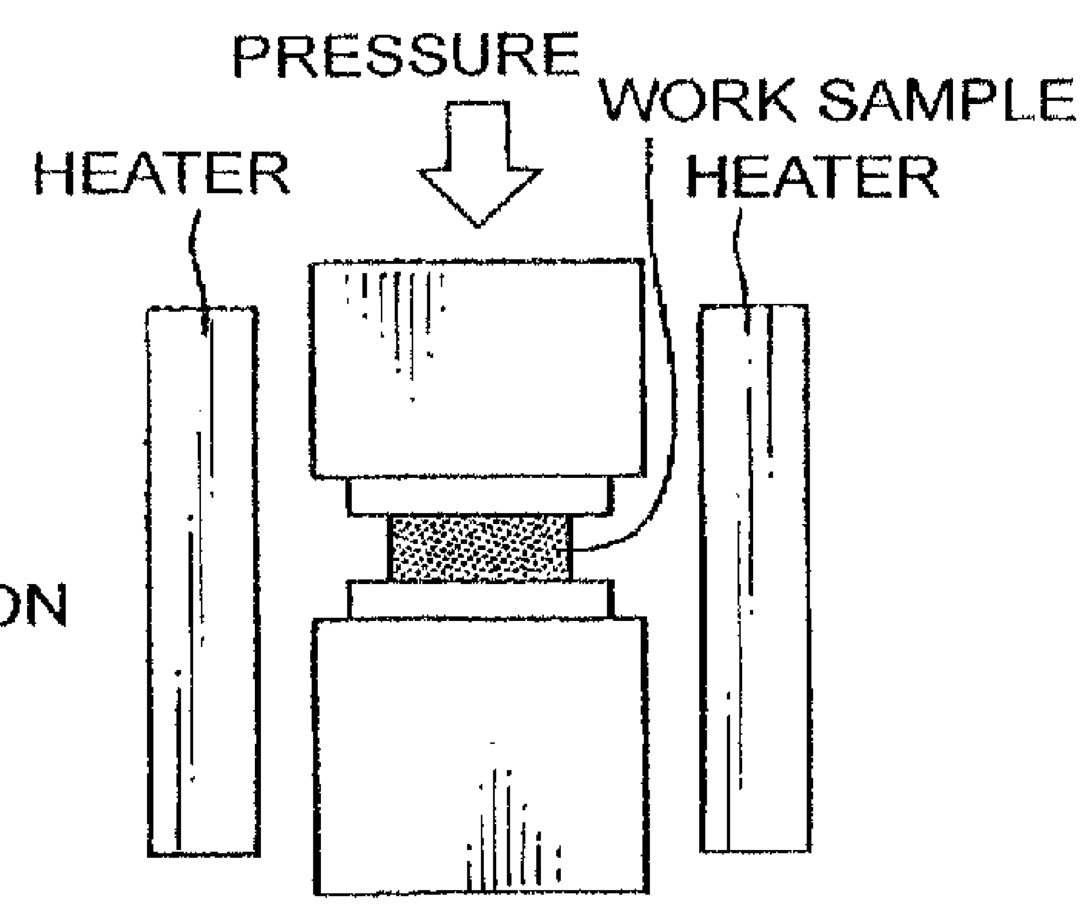


FIG. 8A

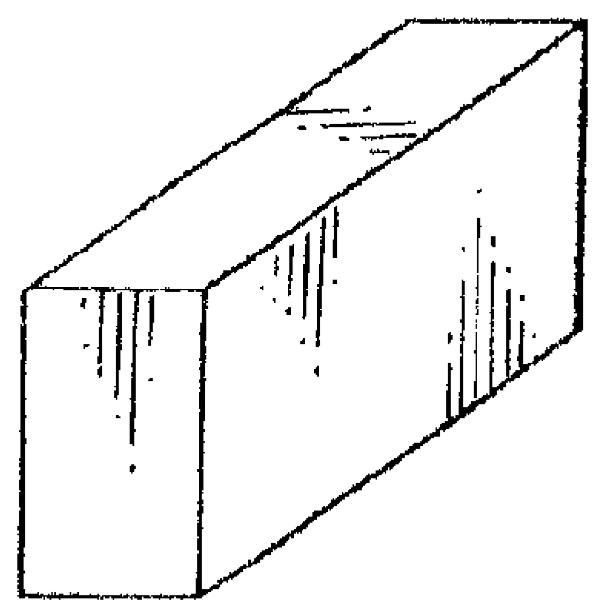


FIG. 8B

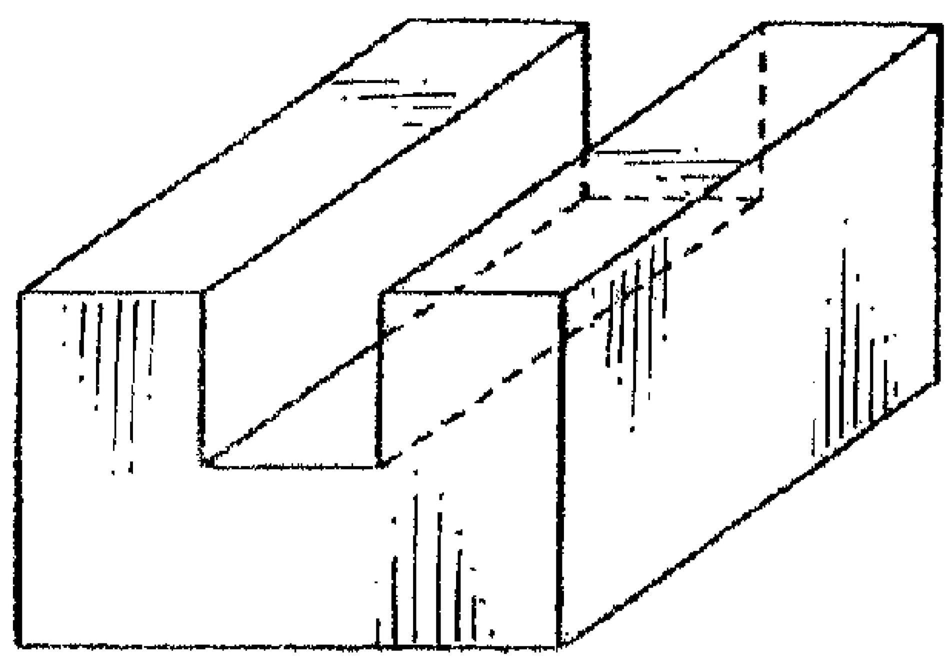


FIG. 8C FIG. 8D

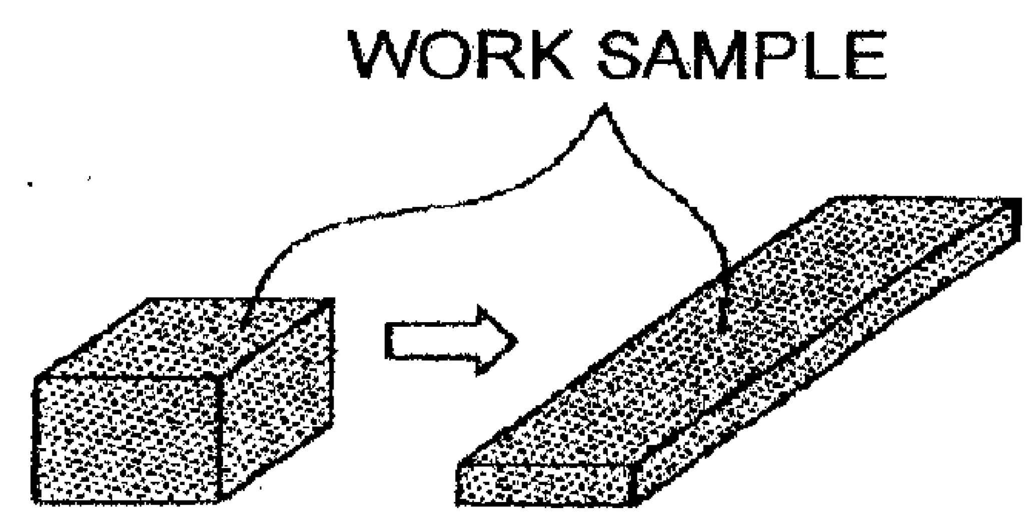


FIG. 9

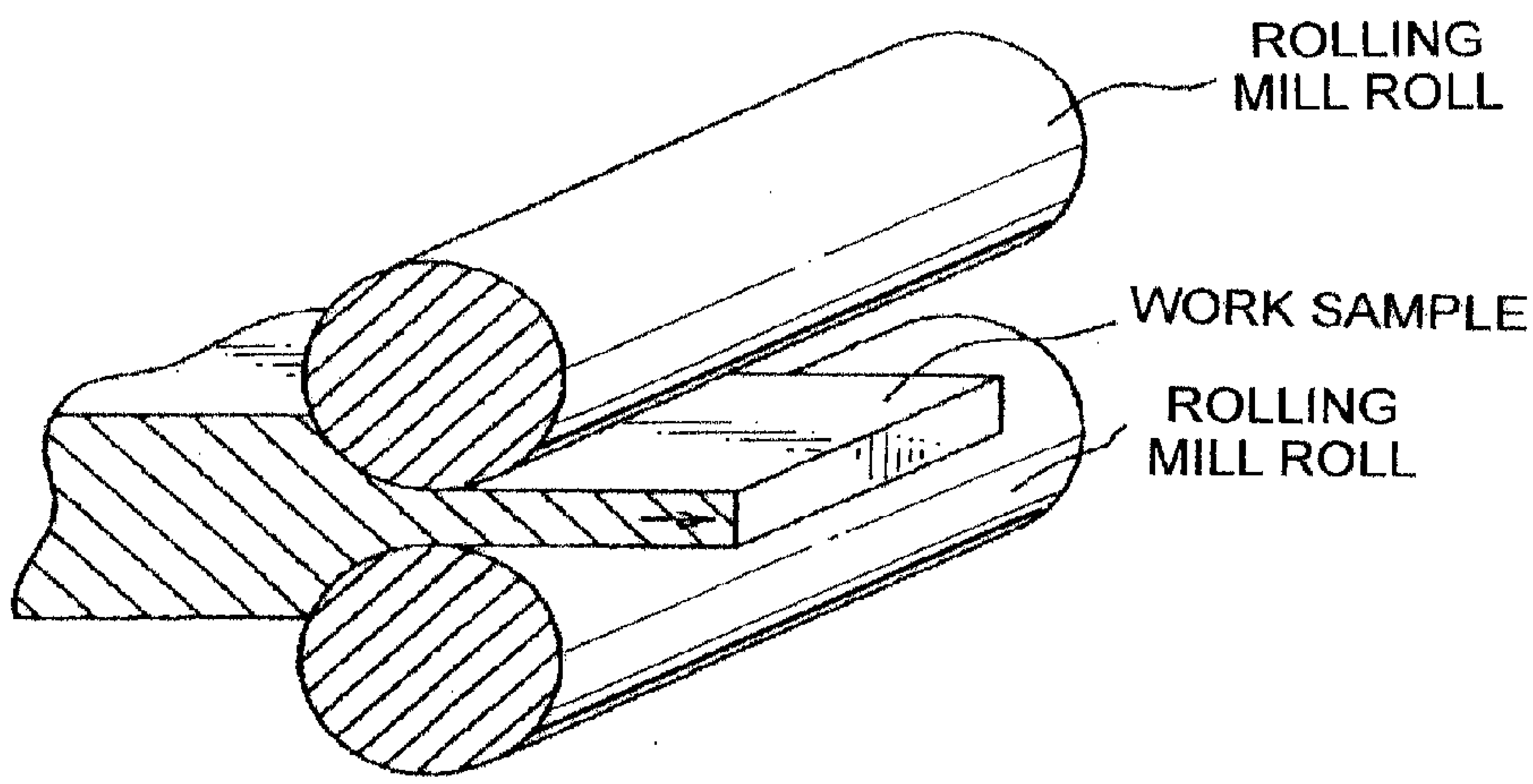


FIG. 10

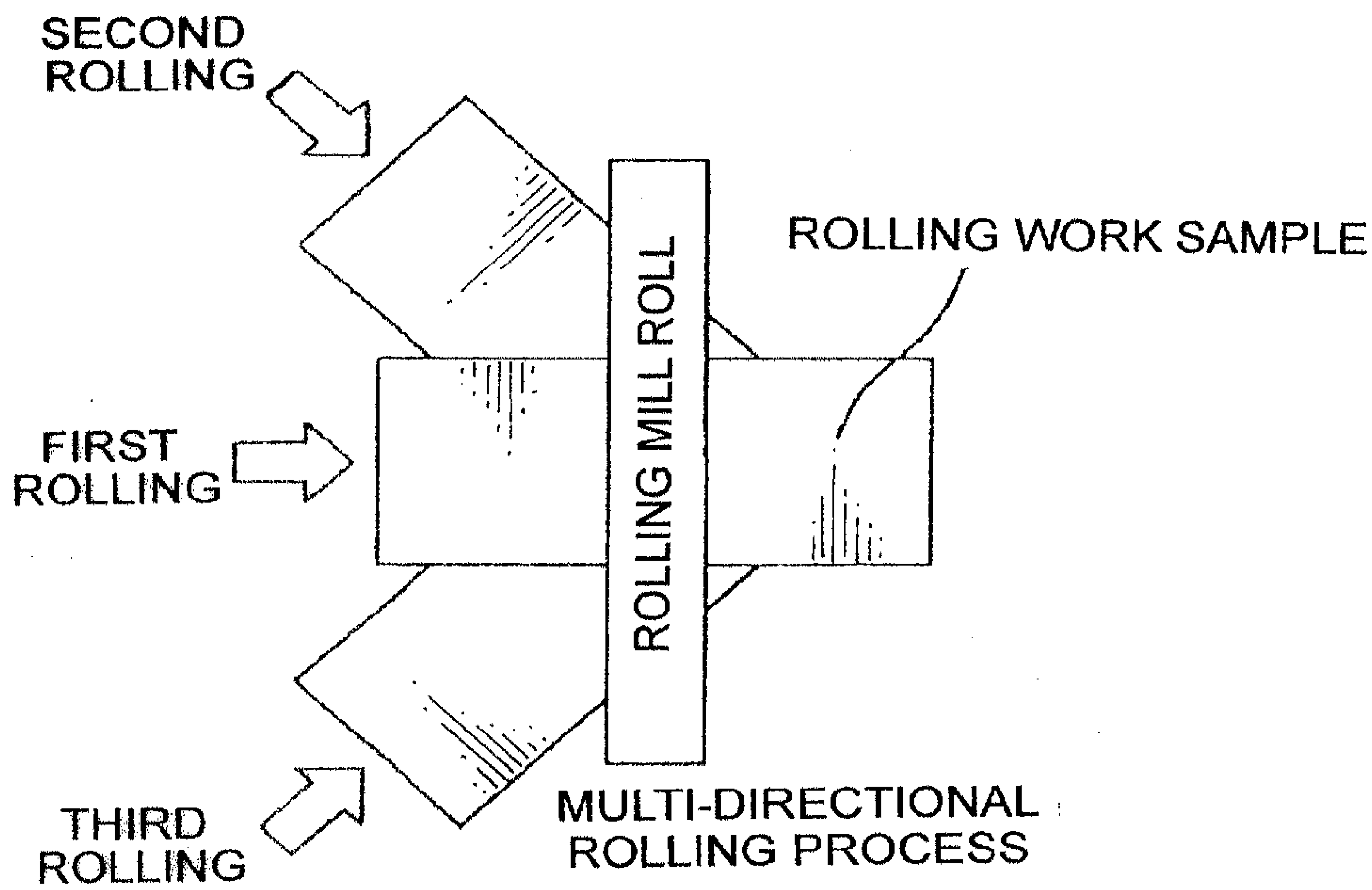

SECOND ROLLING
ROLLING WORK SAMPLE
ROLLING MILL ROLL
FIRST ROLLING
THIRD ROLLING
MULTI-DIRECTIONAL ROLLING PROCESS

FIG. 11

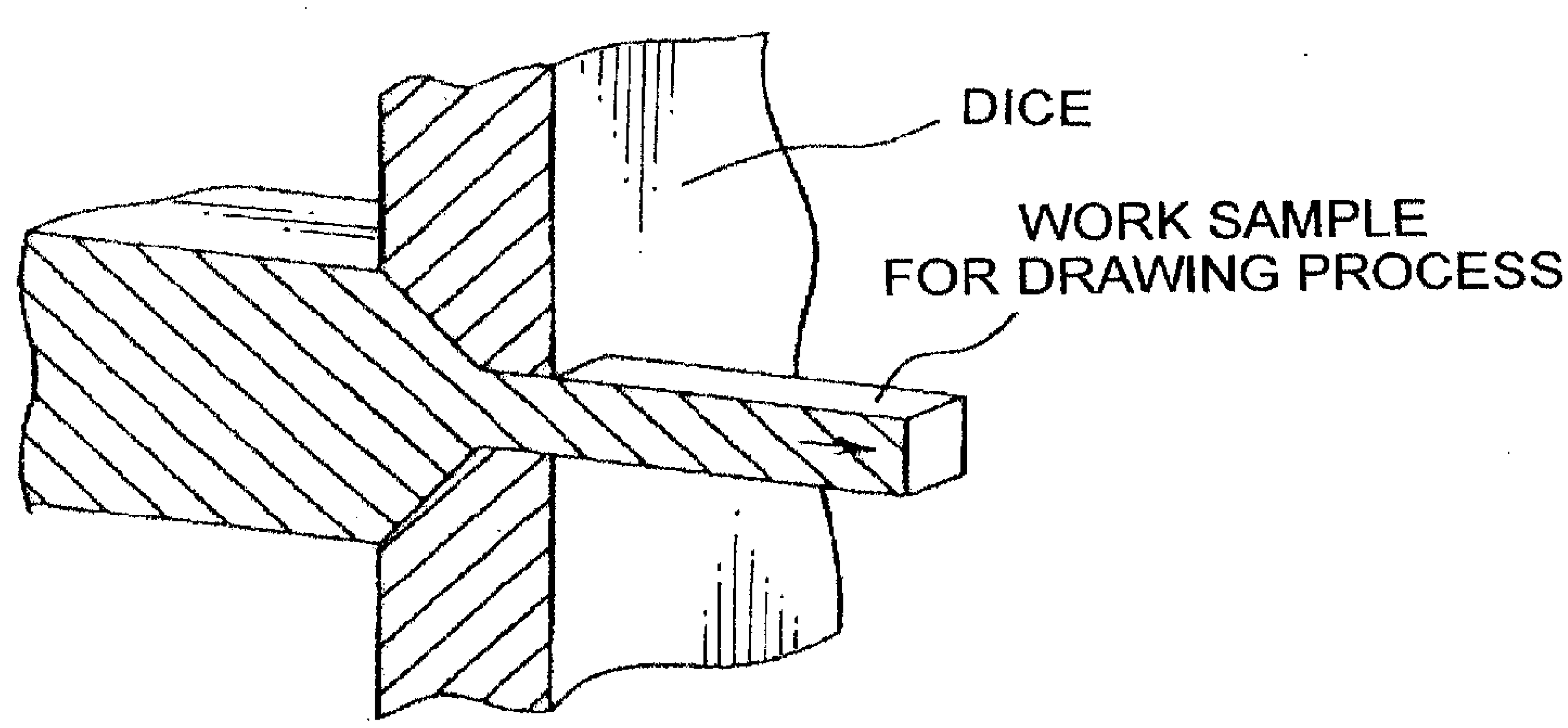
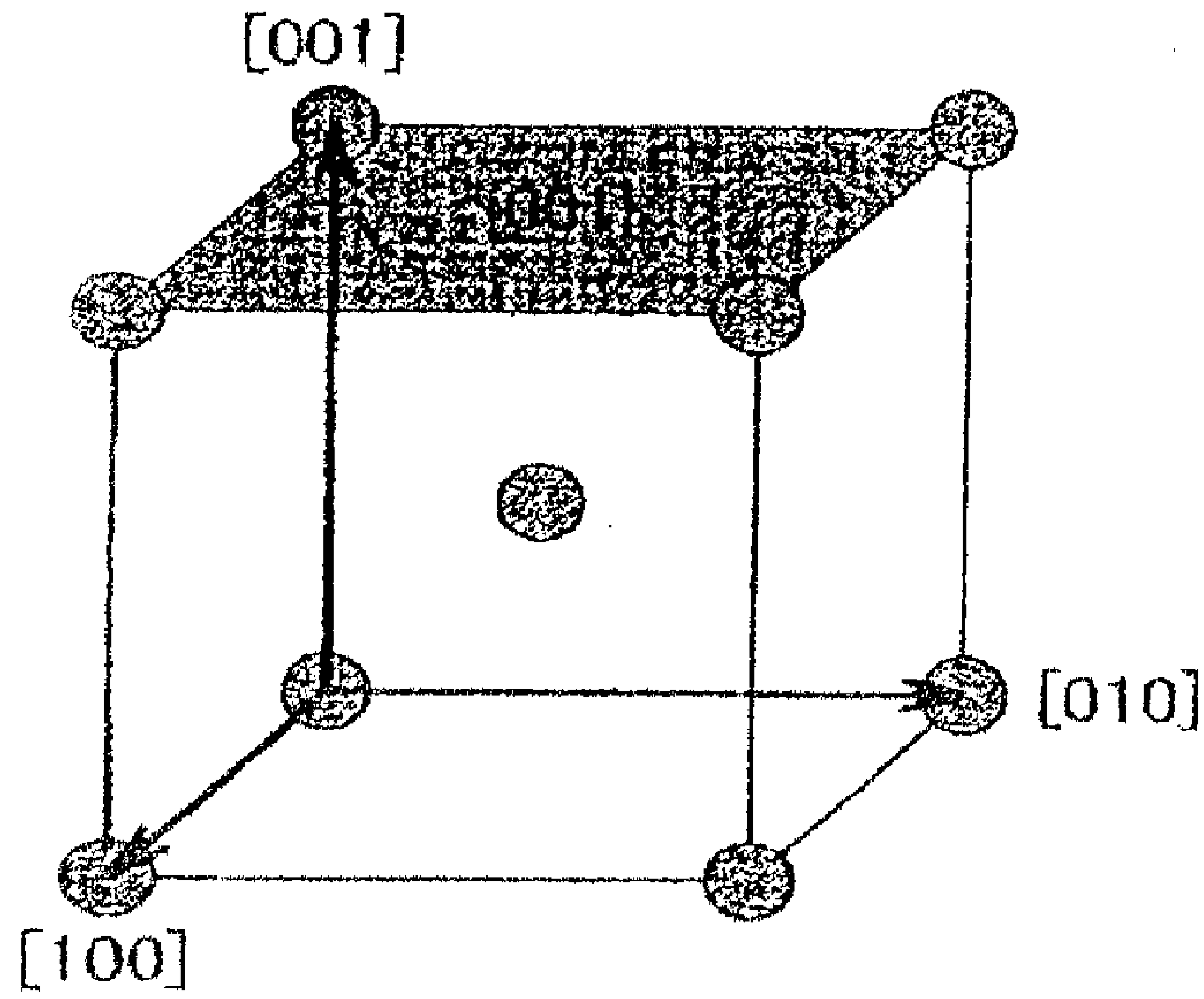

DICE
WORK SAMPLE FOR DRAWING PROCESS

FIG. 12



⟨100⟩ :DIRECTION OF EASY MAGNETIZATION IN A Fe-Si CRYSTAL

FIG. 13A

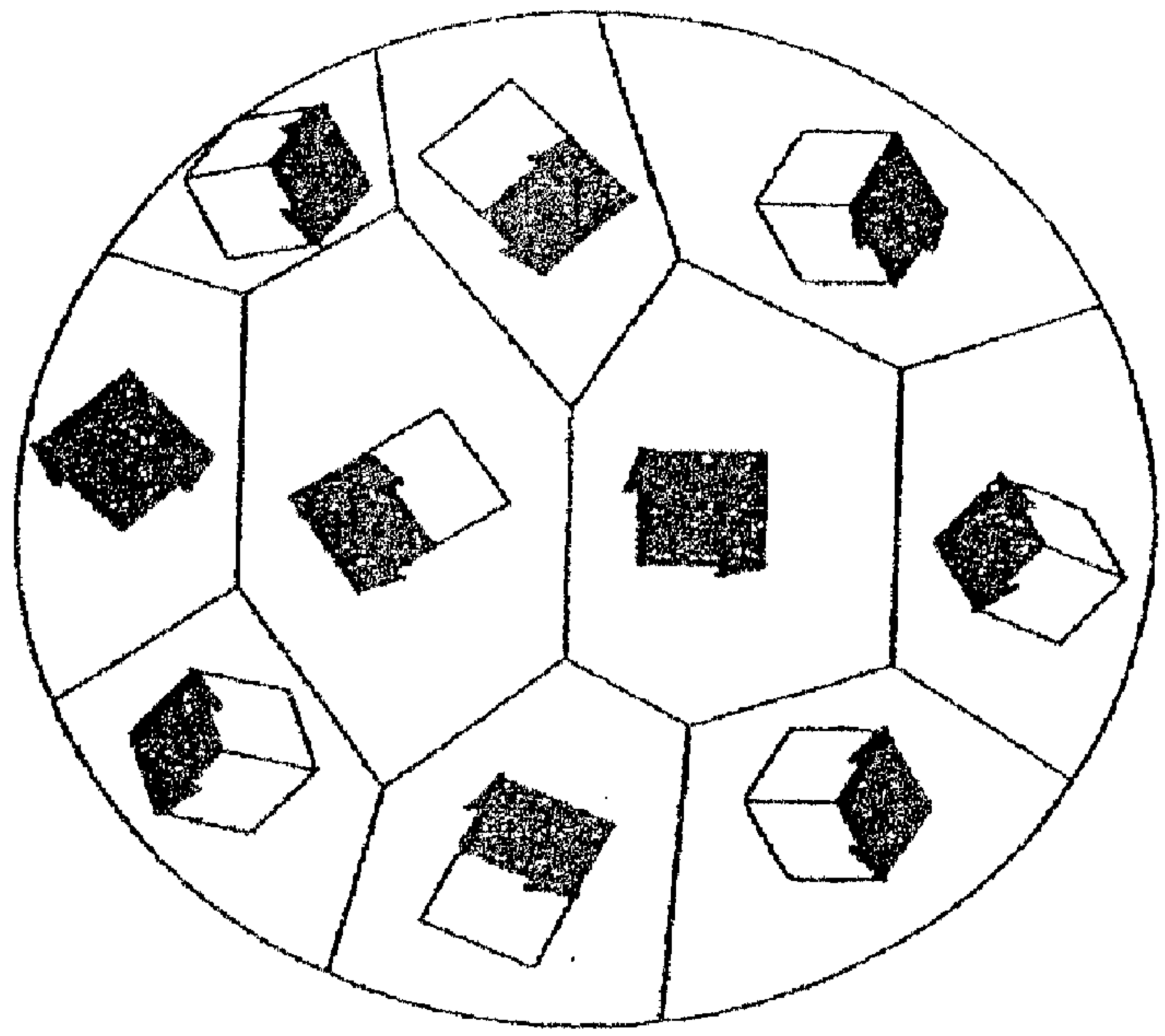


FIG. 13B

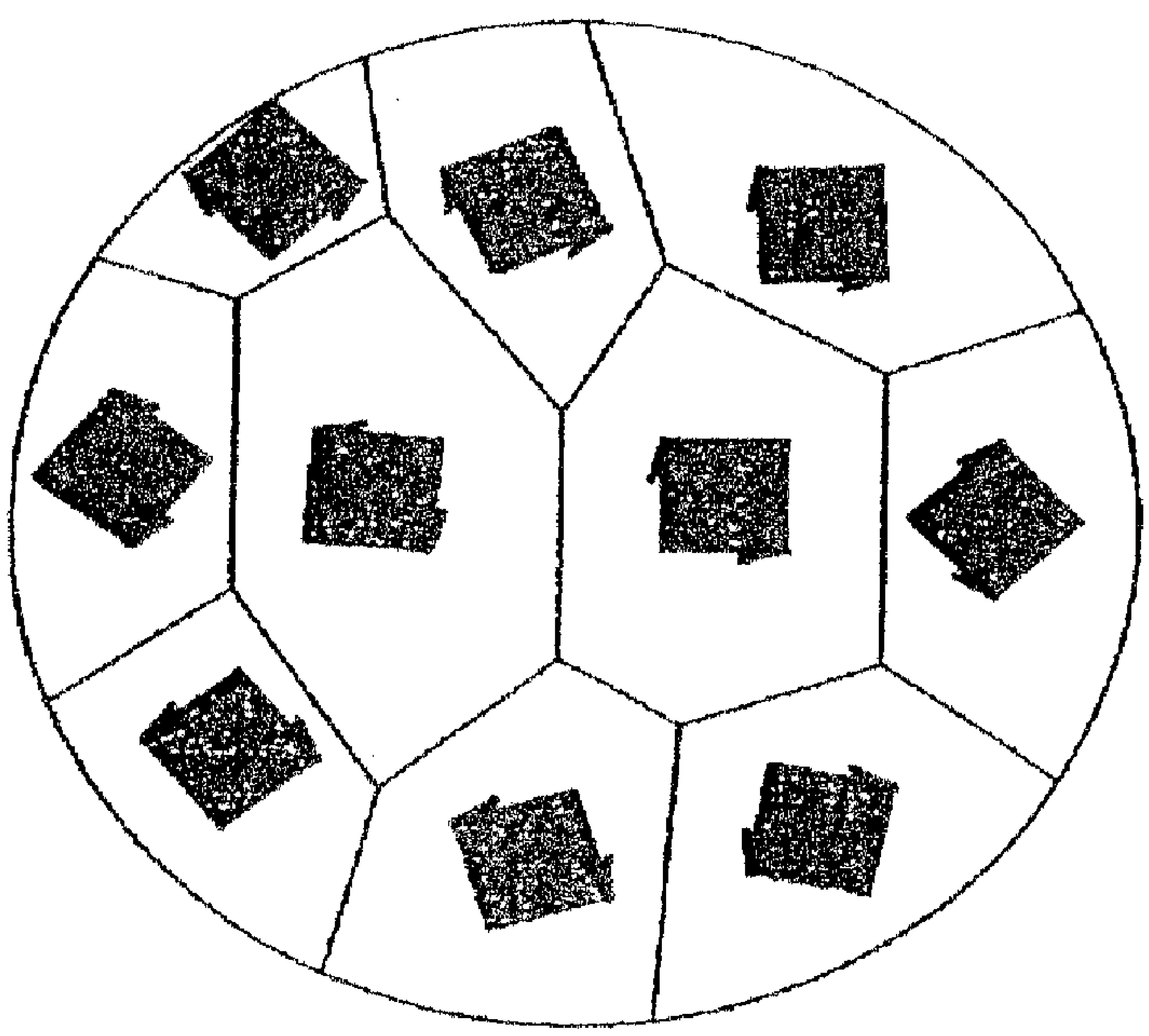


FIG. 14A

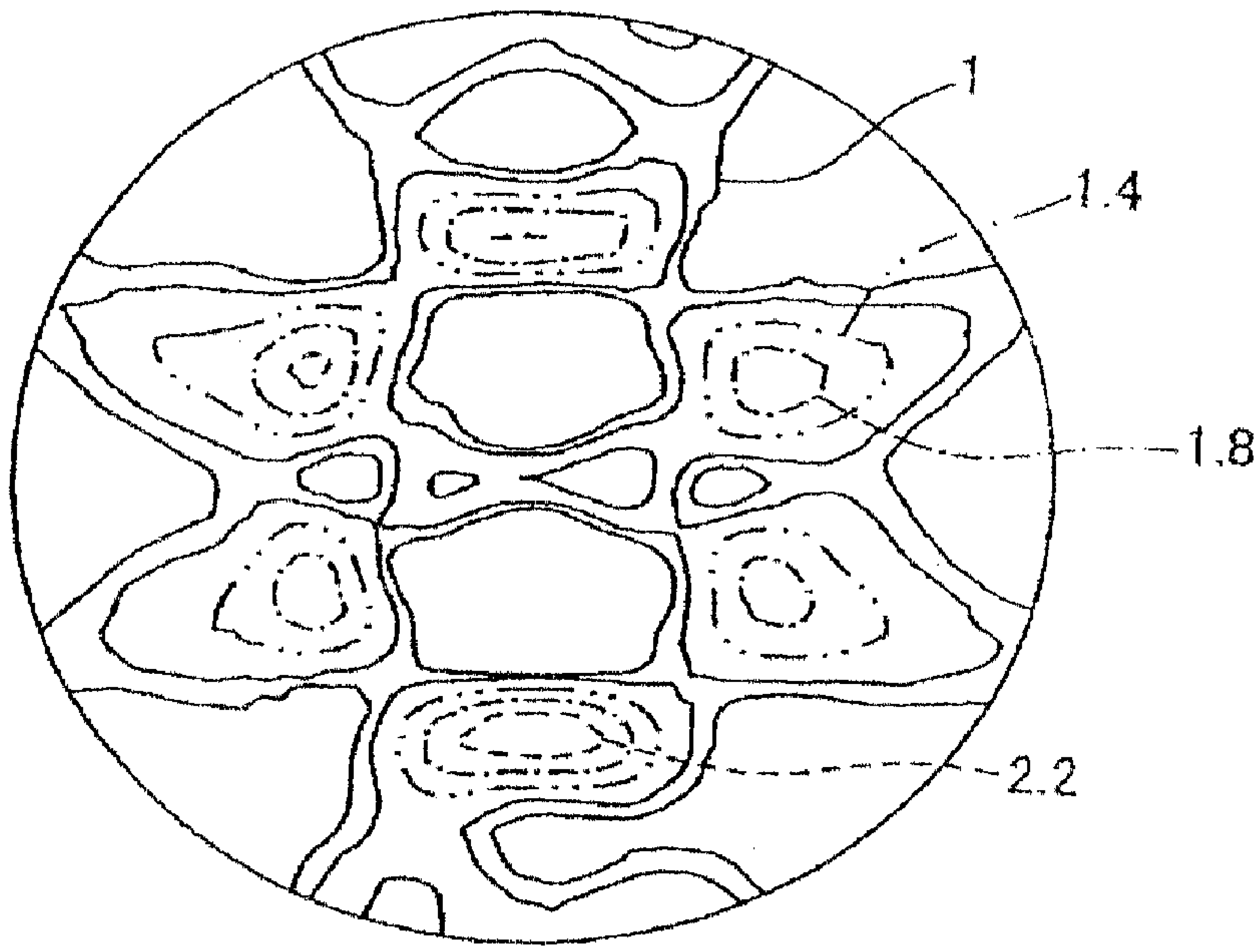


FIG. 14B

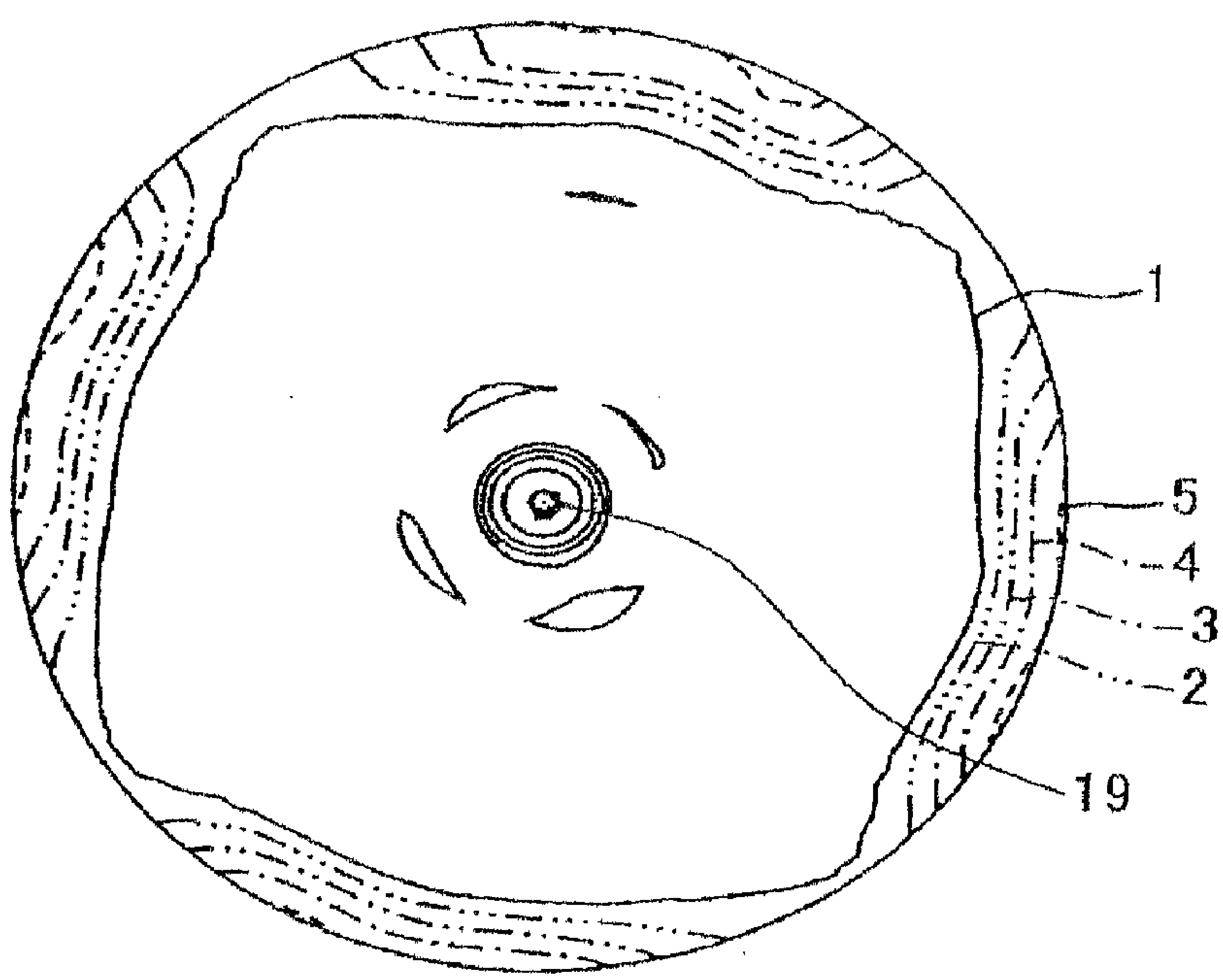
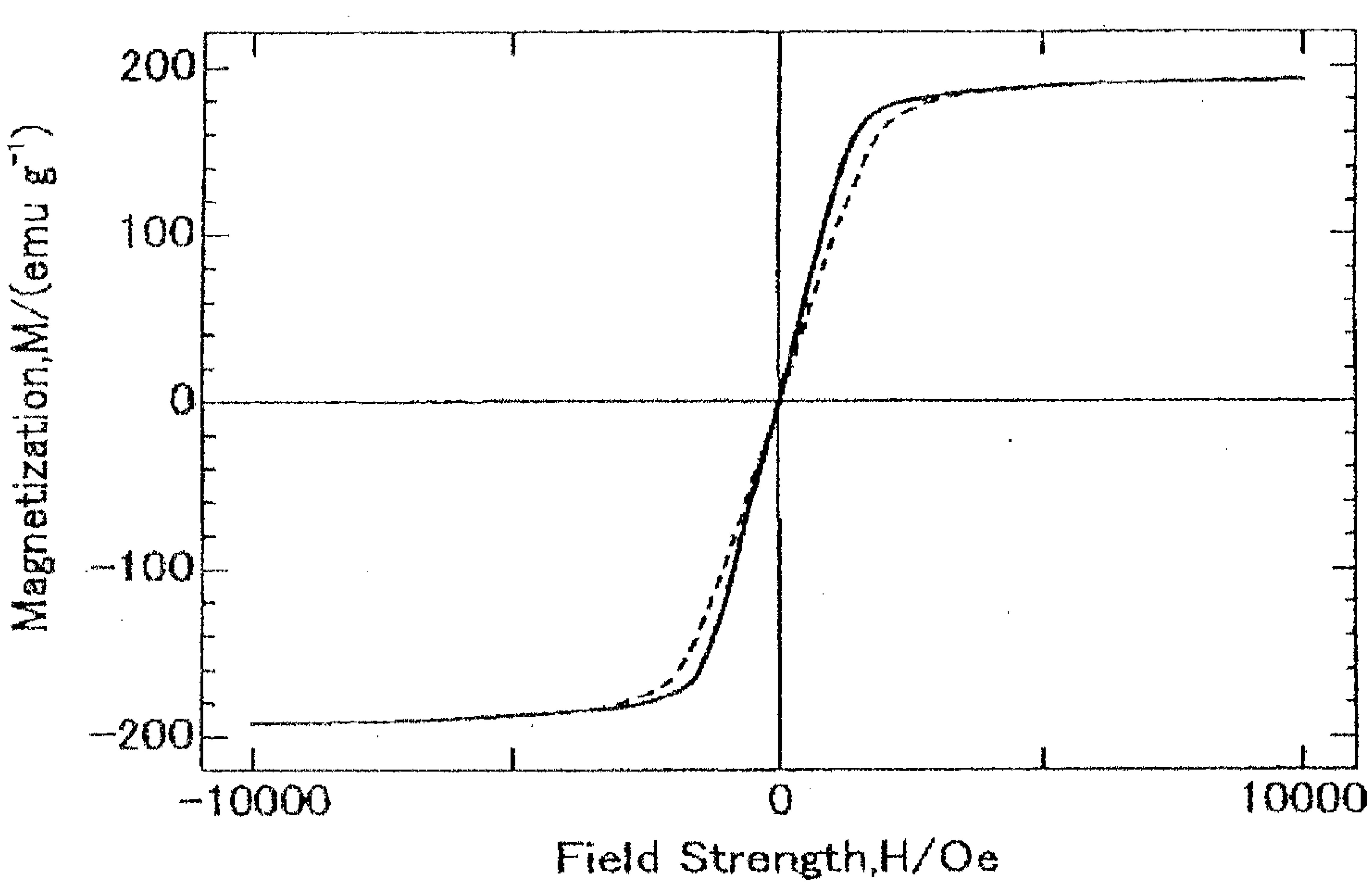


FIG. 15


Magnetization,M/(emu g^{-1})
200
100
0
−100
−200
−10000
0
10000
Field Strength,H/Oe

METALLIC MATERIAL AS A SOLID SOLUTION HAVING A BODY-CENTERED CUBIC (BCC) STRUCTURE, AN ORIENTATION OF CRYSTAL AXIS <001> OF WHICH IS CONTROLLED, AND METHOD OF MANUFACTURING THE SAME

[0001] Metallic Material as A Solid Solution having a body-centered cubic (BCC) structure, an orientation of crystal axis <001> of which is controlled, and Method of Manufacturing the Same.

TECHNICAL FIELD

[0002] This invention relates to a metallic material as a solid solution having a body-centered cubic (BCC) structure, an orientation of crystal axis <001> of which is controlled in a plane, and a method of manufacturing the material, for example an electromagnetic material used for an iron core of an electric device, and the method of manufacturing the material.

BACKGROUND ART

[0003] An electrical steel sheet used widely in electric devices is an example of a material which can perform large effect of technical features by aligning crystal axis of a metal. For example, when a direction of magnetic field as a transformer shown in FIG. **3** is fixed, a grain-oriented electrical steel sheet, in which crystal axis is controlled, is used. Preferably, magnetic lines of force shown with dot lines **33** in FIG. **3** are provided in a plane of core sheets **31**, which are stacked to be aligned in a direction of easy magnetization

[0004] For application of a rotor or a stator of a motor, a known non-oriented electrical steel sheet is used to reduce core loss. A single phase SRM (Switched reluctance motor) shown in FIG. **4** includes a stator **10**, which a coil connected with an outer electric power is wound, and a rotor **20** provided rotatably in the stator **10** and rotated by electromagnetic forces acting between the stator **10** and the rotor **20** when outer electric power is supplied to the stator **10**.

[0005] The stator **10** includes a yoke **12** having a ring shape, a plurality of poles **16** projecting along a radial direction from the yoke **12** toward the rotor **20** at an interval to each other through a predetermined slot **14** along a circumference of the yoke **12**, and a coil **18** wound around the pole **16** and connected with the outer electric power.

[0006] The stator **10** of the motor is manufactured by steps of punching a stator sheet having a plane shape with the yoke **12** and the pole **16** from a thin electrical steel sheet, stacking the stator sheets to be an iron core having a predetermined height, and winding a coil **18** around the magnetic core.

[0007] In such motor, a direction of magnetic field is changed around a rotation axis of the rotor as the center according to rotation of the rotor. Therefore, non-oriented electrical steel sheet is applied for rotors and stators (for example, see Patent Document 1).

[0008] Magnetization of steel has anisotropic property according to a crystal axis. Magnetization along the axis <001> is acted most easily with small hysteresis loss. Magnetization along the axis <011> is acted next most easily with small hysteresis loss. Magnetization along the axis <111> is acted in most difficulty with large hysteresis loss. Therefore, for a rotor and a stator of a motor, the orientation of the axis <001> is mainly aligned preferably along a radial direction of the motor so as to magnetize it easily and reduce core loss by hysteresis. Thus, core material, which orientation of the axis <001> is aligned rotational-symmetrically about an axis of a motor, is expected.

[0009] Unfortunately, no technology for controlling and aligning crystal axis <001> of steel sheet sufficiently exists. As next best way, for avoiding that orientation of crystal axis <111> is aligned along the radial direction, and orientation of crystal axis <001> is aligned eccentrically in a certain direction, non-oriented electrical steel sheet made of silicon steel and having isotropic property in 3-dimensions as shown in FIG. **5** is developed and delivered by Nippon Steel Corporation, and JFE Steel. Electrical steel sheet named by Hi-light core (trade name) and Home core (trade name) is supplied.

[0010] According to the non-oriented electrical steel sheet having non-directional property in 3-dimensions as shown in FIG. **5**, a direction of easy magnetization is eccentrically arranged not in a certain direction in the steel sheet, but many crystal axes <001> as an axis of easy magnetization are not arranged along a surface of steel sheet. Thereby, magnetic flux density along the surface of the steel sheet can not be increased, and improving efficiency of motor is limited.

[0011] Therefore, in a viewpoint of saving energy of a motor, it is expected to develop non-oriented electrical steel sheet which magnetic flux density along a surface of the electrical steel sheet is increased by aligning crystal plane {100} in parallel to the surface of steel sheet so as to arrange crystal axis <001> as axis of easy magnetization uniformly in all directions in the surface of the steel sheet as shown in FIG. **6** (see Unpatent Document 1).

[0012] Furthermore, for improving efficiency of a transformer, it is expected to develop oriented electrical steel sheet, which crystal axis <001> is arranged along magnetic flux path.

[0013] Thus, for improving energy efficiency of an electromagnetic apparatus such a motor and a transformer, it is expected to control an orientation of crystal axis <001> of an electromagnetic material.

CITATION LIST

Patent Document

[0014] Patent Document 1: Japan Patent Application Published No. 2006-87289

Unpatent Document

[0015] Unpatent Document 1: NIPPON STEEL MONTHLY Apr. 2005, P. 11-14

SUMMARY OF INVENTION

Objects to be Solved

[0016] According to a metal having a face-centered cubic (FCC) structure, such as aluminum, it is known as development of a fiber texture {011} (compression plane) that uniaxial compression process is effective for arranging crystal orientation having rotational symmetry around a compression axis. According to a metal having a body-centered cubic (BCC) structure, such as Fe, it is known that by uniaxial compression process in room temperature (cold compression), double fiber texture with {111}+{100}, in which the orientation distribution with rotational symmetry in which crystal planes {111} and {100} are parallel to the compression plane, is formed to have stable orientation for deformation.

[0017] The usual uniaxial compression process has a problem that not only crystal plane {100} arranging crystal axis <001> having excellent magnetic property in parallel to the surface of the steel sheet, but also crystal plane {111} unable to arrange crystal axis <001> in the surface of the steel sheet exist together. The usual uniaxial compression process develops crystal plane {111} in the surface more than crystal plane {100}, so that the uniaxial compression process is not applied as a method for manufacturing electrical steel sheet so as to arrange crystal axis <001> along a surface of the sheet.

[0018] Usually, it is difficult to control orientation of axis of easy magnetization <001> by not only the uniaxial compression process but also other method of manufacturing. Thus, there was no method for manufacturing non-oriented electrical steel sheet which has excellent magnetic property with large magnetic flux density and small core loss by controlling the axis of easy magnetization <001> in parallel to the surface of steel sheet. In short, there was not non-oriented electrical steel sheet which the axis of easy magnetization <001> was arranged in the surface of steel sheet.

[0019] According to the above problems, an object of the present invention is to control crystal axis of metal. For example, the object is to control axis of easy magnetization <001> of an iron based material along a work surface of manufacturing process. The object is to provide a metallic material having excellent magnetic property of easy magnetization along a surface of a sheet and large magnetic flux density and small core loss by controlling the axis of easy magnetization <001> along the work surface of manufacturing process, and a method of manufacturing the metallic material.

How to Attain the Object of the Present Invention

[0020] Usually, it is known that crystallographic texture including crystal plane {110} (compression plane) is formed by uniaxial compression deformation of Al-Mg solid solution alloy having FCC structure in high temperature. In result of proceeding study for crystal plane {100}, present inventors found that with increasing amount of deformation, the crystal plane {100} develops, and after that, the crystallographic texture becomes to be formed by only crystal plane {100}.

[0021] After proceeding the study of its mechanism, it is found experimentally that when amount of dislocation is increased by deformation, a crystal grain having orientation of {100} consumes other crystal grains having orientation of {110} and others by grain boundary migration and grows preferentially.

[0022] Attention was paid that {100} was the orientation with low Taylor factor, which corresponded to the total amount of shear strain and thus the amount of dislocation was considered to be small. Furthermore, it was noticed that {100} is stable orientation for deformation.

[0023] This change from the crystal plane {110} to the crystal plane {100} is not found in pure aluminum (Al) . Therefore, it is considered that deformation of Al-Mg alloy by compression occurs when the solute magnesium (Mg) atmosphere dragging of dislocations dominates the deformation. Thereby, a hypothesis that uniform distribution of dislocation enhances the preferential migration of crystal grain with {100} orientation is proposed.

[0024] According to the hypothesis, the present inventor had a thought that in a solid solution having body-centered cubic (BCC) structure, different crystallographic texture from that of pure metal would be generated. The present inventor focused that different from that of FCC metal, {100} and {111} coexists at room temperature due to difference in slip systems, and Taylor factor of crystal plane {100} is lower than Taylor factor of crystal plane {111}.

[0025] Therefore, the present inventor reached to have an idea that when process condition, in which solute atmosphere dragging of dislocation becomes dominant deformation mechanism and grain boundary migration become possible, could be found, technology of manufacturing process for material, by which {111} would be disappeared and oppositely {100} is frequently arranged along the surface of the sheet material, would be developed.

[0026] This idea could be applied generally for a metallic material having body-centered cubic (BCC) structure. Therefore, after studying iron-silicon alloy having body-centered cubic (BCC) structure, that is silicon steel, which the idea could be applied, it was found that increase of grain diameter and arrangement of <001> along the plane surface for increasing magnetic flux density could be controlled by manufacturing process condition.

[0027] A usual method of manufacturing non-oriented electrical steel sheet is formed by combining two processes of cold working and heat treatment, or hot working and heat treatment, and in contrast, based on the above found phenomena, it was appeared that electrical steel sheet, which can be controlled so as to align axes of easy magnetization <001> along a work surface of manufacturing process, by only one process of hot uniaxial compression process or hot plane strain compression process, can be manufactured. Thus, the present invention is accomplished.

[0028] The present invention is a method for manufacturing metallic material as a solid solution having a body-centered cubic (BCC) structure, in which the metallic material is formed by hot compression process in a temperature range, in which the metallic material becomes BCC single phase solid solution, so as to arrange crystal axis <001> along a work surface of manufacturing process of the metallic material.

[0029] According to the present invention, crystal axis <001> of the metal can be distributed along the work surface of manufacturing process without heat treatment after the manufacturing process, so that principle of the present invention can be applied for a metallic material as a solid solution having body-centered cubic (BCC) structure, and it has varied applications.

[0030] The present invention is a method for manufacturing metallic material, for example electrical steel sheet, having steps of: heating Fe-Si alloy as the metallic material in a temperature range to be BCC single phase solid solution, and applying compression process on the BCC solid solution with a strain rate able to maintain process condition in which solute atmosphere generated in the BCC single phase solid solution dominates dislocation motion and grain boundary can migrate by strain energy stored in a crystal grain as driving force so as to distribute {100} in parallel to a work surface of manufacturing process.

[0031] When the BCC single phase solid solution is processed by compression with the strain rate able to maintain process condition in which solute atmosphere generated in the BCC single phase solid solution can control motion of dislocation and grain boundary can migrate by strain energy stored in a crystal grain as driving force, the crystal plane {100} can be arranged in parallel to a work surface of manufacturing process. Thus, crystal axis <001> is distributed along the work surface of manufacturing process.

[0032] The present invention is a method for manufacturing a metallic material in which Fe-Si alloy is used as the solid solution having the body-centered cubic (BCC) structure; and the Fe-Si alloy is heated in temperature range to become BCC single phase solid solution and compression process with strain rate from 1×10^{-5}/s to 1×10^{-1}/s is applied to the Fe-Si alloy.

[0033] When the solid solution is Fe-Si alloy, the strain rate able to maintain process condition in which solute atmosphere generated in the BCC single phase solid solution can control motion of dislocations and grain boundary can migrate by strain energy stored in a crystal grain as driving force is in range from 1×10^{-5}/s to 1×10^{-1}/s. By applying compression process in the condition, the crystal plane {100} can be distributed in parallel to the work surface of manufacturing process. For example, when applying uniaxial compression process with the strain rate from 1×10^{-5}/s to 1×10^{-1}/s to Fe-Si alloy, an electrical steel sheet of Fe-Si alloy having good properties is manufactured. The Fe-Si alloy includes preferably Si of 1-7 weight %, and Fe remaining and unavoidable impurities.

[0034] The present invention is further characterized in that the temperature range is between 800-1300° C.

[0035] By determining temperature range, electrical steel sheet having good properties can be manufactured with reproducibility.

[0036] The present invention is further characterized in that total amount of strain of at least −0.5 is given at the single phase solid solution having the body-centered cubic (BCC) structure by the compression process.

[0037] By giving total amount of strain of at least −0.5 by uniaxial compression process, a high-quality electrical steel sheet, in which crystal axis <001> is securely controlled along a surface of the sheet, can be provided. The {100} (compression plane) is a crystal orientation with low strain energy under uniaxial compression deformation, and the crystal arranged in the orientation is stable against deformation, so that migration of grain boundary is acted during deformation so as to increase grain size of the crystal. Therefore, when the amount of strain is increased, {100} fiber texture develops. Larger strain provides better results. By making the total amount of strain larger, {100} parallel to the work surface of manufacturing process grows remarkably.

[0038] The present invention is also related to a metallic material as a solid solution having the body-centered cubic (BCC) structure, in which crystal axes <001> are distributed along a work surface of manufacturing process by hot compression process. Especially, the metallic material as a solid solution having body-centered cubic (BCC) structure has 14 times or more orientation density on a line of $\Phi=0°$ at $\phi_2=0°$ section of crystal Orientation Distribution Function (ODF), which indicates a distribution of the crystal axis <001> along the work surface of manufacturing process against an average value 1 of the orientation density.

[0039] According to the present invention, highly concentrated orientation distribution along a specific direction, which could not be provided usually, is realized.

[0040] When the metallic material as the solid solution having body-centered cubic (BCC) structure is deformed by hot uniaxial compression process in a condition in which solute atmosphere dragging of dislocation is main deformation mechanism, the dislocation in the solid solution is distributed uniformly, so that grain boundary migration is acted according to distribution of strain energy corresponding to the dislocation. Thereby, a situation, in which crystal grains with {100} having small strain energy grows in parallel to the surface of the steel sheet, can be generated. Furthermore, when the metallic material is processed by hot rolling or hot plane strain compression, the crystal axis <001> is aligned along a direction of extending the material. In short, in the all above cases, the crystal axis <001> is controlled along the work surface of manufacturing process.

[0041] In case which Fe-Si alloy as the solid solution having the body-centered cubic (BCC) structure, physically an electrical steel sheet, is formed by hot uniaxial compression process, the electrical steel sheet having 14 times or more orientation density on the line of $\Phi=0°$ at $\phi_2=0°$ section of crystal Orientation Distribution Function (ODF) for checking distribution of the crystal axis <001> against the average value 1 thereof can be easily realized.

[0042] Usual metal sheet has two or less orientation density on the line of $\Phi=0°$ at $\phi_2=0°$ section of crystal Orientation Distribution Function (ODF) against the average value 1 thereof.

[0043] The electrical steel sheet by Fe-Si alloy, in which the distribution of the crystal axis {001} is controlled so as to be in parallel to the work surface of manufacturing process, has better properties comparing usual non-oriented electrical steel sheet.

Effects of the Invention

[0044] According to the metallic material and the method for manufacturing the same by the above-mentioned present invention, the metallic material in which the crystal axis is controlled, especially, the electrical steel sheet, in which axis of easy magnetization <001> is controlled to be aligned along the work surface of manufacturing process, is provided, so that the electrical steel sheet having excellent magnetic properties with large magnetic flux and small core loss is supplied.

BRIEF DESCRIPTION OF DRAWINGS

[0045] FIG. **1** is a view at $\phi_2=0°$ section of crystal orientation distribution function (ODF) of non-oriented electrical steel sheet formed by a method for manufacturing using hot uniaxial compression process according to the present invention;

[0046] FIG. **2** is a view at $\phi_2=0°$ section of crystal orientation distribution function (ODF) of usual non-oriented electrical steel sheet by prior art;

[0047] FIG. **3** is an illustration for explaining flow of lines of magnetic force in an electrical steel sheet of a transformer;

[0048] FIG. **4** is an illustration for explaining a structure of a motor using the electrical steel sheet;

[0049] FIG. **5** is an illustration showing a crystal distribution of usual known non-oriented electrical steel sheet;

[0050] FIG. **6** is an illustration showing a crystal distribution of non-oriented electrical steel sheet formed by a method for manufacturing according to present invention;

[0051] FIG. **7**A is an illustration for explaining a condition before compression of uniaxial compression process;

[0052] FIG. **7**B is an illustration for explaining a condition after compression of uniaxial compression process;

[0053] FIG. 8A is an illustration for explaining a forming jig for plane strain compression process;
[0054] FIG. 8B is an illustration for explaining another forming jig for plane strain compression process;
[0055] FIG. 8C is an illustration of a work sample before forming by plane strain compression process;
[0056] FIG. 8D is an illustration of a work sample after forming by plane strain compression process;
[0057] FIG. 9 is an illustration for explaining a rolling process;
[0058] FIG. 10 is an illustration for explaining a multi-direction rolling process;
[0059] FIG. 11 is an illustration for explaining a drawing process;
[0060] FIG. 12 is an illustration of a body-centered cubic (BCC) structure;
[0061] FIG. 13A is an illustration showing orientations of axes of easy magnetization <001> of usual non-oriented electrical steel sheet used in a stator of a motor;
[0062] FIG. 13B is an illustration showing orientations of axes of easy magnetization <001> of ideal non-oriented electrical steel sheet used in a stator of a motor;
[0063] FIG. 14A is an illustration showing a pole figure of {100} of usual non-oriented electrical steel sheet used in a stator of a motor;
[0064] FIG. 14B is an illustration showing a pole figure of {100} of the non-oriented electrical steel sheet by the present invention used in a stator of a motor; and
[0065] FIG. 15 is a chart showing magnetic properties of usual non-oriented electrical steel sheet (by dot line) and the electrical steel sheet according to the present invention (solid line).

DESCRIPTION OF EMBODIMENTS

[0066] Embodiments of an electrical steel sheet and a method for manufacturing the steel sheet according to the present invention will be described as following.
[0067] When a metallic material is deformed in high temperatures, various mechanisms contribute to its deformation. In a metallic material, usually, deformation by movement of dislocation is a basic mechanism.
[0068] One of phenomena affecting mainly the movement of dislocation is a dragging of a solute atmosphere generated in a solid solution alloy under combination of a certain temperature range and a strain rate. The phenomenon is that the dislocation surrounded by the solute atoms moves together with the solute atoms. For example, in Fe-Si alloy, Si as the solute atom forms the solute atom atmosphere existing at higher density than an average density in overall crystal around the dislocation. In a certain range of deforming condition, the dislocation can not break away from the solute atom atmosphere and move with dragging the dislocation. Thereby, velocity of the dislocation is slowed by dragging the solute atom atmosphere. In result, differently from deformation under room temperature, the dislocation is distributed uniformly in the crystal. In short, the dislocation dragging the solute atmosphere is easily distributed uniformly in the crystal.
[0069] Herein, the dislocation is a lattice defect and has strain energy. Depending on an orientation of crystal, an amount of dislocations contributing to its deformation is varied. Thereby, when applying same amount of deformation, the amount of dislocation is different from each crystal, and in result, amount of energy stored in each crystal is varied. In usual manufacturing condition, dislocations are distributed so as to cancel strain energy of each crystal to each other. Difference of dislocation densities about each crystal grain is not directly reflected to difference of the strain energy stored in each crystal grain.
[0070] In contrast, by compression process in high temperature, which generates movement of dislocation dragging solute atom atmosphere, as a condition of deformation according to the present invention, dislocations are distributed uniformly and effect of canceling strain by dislocation is small. Therefore, difference of the amount of dislocation reflects directly to difference of stored strain energy.
[0071] Under the condition that the solute atom atmosphere controls movement of dislocation, amount of strain energy in each crystal grain depends strongly on the orientation of crystal. Thereby, the crystal grain having small strain energy tends to grow up, so that the grain boundary of the crystal having low strain energy is moved preferentially.
[0072] The orientation of crystal having low strain energy under uniaxial compression deformation of a solid solution having the body-centered cubic (BCC) structure is {100} (surface of sheet) . The orientation of crystal under plane strain compression deformation such as rolling is <001> (extending direction) in {100} (surface of plane) . Therefore, the crystal grains in the orientation of crystal consume other crystal grains in other orientations, and grow.
[0073] The crystal in the orientation of crystal plane {100} is stable against compression deformation, so that during deformation, the grain boundary migrates so as to grow the crystal grain. Therefore, when increasing the strain, fiber texture {100} is growing at uniaxial compression deformation, and {100}<001> texture is growing at plane strain compression deformation.
[0074] Herein, {100} shows a work surface of manufacturing process, and <001> shows an extending direction by rolling.
[0075] The present invention is accomplished based on the above-mentioned knowledge. According to the present invention, {100} is arranged in parallel to a sheet surface under both of uniaxial compression deformation and plane strain compression deformation. At compression deformation, the crystal plane {100} is arranged in parallel to the surface of plate. Especially, at uniaxial compression deformation, <001> is distributed uniformly in high density in a direction vertical to a direction of compression in the surface of the plane around the crystal axis <100> as a normal of the crystal plane {100} as a rotation axis. At plane strain deformation such as rolling, when a thickness of the sheet is reduced by compression process, the sheet extends in one direction. In this case, crystal axis <001> is distributed in high density along extending direction.
[0076] For manufacturing an electrical steel sheet in which axes of easy magnetization <001> are distributed in parallel in a surface of the sheet, an Fe-Si alloy, which includes at least Si and Fe remaining and unavoidable impurities, is heated in a temperature range in which the alloy becomes solid solution having body-centered cubic (BCC) structure. In this condition, the solid solution having the body-centered cubic (BCC) structure is processed by the uniaxial compression process or the plane strain compression process with a strain rate which can maintain a process condition which the movement of dislocation dragging the solute atmosphere generated in the BCC solid solution becomes main deformation mechanism, and the grain boundary of the crystal can migrate by the strain

energy stored in the crystal grain as a driving force. Thereby, the crystal plane {100} is distributed in high density in parallel to the work surface.

[0077] For the process condition, the temperature range is between 800-1300° C., and the strain rate is between 1×10^{-5}–1×10^{-1}/s.

[0078] The total amount of strain applied on the solid solution having body-centered cubic (BCC) structure by compression process is more than −0.5 as a true strain. The purposed condition is simply widened according to increasing amount of strain, but is not enough when the amount of strain is small. Larger amount of strain generates better condition, so that amount of strain is not upper-limited, and also, the strain can be applied divisionally.

[0079] Regarding components of the alloy, Si in the solid solution having body-centered cubic (BCC) structure is added to increase specific resistance of the steel sheet and decreases eddy current, and improve core loss by the eddy current. The solid solution having body-centered cubic (BCC) structure can be BCC single phase solid solution which is formed by not only binary alloy, but also ternary or more alloy including a component other than Si. In case that the solid solution having body-centered cubic (BCC) structure is Fe-Si alloy, content of Si is in range between 1-7 weight %. When the content of Si is not larger than 1 weight %, the alloy cannot have enough specific resistance for low core loss. When the content of Si is more than 7 weight %, crack is increased in compression process, so that compression process becomes troublesome. Content of Si is preferably between 1 weight % at the lowest and 7 weight % at the highest.

[0080] As unavoidable impurities in the Fe-Si alloy, C, Mn, P, S, Al and N are listed. Especially, Mn reacts with S to each other so as to extract fine sulfide MnS and deteriorates extremely magnetic properties. And P inhibits manufacturability. Thereby, Mn and P should be controlled less than 0.01 weight %. S, which inhibits growing crystal grain, should be controlled less than 0.0001 weight %.

[0081] Fe-Si alloy, which is used as the solid solution having the body-centered cubic (BCC) structure, is heated in temperature range between 800-1300° C. to become BCC single phase. Fe-Si alloy having Si content of 2-5 weight % has BCC structure always in temperature range from a low temperature to melting point. Fe-Si alloy having Si content less than 2 weight % changes once to FCC structure in high temperature according to the content of Si, so that growing of fiber texture {100} may be inhibited. For solving, Fe-Si alloy having Si content less than 2 weight % is heated in lower temperature area in the temperature range between 800-1300° C. to become BCC single phase.

[0082] The strain rate in compression process for BCC single phase solid solution shows amount of strain per unit time, that is process speed. The process speed, which is low or high, changes main mechanism controlling movement of dislocation affecting the deformation. Therefore, the process speed is limited so as to maintain the process condition, in which solute atmosphere generated in the BCC solid solution controls the motion of dislocation in temperature range of heating solid solution having the body-centered cubic (BCC) structure so as to be BCC single phase. The strain rate of Fe-Si alloy as the solid solution having body-centered cubic (BCC) structure is determined between 1×10^{-5}–1×10^{-1}/s in the temperature range between 800-1300° C.

[0083] The texture of Fe-Si alloy having Si content of 3 weight % was evaluated in strain rate range between 1×10^{-5}–1×10^{-2}/s in the temperature 900° C., and in strain rate range between 1×10^{-4}–1×10^{-2}/s in the temperature 1250° C. It is assumed that when the strain rate is the same, the temperature in process condition, which the same crystal structure is generated, is changed to lower according to increasing Si content; and when the temperature is the same, the strain rate in process condition, which the same crystal structure is generated, is changed to higher according to increasing Si content. The above strain rate of Fe-Si alloy is determined about uniaxial compression process in the above range of Si content and the temperature range based on the above assumption.

[0084] <Embodiment>

[0085] The solid solution having body-centered cubic (BCC) structure as a material is formed by steps of hot rolling (heating temperature 1100° C×60 minutes and finish temperature higher than 850° C.) a 40 Kg ingot made by vacuum melting into 40 mm thick, cutting that into 320 mm length, hot rolling that (heating temperature 1100° C×60 minutes and finish temperature higher than 850° C.) into 20 mm thick, cutting into a plate of 20 mm thick, 140 mm wide, 290 mm length, and forming that into a cylindrical steel piece with round cross-section of 12 mm diameter and 18 mm height by electro-discharge machining.

[0086] The ingots A, B, C and D are formed to have Si of 1.5, 3, 4, and 5 weight %; Mn and P less than 0.01 weight %, and S less than 0.01 weight % as unavoidable impurities. The four materials A, B, C and D include C, Al and N of weight % shown in Table 1 as unavoidable impurities other than Mn, P and S by knowing a content by composition analysis after process shown in Table 1.

TABLE 1

	C	Si	Mn	P	S	Al	N
A	0.0012	1.56	<0.01	<0.01	<0.0001	0.037	0.0009
B	0.0014	3.00	<0.01	<0.01	<0.0001	0.036	0.001
C	0.0013	3.95	<0.01	<0.01	<0.0001	0.037	0.0009
D	0.0018	4.86	<0.01	<0.01	<0.0001	0.036	0.0009

[0087] Each of the above content steel pieces heated at 900° C. or 1250° C. in a heat furnace is formed into a steel piece with **20** mm diameter and **6.6** mm height at strain rate range between 1×10^{-5}–5×10^{-2}/s to have true strain of −1.0% by uniaxial compression process, and the steel piece is cooled gradually in room temperature air.

[0088] Cross-head speed constant function of a tension tester having load capacity of 2 ton shown in FIG. **7** (Shimazu Autograpgh as trademark) is used for uniaxial compression process. For compression process by the tension tester, a cylindrical compression jig is arranged upside and downside the tester, and the steel piece is provided between the compression jigs, and load is applied from upside and downside. For maintaining constant temperature during compression process, the upper and lower jigs and the steel piece are arranged in the heat furnace. In FIG. **7**, the heater is illustrated as a heater.

[0089] An electrical steel sheet manufactured from the above material B selected from the above steel pieces, which includes Si content 3 weight % and is processed by strain rate 5.0×10^{-5}/s in the temperature 900° C., is divided into a disk-shape measurement sample having 20 mm diameter and 3.3 mm height as a half height. A divided surface is polished and measured about distribution of orientation of crystal by Schulz Reflection Method as X-ray diffraction analysis, and thereby, crystal Orientation Distribution Function (ODF) is given. Physically, {100} pole figure, {110} pole figure and {211} pole figure are drawn by data measured respectively by Schulz Reflection Method, and then, the crystal Orientation Distribution Function (ODF) showing three dimensional crystal orientation distribution is calculated by a computer.

[0090] FIG. **1** is a $\phi_2=0^\circ$ section view of ODF given by computer calculation for describing three pole figures with no discrepancies. In FIG. **1**, Φ, ϕ_1, ϕ_2 are Euler angles. Contour lines along an upper side and a lower side of a quadrangle show a distribution of the crystal orientation density in the surface of steel sheet. A value of the contour line shows orientation density indicated by a multiple about an average value as 1. In FIG. **1**, the contour lines of value **18**, **16**, **14**, **12**, **10**, **8**, **6**, **4** are drawn in order between the contour line of value **20** and the contour line of value **1**. At a line of $\Phi=0^\circ$ as a top area in FIG. **1**, concentration over value **14** is found even at a lowest area. High density {100} fiber texture is formed therein. The value is an excellent value much more than a value of usual non-oriented electrical steel sheet shown in FIG. **2**.

[0091] FIG. **2** is a view of $\phi2=0^\circ$ section of popular one of usual non-oriented electrical steel sheet made by prior art. In FIG. **2**, orientation density along an upper side is between 0.5-2.0, so that it can be found that there is almost no texture.

[0092] In the embodiment, crystal orientation distribution of the material before processing is not described. By increasing amount of strain for any material in any condition before processing, the {100} fiber texture, in which {100} is arranged in parallel to the work surface, is formed by hot compression process. Any steel material having the same crystal orientation distribution as the usual non-oriented electrical steel sheet can be applied. The material in the above embodiment is formed into a round cross-section, but, the material can be a plate or cylinder having a rectangular or polygonal cross-section other than round shape. The surface processed by uniaxial compression process can have any shape other than a flat surface by the same reason.

[0093] The structure of the direction of easy magnetization in a motor which is main application of the electrical steel sheet will be physically described. A disk-shaped stator material is punched to cut off a central area and slits. Therefore, properties of poles **16** in FIG. **4** are important for a stator material.

[0094] FIG. **12** shows a model of BCC structure. The BCC structure has symmetry about Up-down and right-left. Axes [100], [010] and [001] shown in FIG. **12** are equivalent, and general term for the three axes is shown by <001>. All surfaces of a cubic are equivalent and surfaces {001}, {100} and {010} are the same.

[0095] The directions of easy magnetization of the usual non-oriented electrical steel sheet for a stator of a motor are shown in FIG. **13**A. In the usual electrical steel sheet, directions of easy magnetization direct at any angle three-dimensionally. In FIG. **13**B, directions of easy magnetization in an almost ideal electrical steel sheet are shown.

[0096] Distribution of directions of easy magnetization <001> by {100} pole figure is shown in FIGS. **14**A and **14**B. FIG. **14**A shows distribution of <001> of the usual non-oriented electrical steel sheet. FIG. **14**B shows distribution of <001> of the electrical steel sheet according to the present invention. Values in the figures show concentration ratio of orientation density <001> about average value 1.

[0097] In the usual non-oriented electrical steel sheet, the smallest value at an outer area much affecting the properties is not larger than 0.8 times of an average value. In contrast, in the pole figure of the electrical steel sheet shown in FIG. **14**B according to the present invention, the smallest value at the outer area is not less than 1.6 multiple of the average value, and the value at central area is more than 19 multiple of the average value. Thus, <001> density at the outer area becomes larger than that of usual material by prior art.

[0098] FIG. **15** shows a magnetic property of the electrical steel sheet according to the present invention. A magnetic property of usual non-oriented electrical steel sheet is shown with a dot line in FIG. **15**, and a magnetic property of the electrical steel sheet according to the present invention is shown with a solid line in FIG. **15**. Undoubtedly, according to the present invention, larger magnetic flux density about added magnetic field is generated, so that it is expected that properties of an electromagnetic device such as a motor can be improved.

[0099] In the embodiment, example of processing single material by uniaxial compression process is shown. For mass production, sheets by overlapping various materials can be simultaneously processed by compression process by a compression machine having larger load capacity. Also, sizes of material can be increased.

[0100] When the above process condition is fulfilled, distribution of {100} in parallel to the steel sheet can be resulted also by the plane strain compression process shown in FIGS. **8**A-**8**D as a method of compression process.

[0101] For mass production, the rolling process shown in FIG. **9** can be applied. According to one-direction rolling shown in FIG. **9**, crystal plane {100} grows in parallel to roll surface, so that the sheet, in which many crystal axes <001> are distributed along rolling direction, can be given. According to multi-directions rolling shown in FIG. **10**, many crystal axes <001> are distributed in many directions in the surface of sheet. Thus, the same effects of uniaxial compression process can be give.

[0102] A wire-shaped metal material can be formed by passing a row material through a die as shown in FIG. **11** under heat condition. <001> of the material are aligned along a drawing direction, so that when magnetic flux flows along the drawing direction, good magnetic property can be given.

[0103] By increasing amount of strain, a thinner electrical steel sheet can be formed. Magnetic properties of the electrical steel sheet formed as mentioned above become further better. The process is operated in high temperature, so that the amount of lattice defect remained after process is small, and non-oriented electrical steel sheet, in which amount of lattice defect is more reduced, can be given by adding short time anneal after the process.

[0104] In the embodiment, Fe-Si alloy as electromagnetic material is exampled. The present invention can applied to all metallic material which can be processed in condition of body-centered. cubic (BCC) structure by hot compression process. According to the present invention, a metallic material, in which {100} grows in parallel to a work surface by hot compression process, can be formed.

Industrial Applicability

[0105] According to the present invention, a method of manufacturing process for a metallic material such as an electromagnetic material, in which orientation of crystal axis is controlled, is determinated, so that an electromagnetic material having good properties is provided, and energy loss of electromagnetic act is increased, and cost down can be performed and support environmental problems.

Remarks

[0106] **10** Stator of a motor
[0107] **12** Yoke
[0108] **14** Slot
[0109] **16** Pole
[0110] **18** Coil
[0111] **20** Rotor of a motor
[0112] **31** Core
[0113] **32** Coil
[0114] **33** Magnetic lines of force

1. A method of manufacturing a metallic material as a solid solution having body-centered cubic (BCC) structure, comprising steps of:

heating the metallic material in a temperature range to be single phase solid solution; and

distributing crystal axes <001> of the metallic material along a work surface of the metallic material by hot compression process in the temperature range.

2. A method of manufacturing Fe-Si alloy as a metallic material, comprising steps of:

heating the Fe-Si alloy in a temperature range to be single phase solid solution having body-centered cubic (BCC) structure; and

applying compression process on the solid solution having body-centered cubic (BCC) structure with a strain rate able to maintain process condition in which solute atmosphere generated in the single phase solid solution having body-centered cubic (BCC) structure can control motion of dislocation and grain boundary can move by strain energy stored in a crystal grain as driving force so as to distribute crystal plane {100} in parallel to a work surface of manufacturing process.

3. The method of manufacturing a metallic material according to claim **1**, wherein Fe-Si alloy is used as the solid solution having the body-centered cubic (BCC) structure; and compression process with strain rate from 1×10^{-5}/s to 1×10^{-1}/s is applied to the Fe-Si alloy heated in the temperature range to become single phase solid solution.

4. The method of manufacturing a metallic material according to claim **3**, wherein the temperature range is between 800-1300° C.

5. The method of manufacturing a metallic material according to claim **4**, wherein a total amount of strain of at least −0.5 is generated at the single phase solid solution having the body-centered cubic (BCC) structure by the compression process.

6. A metallic material as a solid solution having the body-centered cubic (BCC) structure, wherein crystal axes <001> are distributed along a work surface of manufacturing process by hot compression process.

7. The metallic material according to claim **6**, wherein the solid solution having the body-centered cubic (BCC) structure has 14 times or more orientation density on a line of $\Phi=0°$ at $\phi_2=0°$ section of crystal Orientation Distribution Function (ODF) indicating a distribution of the crystal axes <001> along the work surface of manufacturing process against an average value 1 of the orientation density.

8. The metallic material according to claim **6**, wherein Fe-Si alloy is used as the solid solution having the body-centered cubic (BCC) structure.

9. The method of manufacturing a metallic material according to claim **2**, wherein Fe-Si alloy is used as the solid solution having the body-centered cubic (BCC) structure; and compression process with strain rate from 1×10^{-5}/s to 1×10^{-1}/s is applied to the Fe-Si alloy heated in the temperature range to become single phase solid solution.

10. The method of manufacturing a metallic material according to claim **9**, wherein the temperature range is between 800-1300° C.

11. The method of manufacturing a metallic material according to claim **10**, wherein a total amount of strain of at least −0.5 is generated at the single phase solid solution having the body-centered cubic (BCC) structure by the compression process.

12. The metallic material according to claim **7**, wherein Fe-Si alloy is used as the solid solution having the body-centered cubic (BCC) structure.

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