(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 2 610 355 B1

(12) **EUROPEAN PATENT SPECIFICATION**

(45) Date of publication and mention of the grant of the patent:
10.11.2021 Bulletin 2021/45

(21) Application number: **11820051.8**

(22) Date of filing: **26.08.2011**

(51) Int Cl.:
C21D 9/00 (2006.01) *C21D 1/09* (2006.01)
C22C 38/00 (2006.01) *C22C 38/04* (2006.01)
C21D 1/02 (2006.01) *C21D 1/18* (2006.01)

(86) International application number:
PCT/JP2011/069324

(87) International publication number:
WO 2012/026591 (01.03.2012 Gazette 2012/09)

(54) **METHOD FOR HEAT-TREATING STRUCTURAL MATERIAL AND HEAT-TREATED STRUCTURAL MATERIAL**

VERFAHREN ZUR WÄRMEBEHANDLUNG EINES STRUKTURMATERIALS UND WÄRMEBEHANDELTES STRUKTURMATERIAL

PROCÉDÉ POUR LE TRAITEMENT THERMIQUE D'UN MATÉRIAU DE STRUCTURE ET MATÉRIAU DE STRUCTURE TRAITÉ THERMIQUEMENT

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR

(30) Priority: **27.08.2010 JP 2010190741**

(43) Date of publication of application:
03.07.2013 Bulletin 2013/27

(73) Proprietor: **Nippon Steel Corporation**
Tokyo (JP)

(72) Inventors:
- **KUWAYAMA Takuya**
  Tokyo 100-8071 (JP)
- **SUZUKI Noriyuki**
  Tokyo 100-8071 (JP)
- **MIYAZAKI Yasunobu**
  Tokyo 100-8071 (JP)
- **KAWASAKI Kaoru**
  Tokyo 100-8071 (JP)
- **YONEMURA Shigeru**
  Tokyo 100-8071 (JP)

(74) Representative: **Vossius & Partner**
Patentanwälte Rechtsanwälte mbB
Siebertstrasse 3
81675 München (DE)

(56) References cited:
DE-A1-102007 024 797
FR-A1- 2 849 059
JP-A- 7 119 892
JP-A- H07 119 892
JP-A- 2004 114 912
JP-A- 2004 114 912
JP-A- 2007 062 733
JP-A- 2009 286 351
US-A1- 2004 201 256

- **None**

Printed by Jouve, 75001 PARIS (FR)

Description

[0001] The present invention relates to a heat treatment method of a structural material and a heat-treated structural material.

[0002] As structural materials of a vehicle and the like, pipe-like press-formed products having polygonal cross-sections have been widely used. Such structural materials are mainly classified into two categories for use. In one category, there are structures that are used to construct, for example, an engine compartment or a trunk compartment and are structures which operate to be crushed when a vehicle or the like crashes and absorb impact energy. In the other category, there are structures that are used to construct, for example, a cabin and the like and are structures of which deformation is suppressed in terms of ensuring a survival space of an occupant when a vehicle or the like crashes.

[0003] In such structural materials, in order to both absorb impact energy and suppress deformation during the crash, it is necessary to increase the strength of the structural material, and there is a method of increasing the cross-sectional dimensions and the thickness of the structural material. However, this case is connected to an increase in the volume or the weight of the structural material. Therefore, not only a decrease in fuel efficiency but also an increase in damage to a counter vehicle during the crash of vehicles is caused.

[0004] On the other hand, as a method of increasing the strength of the structural material without increasing the cross-sectional dimensions or the thickness of the structural material, various methods of partially performing a laser heat treatment on a structural material such as a press-formed product have been proposed (for example, JP 61-99629 A, JP H4-72010 A, JP H6-73439 A and JP 2004-108541 A). Here, the laser heat treatment refers to irradiating an untreated structural material with a laser beam with a high energy density to locally heat the structural material to a temperature higher than or equal to a transformation temperature or a melting point, and causing the structural material to be subjected to quench hardening by a self-cooling operation.

[0005] For example, in JP 61-99629 A, a method of performing a local heat treatment on a press-formed product by a laser to achieve an increase in the strength of the press-formed product is disclosed. Specifically, in JP 61-99629 A, after cold-forming a steel sheet, the steel sheet is rapidly heated at a temperature of higher than or equal to a predetermined temperature with a laser beam in a streak shape or a grid form and is thereafter cooled, thereby strengthening the cold-formed press-formed product. By employing such a method, the generation of strain after the heat treatment is suppressed compared to a case where the entire press-formed product is uniformly heat-treated. Particularly, in the method disclosed in JP 61-99629 A, a laser heat treatment is performed on the outer surface of a press-formed product in a streak shape in the longitudinal direction or on the entire outer surface of a press-formed product in a grid form.

[0006] In addition, even in the method disclosed in JP H4-72010 A, performing a local heat treatment on a press-formed product for the purpose of increasing the strength of the press-formed body while suppressing the generation of strain is disclosed. Particularly, in the method disclosed in JP H4-72010 A, a site of the press-formed product which requires strength, for example, a high stress portion analyzed by, for example, a vehicle crash test or a finite element method is subjected to the heat treatment. Specifically, a laser heat treatment is performed in a stripe shape or a grid form so as to extend over the entire length in the longitudinal direction of the press-formed product.

[0007] Moreover, in JP H6-73439 A, a method of controlling components contained in a steel sheet to be subjected to a laser heat treatment to specific components and then performing the laser heat treatment thereon is disclosed, and accordingly the strength of spots subjected to the laser heat treatment is enhanced while maintaining the workability of the steel sheet. Even in the method disclosed in JP H6-73439 A, spots of which the strength needs to be increased are subjected to the laser heat treatment. Specifically, the laser heat treatment is performed in a linear form extending over the entire length in the longitudinal direction of the press-formed product.

[0008] In JP 2004-108541 A, for the purpose of enhancing the ability to absorb the impact energy of the press-formed product, a method of performing a laser heat treatment in a line form along the load direction of a compressive load on the outer peripheral surface of the press-formed product is disclosed. According to this method, since the laser heat treatment is performed in the same direction as the input direction of an impact load, a resistance against deformation can be increased, and a regular crushing mode may be achieved. Particularly, in the method disclosed in JP 2004-108541 A, the laser heat treatment is continuously performed over the entire length in the longitudinal direction of the press-formed product along the load direction of the compressive load.

[0009] In any case, in any of the methods disclosed in JP 61-99629 A, JP H4-72010 A, JP H6-73439 A and JP 2004-108541 A, a laser heat treatment is performed on a part of the outer surface of the press-formed product, which requires strength. Specifically, the laser heat treatment is performed in the line form that continuously extends over the entire length in the longitudinal direction of the press-formed product, or the laser heat treatment is performed in the grid form over the entire outer surface of the press-formed product.

[0010] JP H07-119892 A discloses a high strength member, in which, in an effective width (a) from the tops of the corners K to both sides H of a high strength member, a heat treatment is applied locally.

[0011] JP 2004-114912 A discloses a formed member having excellent axial crush resistant characteristic, which has member corner parts which pass a central part in the direction of width of a member upper face and form a pair relative to a vertical face on an upper face and a plurality of sets of quenched hardened regions composed of each of a part of an upper face and a side face nipping the corner parts intermittently in the longitudinal direction of the member.

[0012] FR 2849059 A1 discloses a localized heat treatment of pressed metal components comprising induction heating to austenite temperature and brutal cooling, e.g. for motor vehicle components.

[0013] FIG 1 schematically illustrates the relationship between, when a cylindrical structural material receives a compressive load in the axial line direction (x direction) thereof, the compressive stress in the axial line direction σ_x and the compressive strain ε_x (the amount of deformation in the longitudinal direction with respect to the length in the longitudinal direction of the cylindrical structural material). Here, σ_1, σ_2, and σ_3 in the figure represent peak stresses, and an area shown by oblique lines W represents the amount of energy absorbed by the structural material. Particularly, σ_1 represents the initial peak stress.

[0014] Here, as the structural materials used in a vehicle and the like as described above, there are structural materials that absorb impact energy during a crash (hereinafter, referred to as "structural materials for impact absorption") and structural materials that suppress the deformation thereof during a crash (hereinafter, referred to as structural materials for deformation suppression). The structural materials for impact absorption thereof require as high as possible an absorption energy amount W and require a relatively low initial peak stress σ_1.

[0015] On the other hand, the structural materials for deformation suppression require as high as possible an initial peak stress σ_1 unlike the structural materials for impact absorption. This is because when the initial peak stress σ_1 is increased, it is difficult for the structural materials to buckle even though a high stress is applied to the structural material. Therefore, it is necessary to perform a laser heat treatment on the structural materials for deformation suppression so as to increase the initial peak stress σ_1.

[0016] However, in the methods disclosed in JP 61-99629 A, JP H4-72010 A, JP H6-73439 A and JP 2004-108541 A described above, since the laser heat treatment is performed with no consideration of the initial peak stress (σ_1 at all, and thus it is difficult to say that the ability of the structural material to suppress deformation can be sufficiently increased.

[0017] In consideration of the problems, an object of the present invention is to provide a structural material which can sufficiently increase an ability to suppress deformation by performing a heat treatment on appropriate spots of an untreated structural material and thus locally hardening the structural material.

[0018] The inventors have examined, regarding a structural material having at least one bent portion which extends in one direction (for example, longitudinal direction), the relationship between an area (spot or amount) of an untreated structural material on which a heat treatment is performed, and an ability of a structural material after the heat treatment to suppress deformation, particularly, an initial peak stress.

[0019] As a result, it was found that by appropriately controlling the ratio of a hardened area that is hardened by the heat treatment in an effective width area of which the distance in the width direction from each bent portion is within an effective width, the ability of the structural material to suppress deformation, particularly the initial peak stress may be enhanced.

[0020] The invention has been made on the basis of this knowledge, and the above object can be achieved by the present invention, which is defined in the claims.

[0021] According to the present invention, compared to the conventional technique in which a heat treatment is performed on arbitrary spots in an untreated structural material to locally harden the structural material and thus an ability of the structural material to suppress deformation is enhanced, the value of an elastic-plastic buckling stress $\sigma_{p,Cr}$ corresponding to an initial peak stress σ_1 of buckling can be obtained, and the volume fraction of a hardened area in an effective width area in which the elastic-plastic buckling stress $\sigma_{p,Cr}$ is maximized can be appropriately determined. Accordingly, in a structural material for deformation suppression, a guideline for appropriate deformation suppression can be provided.

[0022] In addition, according to the present invention, the cost of a heat treatment needed to enhance the ability of the structural material to suppress deformation can be optimized (reduced).

[0023] In addition, according to the present invention, by measuring the characteristics of a steel material using specimens, the volume fraction of the hardened area in the effective width can be appropriately determined from the characteristics values of the specimens without evaluating a structure. In particular, in the case of (2) described above, the volume fraction of the hardened area in the effective width can be appropriately determined using as low a number of evaluations of the specimens as possible.

[0024] The invention is described in detail in conjunction with the drawings, in which:

FIG. 1 is a diagram schematically illustrating the relationship between, when a cylindrical structural material receives a compressive load in the axial line direction thereof, the compressive stress in the axial line direction and the compressive strain,

FIG. 2 is a perspective view illustrating an example of a structural material not forming part of the present invention, to which a heat treatment method of a structural material is applied,

FIG. 3 is a transverse sectional view of the structural material illustrated in FIG. 2,

FIG 4A is a transverse sectional view of a structural material not forming part of the present invention,
FIG. 4B is a transverse sectional view of a structural material not forming part of the present invention,
FIG. 4C is a transverse sectional view of a structural material not falling under the present invention,
FIG. 5 is a perspective view of a structural material of another example.
FIG 6A is a diagram for explaining effective width,
FIG. 6B is a diagram for explaining effective width,
FIG. 7 is a true stress-plastic strain curve of a steel sheet,
FIG 8 is a true stress-true strain curve of a steel sheet,
FIG 9A is a true stress-true strain curve of a steel sheet,
FIG. 9B is a true stress-true strain curve of a steel sheet,
FIG. 10 is a diagram showing the relationship between the volume fraction of a hardened area, the proof stress of a steel sheet, and the yield stress,
FIG. 11 is a diagram showing the relationship between the volume fraction of a hardened area, the proof stress of a steel sheet, and the yield stress,
FIG. 12 is a diagram showing the relationship between the volume fraction of a hardened area and a work-hardening coefficient,
FIG. 13A is a diagram illustrating a manufacturing process of a structural material assembly used in Examples,
FIG. 13B is a diagram illustrating the manufacturing process of a structural material assembly used in Examples,
FIG. 13C is a diagram illustrating the manufacturing process of a structural material assembly used in Examples,
FIG. 14 is a side view of the structural material assembly used in Examples,
FIG. 15 is a flowchart of the heat treatment method of a structural material according to the embodiment,
FIG. 16 is a flowchart showing an example of a method of determining the range of the volume fraction of the hardened area (hardening ratio) f_M in the heat treatment method of a structural material according to the embodiment,
FIG. 17 is a flowchart showing an example of the method of determining the range of the volume fraction of the hardened area (hardening ratio) f_M in the heat treatment method of a structural material according to the embodiment, and
FIG. 18 is a flowchart showing an example of the method of determining the range of the volume fraction of the hardened area (hardening ratio) f_M in the heat treatment method of a structural material according to the embodiment.

[0025] Hereinafter, the present invention will be described in detail with reference to the drawings. In addition, in the following description, like elements are denoted by like reference symbols.

[0026] Hereinafter, a heat treatment method of a structural material according the present invention will be described. In the heat treatment method of a structural material according to the invention, Z a heat treatment is performed on a structural material having a bent portion which extends in one direction of the structural material and has a bend in a direction perpendicular to the extending direction, and a hat-shaped cross-section including five flat portions which are arranged so that the cross-section thereof has a hat shape as illustrated in figure 14. In the heat treatment, a predetermined ratio (that is, a part corresponding to a hardening ratio) of an area in the structural material, including the bent portion of which the distance in the direction perpendicular to the extending direction of the bent portion is within an effective width (that is, an effective width area) is hardened.

[0027] As described later, the rate of change in yield stress (yield strength) with respect to a ratio of the area in the effective width area, which is hardened by the heat treatment, (that is, the hardening ratio) varies depending on the hardening ratio, and the amount of change (a degree of change) of the rate of change in yield stress is greater than the amount of change (a degree of change) of the rate of change in flow stress with respect to the hardening ratio. Therefore, the work-hardening ratio of the effective width area needed to increase the initial peak stress of the structural material (an ability to suppress deformation) is influenced by the rate of change in the yield stress with respect to the hardening ratio. Consequently, by performing the heat treatment on the effective width area that mainly receives a load exerted on the structural material so as to satisfy a range of the hardening ratio determined on the basis of the rate of change in the yield stress with respect to the hardening ratio, the ability of the structural material to suppress deformation can be enhanced while reducing cost of the heat treatment.

[0028] The flow stress which is defined as the proof stress which is when 5% plastic strain occurs, is a stress that occurs at a time point at which a transition to flow deformation occurs by exceeding the elastic limit and after the time point. In addition, there may be cases where the hardening ratio is described as a volume fraction.

[0029] In the heat treatment method of a structural material according to the invention, as shown in FIG. 15, necessary data is input (used) (S1), the effective width for the bent portion is determined (S2), the range of the hardening ratio is determined on the basis of the rate of change in the yield stress with respect to the hardening ratio (S3), and the heat treatment is performed on the effective width area of the structural material so as to satisfy the range of the hardening ratio (S4). Here, the effective width can be determined, as described later, from various expressions derived from a definition expression for the effective width, Expression (14). In addition, the range of the hardening ratio is determined using the rate of change in the yield stress with respect to at least one hardening ratio. For example, the rate of change in the yield stress with respect to a predetermined hardening ratio can be determined from a predetermined correlation (for example, an expression) as a parameter. In addition, for example, the range of the hardening ratio can be determined on the basis of the hardening ratio when the rate of change in the yield stress with respect to the hardening ratio satisfies a predetermined condition.

[0030] Hereinafter, the heat treatment method of a structural material according to the invention will be described in more detail.

[0031] FIG. 2 is a perspective view illustrating an example of the structural material to which the heat treatment method of a structural material is applied. In addition, FIG. 3 is a cross-sectional view of a structural material in a cross-section perpendicular to the longitudinal direction of the structural material illustrated in FIG. 2. As illustrated in FIG. 2, the structural material 10 includes flat portions 11 (11a to 11e) having flat sheet shapes extending in the longitudinal direction thereof and a plurality of bent portions 12 (12a to 12d) extending in the longitudinal direction between the flat portions 11. That is, as illustrated in FIG. 3, the structural material 10 includes five flat portions 11a to 11e and four bent portions 12a to 12d provided between the flat portions 11a to 11e.

[0032] The structural material 10 is used as a part of the frame of a vehicle such as a car and is particularly used at a spot of which deformation needs to be suppressed when a car or the like crashes. Therefore, for example, when the frame of a vehicle is exemplified, it is preferable that the structural material 10 be used as a frame that is used to construct a cabin or the like.

[0033] Particularly, in a case where the structural material 10 is used as a part of the frame of a vehicle such as a car, as shown by dot-dashed lines of FIGS. 2 and 3, a member made by welding and joining the structural material 10 to a structural material 20 having a different flat sheet shape is used. Therefore, the flat portions 11a and 11e provided at both edge portions of the structural material 10 from among the five flat portions 11a to 11e of the structural material 10 are formed in flange shapes. When the structural material 10 is welded to the different structural material 20, the flat portions 11a and 11e are welded to the different structural material 20.

[0034] In addition, in the examples illustrated in FIGS. 2 and 3, which do not form part of the present invention, the structural material 10 has the five flat portions 11a to 11e and the four bent portions 12a to 12d provided between the flat portions 11a to 11e. In examples, not forming part of the present invention, the structural material may have any shape as long as at least one bent portion which extends in one direction thereof (for example, longitudinal direction) and has a bend in a direction perpendicular to the extending direction is provided, and for example, may have cross-sectional shapes as illustrated in FIGS. 4A to 4C.

[0035] In the example shown in FIG. 4A, a structural material 10' includes four flat portions 11 and three bent portions 12 provided between the flat portions 11, and the flat portions 11 positioned at both ends in the cross-sectional shape thereof function as flanges for joining the structural material 10' to a structural material (not shown) having a different flat sheet shape. In the example shown in FIG. 4B, a structural material 10" includes five flat portions 11 and four bent portions 12 provided between the flat portions 11, and the flat portions 11 positioned at both ends in the cross-sectional shape thereof function as flanges for joining the structural material 10" to a structural material (not shown) having a different flat sheet shape. In the example shown in FIG. 4C, a structural material 10'" includes four flat portions 11 and four bent portions 12 provided between the flat portions 11 so as to have a quadrangular cross-section.

[0036] In addition, the structural material 10 may not extend linearly in the longitudinal direction, and for example, may be curved or bent as illustrated in FIG. 5. In a case where the structural material 10 is curved or bent, the direction along the curving and bending is referred to as the longitudinal direction. Therefore, in the example illustrated in FIG. 5, the dot-dashed line Z in the figure represents the longitudinal direction of the structural material 10. In addition, the flat portion means a part of the structural material of which the cross-section has a linear shape (band shape). In addition, the bent portion means a part of the structural material having a line shape formed by intersection in the extending directions of two flat portions adjacent to each other in the cross-section of the structural material. Therefore, like flat portions 11a to 11e and bent portions 12a to 12d illustrated in FIG. 5, cases where flat portions and bent portions are curved or bent in the longitudinal direction of a structural material are respectively included in flat portions and bent portions.

[0037] In the heat treatment method of a structural material according to this embodiment, a heat treatment (here, a laser heat treatment as an example) is performed on a specific site of the untreated structural material 10 formed in the shape as described above. As means for the laser heat treatment, a laser heat treatment device using a carbon dioxide laser, a YAG laser, a fiber laser, or the like is used. In addition, with respect to the depth in the sheet thickness direction of an area to be hardened by the laser heat treatment, the area is hardened into a depth of 10% or more of the sheet thickness from the surface irradiated with a laser light. In addition, it is preferable that the depth in the sheet thickness direction of the area to be hardened by the laser heat treatment be controlled to be less than 90% of the sheet thickness from the surface irradiated with the laser light. Hereinafter, a site on which the laser heat treatment is performed will be described.

[0038] When a thin sheet buckles under the compressive load, the stress exerted on the thin sheet is non-uniformly distributed in the cross-section (sheet width direction) of the thin sheet which is perpendicular to the exertion direction of the compressive load. For example, when a thin sheet having a width w as illustrated in FIG. 6A receives a compressive load as shown by arrows and out-of-plane deformation occurs in the thin sheet due to elastic buckling, a stress σ_x in the longitudinal direction (x direction) exerted on the cross-section a thereof is distributed as shown in FIG. 6B. As shown in FIG. 6B, since the stress exerted on the end portions in the width direction (y direction, that is, w direction) of the thin sheet is maximized, thus plastic bulking is more likely to occur from the end portions in the width direction of the thin sheet. Therefore, in an initial stage of buckling (for example, in the case of the structural material, corresponding to deformation until reaching an initial peak stress), it may be thought that parts having a predetermined width from the end surface in the width direction of the thin sheet receive the compressive load. Therefore, it is assumed that the same stress as the stress σ_{max} exerted on the end portions in the width direction of the thin sheet (in the structural material, corresponding to σ_{Y0} described later) is uniformly distributed in the virtual parts having widths 2×e as shown by the broken lines of FIG. 6B and the virtual parts having the widths 2×e receive the total load. The width e is called an effective width, and the effective width e is defined by the following Expression (14), that is, Expression (15).

[Formula 14]

$$\int_0^w \sigma_x dw = 2e\sigma_{max} \quad ...(14)$$

[Formula 15]

$$e = \frac{1}{2\sigma_{Y0}} \int_0^w \sigma_x dw \quad ...(15)$$

[0039] The effective width e is expressed by the following Expression (16) using the elastic modulus E, the Poisson's ratio v, and the thickness t of the thin sheet, and in particular, the effective width e may be expressed by Expression (17) when the yield stress σ_{Y0} of the thin sheet is uniformly distributed.

[Formula 16]

$$e = \frac{\pi t}{\sqrt{12(1-\nu^2)}} \sqrt{\frac{E}{\sigma_{max}}} \quad ...(16)$$

[Formula 17]

$$e = \frac{\pi t}{\sqrt{12(1-\nu^2)}} \sqrt{\frac{E}{\sigma_{Y0}}} \quad ...(17)$$

[0040] In addition, the effective width e expressed by the above Expressions (16) and (17) are theoretical values, and it is demonstrated that when the theoretical values are used, experimental results are significantly different from the yield phenomenon depending on the conditions. Therefore, in consideration of the theoretical results, the effective width e is defined by, for example, the following Expressions (18A) and (19). In addition, in Expression (19), λ is a slenderness factor and is determined as in Expression (20) in the case where the yield stress σ_{Y0} of the thin sheet is uniformly distributed in the parts having the effective width e. In Expression (20), k means a flat sheet buckling coefficient.

[Formula 18A]

$$e = \frac{\sigma w}{2} \quad ...(18A)$$

[Formula 19]

$$\sigma=\frac{1}{\lambda}\left(1-\frac{0.22}{\lambda}\right)\leq 1 \quad ...(19)$$

[Formula 20]

$$\lambda=\frac{1.052}{\sqrt{k}}\left(\frac{w}{t}\right)\sqrt{\frac{\sigma_{Y0}}{E}} \quad ...(20)$$

[0041] In addition, regarding the definition of the effective width e, as in the following Expression (18B), there are various definitions besides the above Expression (18A). In the heat treatment method of a structural material according to this embodiment, any definition from among the various definitions may be used. In addition, a stress distribution in the width direction of the thin sheet when the thin sheet buckles under the compressive load (that is, the stress distribution as shown in FIG. 6B) is calculated by a numerical analysis (for example, a numerical integral such as the finite element method), and from the stress distribution calculated as described above, the effective width e that satisfies the above Expression (14) may be calculated.

[Formula 18B]

$$e=\frac{t}{2}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1.90-\frac{t}{w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad ...(18B)$$

[0042] In consideration of the effective width e as described above, even in the structural material 10 illustrated in FIG. 2 and the like, the area in each of the flat portions 11 that mainly receives the compressive load is an area of which the distance in the width direction from the bent portion 12 (that is, a direction perpendicular to the longitudinal direction of the structural material 10) is within the effective width e. Hereinafter, such an area, that is, the area having a bent portion of which the distance in the width direction from a certain bent portion is within the effective width e is referred to as an effective width area. The effective width areas (effective width areas 15 in FIGS. 2 and 3) are shown by oblique lines in FIG. 2 and the entirety thereof is shaded in FIG. 3.

[0043] As such, in the heat treatment method of a structural material, the effective width of an untreated structural material having at least one bent portion as illustrated as the bent portions 12 (12a to 12d) of FIG. 3 (bent portions of a structural material) is determined.

[0044] In the heat treatment method of a structural material according to the invention, a heat treatment (here, a laser heat treatment as an example) is performed on a part of the effective width area determined as described above. Hereinafter, the ratio of the area on which the laser heat treatment to the effective width area is performed will be described.

[0045] FIG. 7 shows a true stress-true plastic strain curve of a steel sheet in a grade of a tensile strength of 440 MPa. By using the linear hardening law, as shown in FIG. 7, as work-hardening characteristics immediately after the yield of the steel sheet having such stress-strain characteristics, the work-hardening coefficient E_h is expressed by the following Expression (21). In Expression (21), ε_p represents strain after the steel sheet yields (plastic strain), and σ_h represents stress when the plastic strain is ε_p. In addition, in FIG. 7 and FIGS. 9A and 9B described later, σ_h is described as a stress when the plastic strain ε_p is 1%. As shown in the figures, σ_h may be determined from the stress when the plastic strain ε_p is 1%.

[Formula 21]

$$E_h=\frac{\sigma_h-\sigma_Y}{\varepsilon_p} \quad ...(21)$$

[0046] Regarding the elastic-plastic buckling phenomenon of such a steel sheet, a theoretical expression that expresses the elastic-plastic buckling stress $\sigma_{p,Cr}$ as a function of the work-hardening coefficient E_h is proposed, and the elastic-plastic buckling stress $\sigma_{p,Cr}$ is expressed by, for example, the following Expression (22). In the following Expression (22), w is the width of the steel sheet, t is the thickness of the steel sheet, and k is the coefficient corresponding to the sheet shape or the like. As can be seen from Expression (22), the elastic-plastic buckling stress $\sigma_{p,Cr}$ increases in proportion to the work-hardening coefficient E_h.

[Formula 22]

$$\frac{\sigma_{p,Cr}}{E} = k\frac{\pi^2 t^2}{12(1-\nu^2)w^2}\left(\frac{E_h}{E}\right) \quad ...(22)$$

[0047] Here, from the idea that the initial peak stress σ_1 shown in FIG. 1 has the same tendency as the elastic-plastic buckling stress $\sigma_{p,Cr}$, it is thought that the initial peak stress σ_1 also increases in proportion to the work-hardening coefficient E_h. In addition, Expression (22) represents the elastic-plastic buckling stress $\sigma_{p,Cr}$ in a steel sheet as illustrated in FIG. 6A and does not represent the elastic-plastic buckling stress $\sigma_{p,Cr}$ regarding a structural material having a polygonal cross-section as illustrated in FIG. 3. However, when the cross-sectional shape of a structural material is made polygonal, the cross-sectional shape of the structural material becomes close to a cylindrical shape, and the elastic-plastic buckling stress $\sigma_{p,Cr}$ of a cylindrical shell can be expressed by the following Expression (23). In Expression (23), R is the diameter of a cylinder.

[Formula 23]

$$\frac{\sigma_{p,Cr}}{E} = \frac{t}{R\sqrt{3(1-\nu^2)}}\left(\frac{E_h}{E}\right) \quad ...(23)$$

[0048] As can be seen from Expression (23), even in the cylindrical shell, the elastic-plastic buckling stress $\sigma_{p,Cr}$ increases in proportion to the work-hardening coefficient E_h. Therefore, even in the cylindrical shell, it is thought that the initial peak stress σ_1 increases in proportion to the work-hardening coefficient E_h.

[0049] FIG. 8 shows true stress-true strain curves of an untreated steel sheet in a grade of a tensile strength of 440 MPa and the material of a steel sheet in a grade of a tensile strength of 440 MPa of which the entirety is subjected to a heat treatment (is quenched). The solid line of FIG. 8 represents the true stress-true strain curve of the untreated steel sheet, and the broken line represents the true stress-true strain curve of the steel sheet after the heat treatment.

[0050] Regarding the steel sheet after the heat treatment shown in FIG. 8, when the work-hardening coefficient E_h immediately after the yield is calculated by applying the linear hardening law as shown in Fig. 7, the work-hardening coefficient of the untreated steel sheet E_{h0} can be expressed by the following Expression (24) (see FIG. 9A). In Expression (24), σ_{Y0} represents the yield stress of the untreated steel sheet, ε_{Y0} represents the true strain of the untreated steel sheet at the yield stress, ε_{h0} represents a predetermined true strain greater than ε_{Y0}, and σ_{h0} represents the stress (corresponding to a flow stress described later) of the untreated steel sheet when the true strain is ε_{h0}. On the other hand, the work-hardening coefficient of the steel sheet after the heat treatment E_{hM} can be expressed by the following Expression (25) (see FIG. 9B). In Expression (25), σ_{YM} represents the yield stress of the steel sheet after the heat treatment, ε_{YM} represents the true strain of the steel sheet after the heat treatment at the yield stress, ε_{hM} represents a predetermined true strain greater than ε_{YM}, σ_{hM} represents the stress (corresponding to a flow stress described later) of the steel sheet after the heat treatment when the true strain is ε_{hM}.

[Formula 24]

$$E_{h0} = \frac{\sigma_{h0} - \sigma_{Y0}}{\varepsilon_p} = \frac{\sigma_{h0} - \sigma_{Y0}}{\varepsilon_{h0} - \varepsilon_{Y0}} \quad ...(24)$$

[Formula 25]

$$E_{hM} = \frac{\sigma_{hM} - \sigma_{YM}}{\varepsilon_p} = \frac{\sigma_{hM} - \sigma_{YM}}{\varepsilon_{hM} - \varepsilon_{YM}} \quad ...(25)$$

[0051] As can be seen from FIGS. 8, 9A, and 9B, when the heat treatment is performed on the entire steel sheet, the work-hardening coefficient of the steel sheet after the heat treatment E_{hM} is greater than the work-hardening coefficient of the steel sheet before the heat treatment E_{h0}. Therefore, in the case where the heat treatment is performed on the entire steel sheet, the steel sheet after the heat treatment has a greater initial peak stress σ_1 than that of the steel sheet before the heat treatment.

[0052] As such, it is found that between the untreated steel sheet and the steel sheet of which the entirety is subjected to the heat treatment, the steel sheet of which the entirety is subjected to the heat treatment has a greater initial peak stress σ_1. However, in a case where the heat treatment is partially performed on the steel sheet, the relationship between the ratio at which the heat treatment is performed on the steel sheet, that is, the ratio of an area which is hardened to a predetermined or higher hardness by the heat treatment (hereinafter, referred to as a hardened area) to the entire steel sheet and the initial peak stress is found to be unclear.

[0053] Here, the inventors obtained the following knowledge as a result of examining the relationship between the volume fraction f_M the work-hardening coefficient E_h of the steel sheet after the partial hardening, and the initial peak stress σ_1 when the volume fraction of the hardened area (hardening ratio) f_M with respect to the entire steel sheet is changed from 0 to 100%. Hereinafter, the obtained knowledge will be described in detail.

[0054] First, in the case where the volume fraction of the hardened area with respect to the entire steel sheet f_M is changed from 0 to 100%, it is thought that the proof stress σ_h of the steel sheet and the yield stress σ_Y thereof when 5% of plastic strain occurs change as shown in FIG. 10.

[0055] That is, as shown in FIG. 10, the proof stress σ_h of the steel sheet when 5% of plastic strain occurs may be approximated by a substantially straight line with respect to the volume fraction f_M. This is because when a certain degree of limited plastic strain is given to the entire steel sheet, substantially the same plastic strain is exerted on both the hardened area and the non-hardened area (an area of the steel sheet other than the hardened area, that is, an untreated area).

[0056] Therefore, the proof stress σ_h after giving 5% of plastic strain with respect to the volume fraction of the hardened area f_M is expressed by the following Expression (26) as a function of the volume fraction f_M.

[Formula 26]

$$\sigma_h(f_M)=f_M\sigma_{hM}+(1-f_M)\sigma_{h0}=(\sigma_{hM}-\sigma_{h0})f_M+\sigma_{h0} \quad ...(26)$$

[0057] As such, even though an approximation that the proof stress σ_h of the steel sheet is proportionate to the volume fraction of the hardened area f_M (the amount of change of the rate of change in the flow stress with respect to the hardening ratio is substantially 0) is performed, the relationship between the proof stress σ_h of the steel sheet and the volume fraction of the hardened area f_M can be sufficiently and accurately expressed.

[0058] On the other hand, as in FIG. 10, when the yield stress σ_Y is approximated by a convex downward curve (for example, a quadratic function) other than a straight line, the yield stress σ_Y is more accurately expressed using the volume fraction of the hardened area f_M. When the volume fraction of the hardened area f_M is small, the characteristics of the non-hardened area having a relatively small yield stress becomes dominant in the yield phenomenon, and the entire yield stress becomes close to the yield stress of the non-hardened area (see Expression (27)). On the other hand, when the volume fraction of the hardened area f_M increases by a certain degree, the influence of the characteristics of the hardened area increases when the yield phenomenon occurs. In particular, when the volume fraction of the hardened area f_M becomes 1, the entire yield stress becomes equal to the yield stress of the hardened area (see Expression (28)).

[Formula 27]

$$\lim_{f_M=0}\sigma_Y(f_M)\cong\sigma_{Y0} \quad ...(27)$$

[Formula 28]

$$\lim_{f_M=1}\sigma_Y(f_M)\cong\sigma_{YM} \quad ...(28)$$

[0059] Therefore, in the case where the yield stress σ_Y is approximated by the quadratic function of the volume fraction of the hardened area f_M, the yield stress σ_Y ($\sigma_Y(f_M)$) can be expressed by the following Expression (29) as a function of the volume fraction f_M. In addition, in Expression (29), a, b, and c are constants.

[Formula 29]

$$\sigma_Y(f_M) = a f_M^2 + b f_M + c \quad ...(29)$$

[0060] Here, when Expression (29) is differentiated once with respect to the volume fraction f_M and the volume fraction f_M is substituted by 0, the constant b of the above Expression (29) can be represented by the following Expression (30). That is, the constant b can be approximated by the gradient of the change in the yield stress $\sigma_Y(f_M)$ with respect to the volume fraction f_M when the volume fraction of the hardened area f_M is 0.
[Formula 30]

$$b = \left.\frac{\partial \sigma_Y}{\partial f_M}\right|_{f_M=0} \quad ...(30)$$

[0061] When Expressions (26) to (30) obtained as described above are substituted in Expression (21), the work-hardening coefficient E_h is expressed by a function of the volume fraction of the hardened area f_M, that is, the following Expression (31).
[Formula 31]

$$\begin{aligned} E_h(f_M) &= \frac{\sigma_h(f_M) - \sigma_Y(f_M)}{\varepsilon_p} \\ &= \frac{1}{\varepsilon_p}\left\{-(\sigma_{YM} - \sigma_{Y0} - b) f_M^2 + (\sigma_{hM} - \sigma_{h0} - b) f_M + \sigma_{h0} - \sigma_{Y0}\right\} \quad ...(31) \end{aligned}$$

[0062] Here, for example, assuming that the plastic strain ε_p is 0.05, the yield stress of the hardened area σ_{YM} is 794 MPa, the yield stress of the non-hardened area σ_{Y0} is 301 MPa, the proof stress σ_{hM} of the hardened area when the plastic strain ε_p is given is 1017 MPa, the proof stress σ_{h0} of the non-hardened area when the plastic strain ε_p is given is 447 MPa, and b is 350 MPa, $\sigma_h(f_M)$ calculated by Expression (26) and $\sigma_Y(f_M)$ calculated by Expression (29) can be expressed by FIG. 11. In addition, here, the work-hardening coefficient $E_h(f_M)$ calculated by Expression (31) can be expressed by FIG. 12.

[0063] For example, as can be seen from Expression (31), in a case where the yield stress σ_Y is approximated by a quadratic function (a convex downward function the volume fraction f_M in a range of 0 to 1) of the volume fraction of the hardened area f_M, the work-hardening coefficient $E_h(f_M)$ can also be expressed as a quadratic function (a convex upward function of the volume fraction f_M in a range of 0 to 1) of the volume fraction of the hardened area f_M. Accordingly, as can be seen from FIG. 12, the work-hardening coefficient $E_h(f_M)$ is maximized at a specific volume fraction $f_{M\text{-}max}$. Therefore, there may be cases where the work-hardening coefficient $E_h(f_M)$ is higher than the work-hardening coefficient which is when the volume fraction of the hardened area f_M is 1 (100%) depending on the volume fraction of the hardened area f_M. In the example shown in FIG. 12, when the volume fraction of the hardened area f_M is $f_{M\text{-}min}$ to 1, the work-hardening coefficient E_h is higher than or equal to the work-hardening coefficient E_h (f_M=1) which is when the volume fraction of the hardened area f_M is 1 (100%). In other words, in the example shown in FIG. 12, the initial peak stress when the volume fraction of the hardened area f_M is $f_{M\text{-}min}$ to 1 becomes higher than or equal to the initial peak stress which is when the volume fraction of the hardened area f_M is 1 (100%) (that is, when the heat treatment is performed on the entire effective width).

[0064] However, as described above, as the heat treatment for locally hardening a part of the steel sheet, for example, the laser heat treatment is used. In such a laser heat treatment, the amount of energy consumed increases as the treatment area increases, resulting in an increase in manufacturing cost. Accordingly, in terms of a reduction in manufacturing cost, it is preferable that an area on which the laser heat treatment be as narrow as possible.

[0065] Here, as described above, when the volume fraction of the hardened area f_M is higher than or equal to $f_{M\text{-}min}$, the work-hardening coefficient E_h can be increased to be higher than or equal to the work-hardening coefficient $E_h(f_M$=1) which is when the volume fraction of the hardened area f_M is 1 (100%). As a result, the initial peak stress can be increased to be higher than or equal to the initial peak stress which is when the volume fraction of the hardened area f_M is 1 (100%).

Here, it is preferable that the volume fraction of the hardened area f_M be controlled to be higher than or equal to the volume fraction $f_{M\text{-}min}$ (hereinafter, referred to as "minimum volume fraction") which is when the work-hardening coefficient $E_h(f_M=1)$ which is when the volume fraction of the hardened area f_M is 1 (100%) becomes equal to the work-hardening coefficient $E_h(f_M=f_{M\text{-}min})$ thereof.

[0066] In addition , according to the present invention, in the case where the yield stress σ_Y is approximated by a quadratic function of the volume fraction of the hardened area f_M, the minimum volume fraction $f_{M\text{-}min}$ is expressed by the following Expression (32). In Expression (32), $\Delta\sigma_h$ is the difference between σ_{hM} and σ_{h0} ($\Delta\sigma_h=\sigma_{hM}-\sigma_{h0}$), $\Delta\sigma_Y$ is the difference between σ_{YM} and σ_{Y0} ($\Delta\sigma_Y=\sigma_{YM}-\sigma_{Y0}$). In particular, in the case of the conditions as described above (that is, the case of the conditions shown in FIGS. 11 and 12), the minimum volume fraction $f_{M\text{-}min}$ is 53.3%. In addition, since the minimum volume fraction $f_{M\text{-}min}$ needs to satisfy $0<f_{M\text{-}min}<1$, the constants b and $\Delta\sigma_h$ also need to satisfy $0<b<2\Delta\sigma_Y-\Delta\sigma_h$ and $\Delta\sigma_Y<\Delta\sigma_h<2\Delta\sigma_Y$.

[Formula 32]

$$f_{M\text{-min}}=\frac{\Delta\sigma_h-\Delta\sigma_Y}{\Delta\sigma_Y-b}\quad ...(32)$$

[0067] In addition, as described above, the work-hardening coefficient $E_h(f_M)$, that is, the initial peak stress is maximized at a specific volume fraction $f_{M\text{-}max}$. Accordingly, in terms of increasing the initial peak stress while narrowing the area on which the laser heat treatment is performed, it is preferable that the volume fraction of the hardened area f_M be controlled to be less than or equal to the volume fraction $f_{M\text{-}max}$ which is when the work-hardening coefficient $E_h(f_M)$ is maximized.

[0068] Otherwise, in terms of maximizing the peak stress of a steel sheet (structural material), it is preferable that the volume fraction of the hardened area f_M be controlled to be the volume fraction $f_{M\text{-}max}$ which is when the work-hardening coefficient $E_h(f_M)$ is maximized. Therefore, the volume fraction of the hardened area f_M may be controlled to be the volume fraction $f_{M\text{-}max}$ (hereinafter, referred to as "maximum volume fraction") which is when the work-hardening coefficient $E_h(f_M)$ is maximized.

[0069] In addition , according to the present invention, in the case where the yield stress σ_Y is approximated by a quadratic function of the volume fraction of the hardened area f_M, the maximum volume fraction $f_{M\text{-}max}$ is expressed by the following Expression (33). In particular, in the case of the conditions as described above (that is, the case of the conditions shown in FIGS. 11 and 12), the maximum volume fraction $f_{M\text{-}max}$ is 76.6%. In addition, even in this case, since the maximum volume fraction $f_{M\text{-}max}$ needs to satisfy $0<f_{M\text{-}max}<1$, the constants b and $\Delta\sigma_h$ also need to satisfy $0<b<\Delta\sigma_h$ and $0<b<\Delta\sigma_Y$.

[Formula 33]

$$f_{M\text{-max}}=\frac{\Delta\sigma_h-b}{2(\Delta\sigma_Y-b)}\quad ...(33)$$

[0070] However, the relationship between the volume fraction of the hardened area f_M described above and the initial peak stress or the work-hardening coefficient E_h is a relationship obtained for a steel sheet, and is not a relation obtained for, for example, the structural material 10 having the shape as illustrated in FIG. 2. Here, in the structural material 10 illustrated in FIG. 2, as described above, areas that mainly receive the compressive load is the effective width areas 15, and the effective width areas 15 can be assumed to be a steel sheet having a width of 2×e. Therefore, the volume fraction of the hardened area f_M in such an effective width area, that is, the ratio of an area in the effective width area on which a hardening treatment (for example, a laser heat treatment) is performed can be set by the method as described above.

[0071] For example, the laser heat treatment is performed so that the volume fraction of the hardened area f_M in each of the effective width areas 15 becomes higher than or equal to $f_{M\text{-}min}$ expressed by Expression (32) and less than or equal to $f_{M\text{-}max}$ expressed by Expression (33). In addition, in this case, σ_{hM}, σ_{h0}, σ_{YM}, and σ_{Y0} regarding $\Delta\sigma_h(=\sigma_{hM}-\sigma_{h0})$ and $\Delta\sigma_Y(=\sigma_{YM}-\sigma_{Y0})$ in Expressions (32) and (33) respectively represent the proof stress of the heat-treated area (hardened area) when a predetermined strain is given, the proof stress of the untreated area (non-hardened area) when a predetermined strain is given, the yield stress of the heat-treated (hardened area), and the yield stress of the untreated area (non-hardened area). In addition, σ_{hM}, σ_{h0}, σ_{YM}, and σ_{Y0} are parameters regarding the material (steel sheet) used in the structural material.

[0072] By setting the volume fraction of the hardened area f_M in each of the effective width areas 15 as described above, the initial peak stress of the structural material 10 can be increased while causing the area on which the laser heat treatment is performed to be small.

[0073] In the above description, the volume fraction of the hardened area f_M in each of the effective width areas 15 is controlled to be higher than or equal to f_{M-min} and less than or equal to f_{M-max}. However, as described above and according to the present invention, the volume fraction of the hardened area f_M may also be controlled to be higher than or equal to f_{M-min} and less than or equal to 1 (100%) or less than 1. In this case, it may be determined that the volume fraction of the hardened area f_M in each of the effective width areas 15 is set so that the work-hardening coefficient E_h of each of the effective width areas 15 becomes equal to or higher than the work-hardening coefficient which is when the entire area of the effective width areas 15 is hardened by the laser heat treatment. Otherwise, as described above, the volume fraction of the hardened area f_M in each of the effective width areas 15 may also be controlled to be f_{M-max}.

[0074] In summary, as shown in FIG. 17, the minimum value of the volume fraction f_M is determined on the basis of the rate of change of the yield stress σ_Y with respect to the volume fraction f_M in the case where the volume fraction of the hardened area f_M is 0, the rate of change (constant) is called b (S311), and the maximum value of the range of the volume fraction f_M is determined to be less than or equal to 1 or less than 1 (S312), thereby the range of the volume fraction of the hardened area f_M may be determined. In addition, after determining the minimum value of the range of the volume fraction f_M (S311), the maximum value of the range of the volume fraction f_M may also be determined on the basis of the rate of change of the yield stress σ_Y with respect to the volume fraction f_M in the case where the volume fraction of the hardened area f_M is 0, the rate of change (constant) is called b (S313).

[0075] Here, an example of a method of determining the constant b for determining the range of the volume fraction of the hardened area f_M described above will be described. As a first method, a tensile test is performed on three specimens of which the volume factions f_M of the hardened areas of steel sheets are 0, 1, and an arbitrary value that is higher than 0 and less than 1 (for example, 0.5), the yield stresses σ_Y of the specimens are obtained, and the method of least squares is performed thereon, thereby the constants a, b, and c can be determined. As a second method, a tensile test is performed on two specimens of which the volume factions f_M of the hardened areas of steel sheets are 0, and an arbitrary value that is higher than 0 and close enough to 0 (for example, 0.1), the yield stresses σ_Y of the specimens are obtained, and the constant b can be determined as the rate of increase in the yield stress σ_Y with respect to the volume faction of the hardened area f_M. Here, the method of determining the constant b using the minimum number of pieces of data needed (the number of pieces of data of the yield stresses σ_Y) as a simple method has been described. However, the upper limit of the number of pieces of data is not particularly limited. As the number of pieces of data increases, the range of the volume fraction f_M can be determined with higher precision.

[0076] Moreover, the yield stress σ_Y and the proof stress σ_h can be measured by performing a tensile test according to JIS Z2241 on JIS No. 5 specimens (specimens) sampled from a steel sheet (no heat treatment and bending process) used as structural material. In particular, for measurement of the yield stress σ_{YM} and the proof stress σ_{hM} in the case where the volume fraction of the hardened area f_M is 1, specimens obtained by performing a predetermined heat treatment on the above specimens may be used. As the predetermined heat treatment, for example, the specimens may be heated to the A_{e3} point (A_{e3} temperature) or higher, and thereafter may be cooled to the M_s point (M_s temperature) or less at a cooling rate of higher than or equal to 10 °C/s, and preferably higher than or equal to 30 °C/s by cooling means such as water cooling and/or air cooling.

[0077] In addition, for measurement of the yield stress σ_{YM} and the proof stress σ_{hM} in the case where the volume fraction of the hardened area f_M is higher than 0 and less than or equal to 1, the tensile test described above may be performed on the above specimens which is performed a laser heat treatment in the longitudinal direction under the conditions corresponding to the abovementioned predetermined heat treatment. In this case, by measuring the volume fraction of the hardened area f_M after the tensile test, the correspondence relationship between the volume fraction f_M, the yield stress σ_{YM}, and the proof stress σ_{hM} may be determined. For controlling the volume fraction of the hardened area f_M by the laser heat treatment, the laser heat treatment (1 pass) may be repeatedly performed on one surface or both surfaces of the specimens in the longitudinal direction of the specimens while displacing the positions of the specimens in the width direction (a direction perpendicular to the longitudinal direction).

[0078] In addition, as the steel sheet used for the specimens, specimens on which a strain history corresponding to the bend-processed portion (bent portion) of the structural material before the heat treatment is applied may also be used.

[0079] In addition, the volume fraction of the hardened area f_M can be determined by a method as follows. For example, the area of the hardened area in a cross-section perpendicular to the longitudinal direction of the specimen is measured, and the volume of the hardened area is obtained by multiplying the area by a length (total length) on which the laser heat treatment is performed, and the volume of the hardened area is divided by the total volume of the specimen, thereby the volume fraction of the hardened area f_M can be obtained. In addition, the area of the hardened area may be determined from a quenched structure observed with an optical microscope from the cross-section perpendicular to the longitudinal direction of the specimen, and, according to the present invention, is determined by obtaining the Vickers hardness using a Vickers hardness tester as described later.

[0080] In addition, in the method of determining the range of the volume fraction of the hardened area f_M described above, the relationship between the proof stress σ_h of the steel sheet and the volume fraction of the hardened area f_M is expressed by a linear function, and the relationship between the yield stress σ_Y of the steel sheet and the volume fraction of the hardened area f_M is expressed by a quadratic function. However, such functions may not be necessarily used.

[0081] In order to determine the range of the volume fraction of the hardened area f_M, the fact that the rate of change in the yield stress with respect to the volume fraction of the hardened area f_M varies depending on the volume fraction of the hardened area f_M and the amount of change (a degree of change) is greater than the amount of change (a degree of change) of the rate of change in flow stress with respect to the volume fraction of the hardened area f_M may be used.

[0082] Therefore, for example, the relationship between the yield stress σ_Y of the steel sheet and the volume fraction of the hardened area f_M may be expressed by an arbitrary function $\sigma_Y(f_M)$, and the range of the volume fraction of the hardened area f_M may be determined using the rate of change in the yield stress (in a case of a quadratic function, corresponding to the constant b) with respect to at least one hardening ratio. In a case where the quadratic function is extended to a general function, the minimum volume fraction $f_{M\text{-}min}$ (other than 1) and the maximum volume fraction $f_{M\text{-}max}$ may be determined to satisfy the following Expressions (34) and (35). Here, $\sigma_Y(f_M)$ can be expressed as a function including the constant b described above.

[Formula 34]

$$\sigma_Y(f_{M-\min}) = \sigma_{YM} \quad \ldots(34)$$

[Formula 35]

$$\left.\frac{\partial \sigma_Y(f_M)}{\partial f_M}\right|_{f_M = f_{M-\max}} = \sigma_{hM} - \sigma_{h0} \quad \ldots(35)$$

[0083] In addition, the relationship between the proof stress σ_h of the steel sheet and the volume fraction of the hardened area f_M may be expressed by an arbitrary function $\sigma_h(f_M)$. Here, in a case where the linear function and the quadratic function described above are extended to general functions, the maximum volume fraction $f_{M\text{-}max}$ can be determined to satisfy the following Expression (36).

[Formula 36]

$$\left.\frac{\partial \sigma_Y(f_M)}{\partial f_M}\right|_{f_M = f_{M-\max}} = \left.\frac{\partial \sigma_h(f_M)}{\partial f_M}\right|_{f_M = f_{M-\max}} \quad \ldots(36)$$

[0084] Moreover, other than in the above-described range (for example, of higher than or equal to $f_{M\text{-}min}$ and less than or equal to 1 (less than 1) or in the range of the following Expression (41)), for example, using the maximum volume fraction (boundary hardening ratio) $f_{M\text{-}max}$, the range of the volume fraction of the hardened area f_M may be determined within the range of any of the following Expressions (37) to (40).

[Formula 37]

$$0.5 f_{M-\max} \leq f_M < 1 \quad \ldots(37)$$

[Formula 38]

$$0.5 f_{M-\max} \leq f_M \leq 0.5(f_{M-\max} + 1) \quad \ldots(38)$$

[Formula 39]

$$0.5 f_{M-\max} \leq f_M \leq f_{M-\max} \quad ...(39)$$

[Formula 40]

$$f_{M-\min} \leq f_M \leq 0.5\left(f_{M-\max}+1\right) \quad ...(40)$$

[Formula 41]

$$f_{M-\min} \leq f_M \leq f_{M-\max} \quad ...(41)$$

[0085] By determining the range of the volume fraction of the hardened area f_M as in the above Expressions (37) to (41), a stable heat treatment can be performed with an excellent balance between a reduction of cost of the heat treatment and the enhancement of the ability of the structural material to suppress deformation. In addition, correction terms including cost, heat treatment conditions, and the like may be appropriately included as the upper limit and lower limit in the range of the volume fraction of the hardened area f_M.

[0086] Moreover, besides the above-described range, as shown in FIG. 16, the work-hardening coefficient E_h (the relationship between the volume fraction f_M and the work-hardening coefficient E_h) is estimated or calculated on the basis of the range of change in the yield stress σ_Y with respect to the volume fraction of the hardened area f_M (S301), and the range of the volume fraction f_M may be determined so that the estimated or calculated work-hardening coefficient E_h becomes higher than or equal to a predetermined value (S302). For example, the difference between the work-hardening coefficient E_h in the case where the volume fraction f_M is 1 and the work-hardening coefficient E_h in the case where the volume fraction f_M is $f_{M\text{-}max}$ is defined as ΔE_h, an arbitrary value that is higher than or equal to 0 and less than or equal to 1 is defined as an improvement coefficient n, and a value obtained by adding $n \times \Delta E_h$ to the work-hardening coefficient E_h in the case where the volume fraction f_M is 1 may be determined as a predetermined value. Therefore, the predetermined value may be the work-hardening coefficient E_h in the case where the volume fraction of the hardened area f_M is 1. In addition, instead of the work-hardening coefficient E_h expressed by the above Expression (21), a different index of work-hardening including the yield stress σ_Y as at least a variable may also be used.

[0087] In addition, when the relationship between the proof stress σ_h of the steel sheet and the volume fraction of the hardened area f_M is expressed by a linear function and the relationship between the yield stress σ_Y of the steel sheet and the volume fraction of the hardened area f_M is expressed by a quadratic function, the range of the volume fraction of the hardened area f_M can be determined most simply. In this case, the range of the volume fraction of the hardened area f_M can be determined using the constant a instead of the constant b. However, as expressed by the following Expression (42), the constant a can be expressed using the constant b (the constant a is a dependent variable of the constant b), and thus it is assumed that the use of the constant a is the same as the use of the constant b. Similarly, even in the case where a variable (for example, the rate of change in the yield stress σ_Y with respect to the volume fraction f_M in the case where the volume fraction f_M is 1) which is subordinate to the range of change in the yield stress σ_Y with respect to the volume fraction f_M is used, it is assumed that the rate of change in the yield stress σ_Y with respect to the volume fraction f_M is used. That is, as expressed by the following Expression (43) obtained by substituting the first order differential equation of the above Expression (29) with the following Expression (42), b which is the range of change in the yield stress σ_Y in the case where the volume fraction f_M is 0 can also be obtained using the rate of change in the yield stress σ_Y at an arbitrary volume fraction f_M. For example, as expressed by the following Expression (44), even in the case where the rate of change in the yield stress σ_Y in the case where the volume fraction f_M is 1 is defined as d, b can be obtained using d from the following Expression (45).

[Formula 42]

$$a = \sigma_{YM} - \sigma_{Y0} - b \quad ...(42)$$

[Formula 43]

$$\frac{\partial \sigma_Y(f_M)}{\partial f_M} = 2(\sigma_{YM} - \sigma_{Y0} - b)f_M + b \quad ...(43)$$

[Formula 44]

$$b = 2\sigma_{YM} - 2\sigma_{Y0} - d \quad ...(44)$$

[0088] Moreover, the range of the volume fraction f_M can be determined on the basis of the volume fraction f_M which is when the rate of change in the yield stress σ_Y with respect to the volume fraction of the hardened area f_M satisfies a predetermined condition. For example, upon considering that the work-hardening coefficient E_h draws a convex downward curve with respect to the volume fraction of the hardened area f_M, the volume fraction f_M which is when the first order differential of the work-hardening coefficient E_h expressed by the above Expression (21) with respect to volume fraction f_M becomes 0, that is, the volume fraction (boundary hardening ratio) f_M that satisfies the above Expression (36) may be determined as the maximum volume fraction $f_{M\text{-}max}$. In this case, the range of the volume fraction of the hardened area f_M can be determined as, for example, a range that satisfies the above Expressions (37) to (41). Here, regarding Expressions (37) to (41), the minimum volume fraction $f_{M\text{-}min}$ (other than 1) can be determined using the above Expression (34). In addition, ΔE_h described above is determined from the minimum volume fraction $f_{M\text{-}min}$ and the maximum volume fraction $f_{M\text{-}max}$ determined by Expressions (34) and (36), and the range of the volume fraction f_M may be determined using the improvement coefficient n described above so that the work-hardening coefficient E_h is higher than or equal to a value obtained by adding $n \times \Delta E_h$ to the work-hardening coefficient E_h in the case where the volume fraction f_M is 1.

[0089] That is, as shown in FIG. 18, the maximum volume fraction $f_{M\text{-}max}$ of the volume fraction f_M is determined on the basis of the rate of change in the yield stress σ_Y with respect to the volume fraction of the hardened area f_M (S321), the minimum value of the range of the volume fraction f_M is determined as a value smaller than the maximum volume fraction $f_{M\text{-}max}$ by a predetermined value (S322), and the maximum value of the range of the volume fraction f_M may be determined to be less than or equal to 1 or less than 1 (S323). In addition, after determining the minimum value of the range of the volume fraction of the hardened area f_M (S322), the maximum value of the range of the volume fraction f_M may be determined to be a value greater than the maximum volume fraction $f_{M\text{-}max}$ by a predetermined value (S324).

[0090] In addition, regarding the relationship between the yield stress (σ_Y of the steel sheet and the volume fraction of the hardened area f_M, the same function (for example, a linear function such as a quadratic function) may be used in a range in which the volume fraction f_M is 0 to 1, however, this range may be divided into a plurality of ranges and the different functions may also be used for each ranges. However, since the change in the rate of change in the yield stress σ_Y with respect to the volume fraction f_M is used, in the case where the same function is used in the range in which the volume fraction is 0 to 1, the function in this range needs to be able to differentiated twice with respect to the volume fraction f_M. In addition, as a method of dividing the range of 0 to 1 into a plurality of ranges and using different functions for each ranges, for example, an interpolation function (including a case where the interpolation function is linear (a graph of broken line)) according to various interpolation methods (for example, spline interpolation) may be used. In this case, actual measurement data (for example, 5 or more points) can be directly used as data of a database.

[0091] Similarly, even regarding the relationship between the flow stress σ_h of the steel sheet and the volume fraction of the hardened area f_M, the same function (for example, a linear function such as a linear function) may also be used in a range in which the volume fraction f_M is 0 to 1, however, this range may be divided into a plurality of ranges and different functions may also be used for each ranges.

[0092] Here, as described above, in order to determine the range of the volume fraction of the hardened area f_M using as low a number of measurements (the number of instances of manufacturing of the specimens and the number of tests of tensile strength) as possible, it is preferable that the relationship between the proof stress σ_h of the steel sheet and the volume fraction of the hardened area f_M be expressed by a linear function and the relationship between the yield stress σ_Y of the steel sheet and the volume fraction of the hardened area f_M be expressed by a quadratic function.

[0093] In addition, in the above embodiments, $\sigma_h(f_M)$ is defined as the proof stress which is when 5% of plastic strain occurs. However, in examples not forming part of the present invention, the plastic strain corresponding to the proof stress may not be necessarily limited to 5% and may not be 5% as long as it is greater than 0%. For example, as shown in FIGS. 7, 9A, and 9B, $\sigma_h(f_M)$ can also be defined as a proof stress which is when 1% of plastic strain occurs. Therefore, when a proof stress which is when a predetermined plastic strain occurs (or a stress needed to cause plastic deformation from a state where a predetermined plastic strain occurs) is defined as a flow stress, $\sigma_h(f_M)$ represents the flow stress, σ_{hM} represents the flow stress of the hardened area, σ_{h0} represents the flow stress of the non-hardened area (untreated structural material).

[0094] Here, the flow stress may be a stress at a strain amount determined in a range which is greater than a strain amount (that is, the plastic strain is greater than 0) corresponding to the yield stress and smaller than a uniform elongation strain amount (for example, the maximum amount of nominal strain). According to the present invention the flow stress be 5%.

[0095] In addition, in the above description, the structural material 10 is locally heated and hardened by the laser heat treatment. However, local hardening of the structural material 10 may not necessarily be performed by the laser heat treatment and may also be performed by another heat treatment. The hardness of the area hardened by the heat treatment is higher than or equal to the reference hardness (Vickers hardness) Hv calculated by the following Expressions (45) and (46) when the carbon content of the structural material 10 which is a steel material is defined as C, the silicon content is defined as Si, the manganese content is defined as Mn, the nickel content is defined as Ni, the chromium content is defined as Cr, the molybdenum content is defined as Mo, the niobium content is defined as Nb, the vanadium content is defined as V.

[Formula 45]

$$Hv = 0.8(950 C_{eq} + 260) \quad \ldots(45)$$

[Formula 46]

$$C_{eq} = C + 0.004Si + 0.011Mn + 0.02Ni + 0.012Cr + 0.016Mo + 0.006Nb + 0.0025V \ldots(46)$$

[0096] Moreover, in the example, not forming part of the present invention, shown in FIGS. 2 and 3, the laser heat treatment is performed on the effective width areas 15 in the peripheries of the two bent portions 12b and 12c and the laser heat treatment is not performed on the effective width areas 15 in the peripheries of the two different bent portions 12a and 12d. However, the laser heat treatment may also be performed on the effective width areas in the peripheries of the two different bent portions, or the laser treatment may be performed only on the effective width area 15 in the periphery of one bent portion of the two bent portions 12b and 12c. In other words, in the present invention, in the case where a structural material has a plurality of bent portions, the heat treatment may be performed on the effective width area including at least one bent portion at a volume fraction f_M as described above.

[0097] In addition, a heat-treated structural material according to present invention will be described.

[0098] The heat-treated structural material according to the present invention comprises flat portions having flat sheet shapes extending in a longitudinal direction of the structural material, a bent portion that extends in the longitudinal direction of the structural material between the flat portions and has a bend in a direction perpendicular to the longitudinal direction, and a hat shaped cross-section including five flat portions which are arranged so that the cross-section thereof has a hat shape as illustrated in figure 14. Moreover, the volume fraction of the above-described hardened area with respect to the above-described effective width areas is less than 1 and is included in the range of the volume fraction f_M determined on the basis of the rate of change in the yield stress σ_Y with respect to the volume fraction f_M.

[0099] Thereafter, the heat-treated structural material according to the present invention may exhibit a higher ability to suppress deformation than that according to the conventional technique while maintaining costs as low as possible.

[0100] Moreover, the range of the volume fraction of the hardened area f_M is determined on the basis of the rate of change in the yield stress σ_Y with respect to the volume fraction f_M in the case where the value of the volume fraction f_M is 0 as described above. The range of the volume fraction f_M is a range determined so that the work-hardening coefficient E_h calculated on the basis of the rate of change in the yield stress σ_Y with respect to the volume fraction f_M is higher than or equal to a predetermined value. In particular, the predetermined value is preferably the value of the work-hardening coefficient E_h in the case where the volume fraction f_M is 1, and more preferably a value greater than the work-hardening coefficient E_h in the case where the volume fraction f_M is 1. In addition, it is preferable that the range (lower limit) of the volume fraction of the hardened area f_M be higher than or equal to the minimum volume fraction $f_{M\text{-}min}$ expressed by the above Expression (32). Similarly, it is preferable that the range (upper limit) of the volume fraction of the hardened area f_M be lower than or equal to the maximum volume fraction $f_{M\text{-}max}$ expressed by the above Expression (33). In addition, three JIS No. 5 specimens are sampled from the flat portion of the structural material, the heat treatment is performed on the two specimens so that the volume fractions f_M of the hardened areas of the specimens are 0, 1, and 0.5, a tensile test is thereafter performed on the three specimens to obtain needed mechanical strengths, and the method of least squares is performed on the relationship between the yield stress σ_Y and the volume fraction f_M, thereby determining the constant b of Expression (30).

[0101] In addition, the flow stress is defined as a proof stress which is when 5% of plastic strain occurs. Moreover, in order to determine the effective width area, the effective width e according to the present invention, is defined by the above Expressions (15), and (18B) or the following Expression (47). In addition, in the case where the effective width e is defined by Expression (15), the finite element method may be used. In addition, Expression (47) is derived from the above Expressions (18A) to (20) assuming that the flat sheet buckling coefficient is 4.

[Formula 47]

$$e=\frac{t}{1.052}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1-\frac{0.44t}{1.052w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad ...(47)$$

[0102] In addition, the hardened area (the area hardened by the heat treatment) is obtained by the same method as described above. That is, the hardened area according to the present invention, is "determined to be an area that has a hardness of higher than or equal to the Vickers hardness calculated by above Expressions (45) and (46). In addition, it is preferable that the heat treatment be performed using a laser. The history of the heat treatment using the laser may be checked by observing the structure of the cross-section of the structural material.

[Examples]

[0103] From a single 440 MPa-grade steel sheet BP having a thickness of 1.0 mm, a yield stress of 301 MPa, a tensile strength of 457 MPa, an elongation of 39%, a carbon content of 0.09%, a silicon content of 0.02%, a manganese content of 1.24%, 11 JIS No. 5 specimens were sampled. A laser heat treatment was performed in a plurality of passes on the 10 specimens among the specimens in the longitudinal direction (tension direction) of the specimens to achieve predetermined volume fractions, thereby manufacturing specimens in which the volume fractions of the hardened areas with respect to effective width areas were 0.1 to 1 (increment of 0.1). As the laser heat treatment, a carbon dioxide laser was used, a laser output was controlled to 5 kW, and a heat treatment speed was controlled to 12 m/min. Moreover, a tensile test was performed on the 11 specimens to evaluate yield stresses and tensile stresses.

[0104] As a result, from the untreated specimen, the yield stress of the non-hardened area σ_{Y0} was determined as 301 MPa, and the proof stress σ_{h0} of the non-hardened area when a plastic strain ε_p of 0.05 (0.0537) was given was determined as 447 MPa. Similarly, from the specimen having a volume fraction of 1 (100%), the yield stress of the hardened area σ_{YM} was determined as 794 MPa, and the proof stress σ_{hM} of the hardened area when a plastic strain ε_p of 0.05 (0.0537) was given was determined as 1017 MPa. Moreover, the yield stresses obtained from the 11 specimens were plotted with respect to the volume fractions, and the method of least squares using the above Expression (29) as a regression equation was applied to the plot, thereby determining the constant b as 350 MPa. Here, it was confirmed that even when the method of least squares was performed on the three plots of the yield stress of the untreated specimen, the specimen having a volume fraction of 0.5 (50%), and the specimen having a volume fraction of 1 (100%), the same constant b was obtained.

[0105] As a result of substituting the value of b (b=350 MPa), the values of $\Delta\sigma_h$ and $\Delta\sigma_Y$ ($\Delta\sigma_h$=569.2 MPa, $\Delta\sigma_Y$=493.0 MPa) obtained by the tensile test in Expression (32), $f_{M\text{-}min}$=53.3% was obtained.

[0106] In addition, as a result of substituting the value of b and the values of $\Delta\sigma_h$ and $\Delta\sigma_Y$ in Expression (33), $f_{M\text{-}max}$ ($f_{M\text{-}max}$=76.6%) was obtained.

[0107] In addition, as a result of calculating the effective width e using the above Expressions (18A) to (20) (or the above Expression (47)), 19.2 mm was obtained as the effective width e. Here, the flat sheet buckling coefficient k which is a coefficient in response to the sheet shape or the like was 4, the sheet width w was 60 mm, the sheet thickness t was 1.0 mm, the yield stress σ_{Y0} was 301 MPa, and the elastic modulus E was 180 GPa. In addition, regarding the sheet width w, the average value (60 mm) of the height (50 mm) illustrated in FIG. 14 and the width (70 mm) of the top portion was used as a representative value.

[0108] In addition, the steel sheet BP (FIG. 13A) was subjected to a bending process, thereby manufacturing an untreated structural material 10 having a shape as illustrated in FIG. 13B. The untreated structural material 10 includes five flat portions which are arranged so that the cross-section thereof has a hat shape as illustrated in FIG. 14. The lengths of sides in the vertical cross-section of the sides including the three flat portions 11 at the center were 50 mm, 70 mm, and 50 mm, respectively.

[0109] The untreated structural material 10 manufactured as such was spot-welded to a different structural material 20 having a flat sheet shape, thereby manufacturing a structural material assembly as illustrated in FIG. 13. Spot welding S was performed on the center in the width direction of the flat portions constituting flange portions at an interval of 30 mm in the longitudinal direction. In addition, the distance from the end portion in the longitudinal direction (the end portion on a side on which an impact is inserted, hereinafter, referred to as "impact exertion side end portion") to the initial spot weld was 15 mm.

[0110] On the structural material assembly manufactured as such, the laser heat treatment was performed in a plurality of passes in the longitudinal direction (tensile direction) of the specimens using the carbon dioxide laser. The laser output was controlled to 5 kW, and the heat treatment speed was controlled to 12 m/min. The laser output and the heat treatment speed in the laser heat treatment were controlled in the same manner in the following examples. In a test No. 1, the laser heat treatment was performed over the entirety of an area of 19.2 mm from the bent portion shaded in black in FIG. 14, that is, over the entirety of the effective width area. Therefore, in this case, the volume fraction of the hardened area with respect to the effective width area was 100%. Here, the work-hardening coefficient E_h calculated by the above Expression (31) using the above-described data was 4155.8 MPa (here,ε_p=0.05).

[0111] Measurement of Vickers hardness was performed on the spots on which the laser heat treatment was performed. While the Vickers hardness of the untreated structural material was 140, the Vickers hardness after the laser heat treatment was 306. It was confirmed that the hardened area was sufficiently quench-hardened.

[0112] The structural material assembly was installed so that the longitudinal direction of the structural material assembly on which the laser heat treatment was performed as such was aligned with the vertical direction and the impact exertion side end portion thereof has an upward trend, and an impact test was performed by falling a falling weight of 300 kg positioned immediately thereon from a height of 2 m.

[0113] When the impact test was performed, a load meter (load cell) was installed immediately under the structural material assembly, and the load history after the falling weight came in contact with the structural material assembly was measured. At the same time, the displacement history of the falling weight after the falling weight came in contact with the structural material assembly (the time history of the falling amount of the falling weight after the falling weight came in contact with the structural material assembly) was also measured by a laser displacement meter. A load-strain curve was created on the basis of the load history and the displacement history measured as such. An initial peak reaction force was calculated from the load-strain curve, and an initial peak stress was calculated from the initial peak reaction force divided by the cross-sectional area of the structural material assembly (340 mm^2). The initial peak reaction force at this time was 146.9 kN, and the initial peak stress was 432.0 MPa.

[0114] In a test No. 2, an untreated structural material assembly was manufactured as in the test No. 1, and the laser heat treatment was performed on the structural material assembly. The laser heat treatment was performed so that the volume fraction of the hardened area with respect to the effective width area becomes 76.6%. Here, the work-hardening coefficient E_h calculated by the above Expression (31) using the above-described data was 4301.6 MPa (here, ε_p=0.05).

[0115] As in the test No. 1, an impact test was performed on the structural material assembly on which the laser heat treatment was performed as such, and an initial peak reaction force and an initial peak stress were calculated on the basis of the test results. The initial peak reaction force at this time was 150.6 kN, and the initial peak stress was 443.0 MPa.

[0116] In a test No. 3, an untreated structural material assembly was manufactured as in the test No. 1, and the laser heat treatment was performed on the structural material assembly. The laser heat treatment was performed so that the volume fraction of the hardened area with respect to the effective width area becomes 53.3%. Here, the work-hardening coefficient E_h calculated by the above Expression (31) using the above-described data was 4155.8 MPa (here, ε_p=0.05).

[0117] As in the test No. 1, an impact test was performed on the structural material assembly on which the laser heat treatment was performed as such, and an initial peak reaction force and an initial peak stress were calculated on the basis of the test results. The initial peak reaction force at this time was 146.3 kN, and the initial peak stress was 430.1 MPa.

[0118] The results are collected in the following Table 1.

[Table 1]

Test No.	f_M (%)	E_h (MPa)	Initial peak reaction force (kN)	Initial peak stress (MPa)
1	100	4155.8	146.9	432.0
2	76.6	4301.6	150.6	443.0
3	53.3	4155.8	146.3	430.1

[0119] From Table 1, it can be seen that the initial peak stress which is when the volume fraction (f_M) of the hardened area with respect to the effective width area is 53.3% (=$f_{M\text{-}min}$) is substantially equal to the initial peak stress which is when the volume fraction is 100%. In addition, it can be seen that the initial peak stress which is when the volume fraction of the hardened area with respect to the effective width area is 76.6% (=$f_{M\text{-}max}$) is substantially equal to the initial peak stresses which is when the volume fractions are 53.3% and 100%. As such, in the test No. 3, substantially the same ability to suppress deformation to that of the test No. 1 can be obtained at lower cost than that of the test No. 1. In addition, in the test No. 2, a higher ability to suppress deformation than that of the test No. 1 can be obtained at lower cost than that of the test No. 1.

Industrial Applicability

[0120] By performing a heat treatment on appropriate spots of an untreated structural material to locally harden the structural material, the structural material having a sufficiently high ability to suppress deformation can be provided.

Reference Signs List

[0121]

10 structural material
11 flat portion
12 bent portion
15 effective width area
20 structural material

Claims

1. A heat treatment method of a structural material (10) which is a steel material, includes flat portions (11) having flat sheet shapes extending in a longitudinal direction of the structural material (10), a bent portion (12) that extends in the longitudinal direction of the structural material (10) between the flat portions (11) and has a bend in a direction perpendicular to the longitudinal direction, and a hat shaped cross-section including five flat portions which are arranged so that the cross-section thereof has a hat shape, the heat treatment method comprising:

    determining an effective width (e) of the bent portion (12);
    defining an effective width area (15) as an area which includes the bent portion (12) and of which a distance in the direction perpendicular to the longitudinal direction from the bent portion (12) is within the effective width (e);
    defining a hardening ratio f_M as a ratio between an area which is quench-hardened by a heat treatment in the effective width area (15) and the effective width area (15),
    wherein the area of the hardened area is measured in a cross-section perpendicular to the longitudinal direction, and
    wherein, in a case where, regarding chemical components contained in the structural material (10), a mass percentage of carbon is defined as C, a mass percentage of silicon is defined as Si, a mass percentage of manganese is defined as Mn, a mass percentage of nickel is defined as Ni, a mass percentage of chromium is defined as Cr, a mass percentage of molybdenum is defined as Mo, a mass percentage of niobium is defined as Nb, and a mass percentage of vanadium is defined as V, the area hardened by the heat treatment is an area which has a hardness higher than or equal to a Vickers hardness calculated by the following Expressions (45) and (46),

$$Hv = 0.8(950C_{eq} + 260) \quad \ldots(45)$$

$$C_{eq} = C + 0.004Si + 0.011Mn + 0.02Ni + 0.012Cr + 0.016Mo + 0.006Nb + 0.0025V \ldots(46)$$

,

    determining a range of the hardening ratio f_M on the basis of a rate of change in a yield stress σ_Y with respect to the hardening ratio f_M; and
    performing the heat treatment on the effective width area (15) of the structural material (10) to satisfy the range of the hardening ratio f_M,

    wherein the area in each of the flat portions (11) that mainly receives the compressive load is an area of which the distance in the width direction from the bent portion (12) is within the effective width (e) and the effective width (e) is defined by the following Expression (15),

$$e = \frac{1}{2\sigma_{Y0}} \int_0^w \sigma_x dw \quad ...(15)$$

when the average value of the height and the width of the top portion of the structural material (10) in the hat shaped cross-section is defined as w, a yield stress in the case where the hardening ratio f_M is 0 is defined as σ_{Y0}, and a stress at each position in a width direction perpendicular to the longitudinal direction when a stress at which a maximum stress in the longitudinal direction of the structural material (10) is σ_{Y0} is given in the longitudinal direction is defined as σ_x,
or
by the following Expression (18B),

$$e = \frac{t}{2}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1.90 - \frac{t}{w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad ...(18B)$$

,

when a thickness dimension is defined as t, a Poisson's ratio is defined as v, an elastic modulus is defined as E, and a yield stress in a case where the hardening ratio f_M is 0 is defined as σ_{Y0},
or
by the following Expression (47),
when a thickness dimension is defined as t, an elastic modulus is defined as E, and a yield stress in a case where the hardening ratio f_M is 0 is defined as σ_{Y0},

$$e = \frac{t}{1.052}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1 - \frac{0.44t}{1.052w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad ...(47)$$

,

and
wherein the rate of change is a value in a case where a value of the hardening ratio f_M is 0, and
wherein, when a difference between a flow stress, which is defined as the proof stress which is when 5% plastic strain occurs, in a case where the hardening ratio f_M is 1 and a flow stress in the case where the hardening ratio f_M is 0 is defined as $\Delta\sigma_h$, a difference between a yield stress in the case where the hardening ratio f_M is 1 and a yield stress in the case where the hardening ratio f_M is 0 is defined as $\Delta\sigma_Y$, and the rate of change is defined as b, the range of the hardening ratio f_M is higher than or equal to $f_{M\text{-min}}$ expressed by the following Expression (32) and less than 1, and optionally the range of the hardening ratio f_M is less than or equal to $f_{M\text{-max}}$ expressed by the following Expression (33),

$$f_{M\text{-min}} = \frac{\Delta\sigma_h - \Delta\sigma_Y}{\Delta\sigma_Y - b} \quad ...(32)$$

$$f_{M\text{-max}} = \frac{\Delta\sigma_h - b}{2(\Delta\sigma_Y - b)} \quad ...(33)$$

,

wherein the rate of change is determined with the method described in the description.

2. The heat treatment method according to claim 1,

wherein a boundary hardening ratio f_M at which the rate of change becomes equal to a rate of change in the flow stress σ_h with respect to the hardening ratio f_M is determined as f_{M-max}, and the range of the hardening ratio f_M is determined on the basis of the f_{M-max}, and optionally
wherein the range of the hardening ratio f_M is determined in a range that satisfies the following Expression (37), or optionally
wherein the range of the hardening ratio f_M is determined to be higher than or equal to a hardening ratio f_{M-min}, in which the hardening ratio f_{M-min} is a hardening ratio in a case where a work-hardening coefficient E_h is equal to the work-hardening coefficient E_h when the hardening ratio f_M is 1, and less than 1,

$$0.5 f_{M-max} \leq f_M < 1 \dots (37).$$

3. The heat treatment method according to claim 1,
wherein the heat treatment is performed using a laser.

4. The heat treatment method according to claim 1,
wherein a pass of the heat treatment is continuously performed over the entire length of the longitudinal direction.

5. A structural material which is a steel material heat-treated according to the method of any of the previous claims 1 to 4 comprising:

flat portions (11) having flat sheet shapes extending in a longitudinal direction of the structural material (10), a bent portion (12) that extends in the longitudinal direction of the structural material (10) between the flat portions (11) and has a bend in a direction perpendicular to the longitudinal direction, and a hat shaped cross-section including five flat portions which are arranged so that the cross-section thereof has a hat shape,
wherein, in a case where an area which includes the bent portion (12) and of which a distance in a direction perpendicular to the longitudinal direction from the bent portion (12) is within an effective width (e) is defined as an effective width area (15) and a ratio between an area which is quench-hardened by a heat treatment in the effective width area (15) and the effective width area is defined as a hardening ratio f_M, the hardening ratio f_M is less than 1 and is contained in a range of the hardening ratio f_M determined on the basis of a rate of change in a yield stress σ_Y with respect to the hardening ratio f_M wherein the area in each of the flat portions (11) that mainly receives the compressive load is an area of which the distance in the width direction from the bent portion (12) is within the effective width (e) and the effective width (e) is defined by the following Expression (15),

$$e = \frac{1}{2\sigma_{Y0}} \int_0^w \sigma_x dw \quad \dots (15)$$

when the average value of the height and the width of the top portion of the structural material (10) in the hat shaped cross-section is defined as w, a yield stress in the case where the hardening ratio f_M is 0 is defined as σ_{Y0}, and a stress at each position in a width direction perpendicular to the longitudinal direction when a stress at which a maximum stress in the longitudinal direction of the structural material (10) is σ_{Y0} is given in the longitudinal direction is defined as σ_x,
or
by the following Expression (18B),

$$e = \frac{t}{2}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1.90 - \frac{t}{w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad \dots (18B)$$

,

when a thickness dimension is defined as t, a Poisson's ratio is defined as v, an elastic modulus is defined as E, and a yield stress in a case where the hardening ratio f_M is 0 is defined as σ_{Y0},
or
by the following Expression (47),
when a thickness dimension is defined as t, an elastic modulus is defined as E, and a yield stress in a case

where the hardening ratio f_M is 0 is defined as σ_{Y0},

$$e=\frac{t}{1.052}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1-\frac{0.44t}{1.052w}\sqrt{\frac{E}{\sigma_{Y0}}}\right)\quad\ldots(47)$$

,

and

wherein the rate of change is a value in a case where a value of the hardening ratio f_M is 0, and

wherein, when a difference between a flow stress, which is defined as the proof stress which is when 5% plastic strain occurs, in a case where the hardening ratio f_M is 1 and a flow stress in the case where the hardening ratio f_M is 0 is defined as $\Delta\sigma_h$, a difference between a yield stress in the case where the hardening ratio f_M is 1 and a yield stress in the case where the hardening ratio f_M is 0 is defined as $\Delta\sigma_Y$, and the rate of change is defined as b, the range of the hardening ratio f_M is higher than or equal to $f_{M\text{-min}}$ expressed by the following Expression (32) and less than 1, and optionally the range of the hardening ratio f_M is less than or equal to $f_{M\text{-max}}$ expressed by the following Expression (33).

$$f_{M\text{-min}}=\frac{\Delta\sigma_h-\Delta\sigma_Y}{\Delta\sigma_Y-b}\quad\ldots(32)$$

$$f_{M\text{-max}}=\frac{\Delta\sigma_h-b}{2(\Delta\sigma_Y-b)}\quad\ldots(33)$$

,

wherein the area of the hardened area is measured in a cross-section perpendicular to the longitudinal direction, and

wherein, in a case where, regarding chemical components contained in the structural material (10), a mass percentage of carbon is defined as C, a mass percentage of silicon is defined as Si, a mass percentage of manganese is defined as Mn, a mass percentage of nickel is defined as Ni, a mass percentage of chromium is defined as Cr, a mass percentage of molybdenum is defined as Mo, a mass percentage of niobium is defined as Nb, and a mass percentage of vanadium is defined as V, the area hardened by the heat treatment is an area which has a hardness higher than or equal to a Vickers hardness calculated by the following Expressions (45) and (46),

$$Hv=0.8(950C_{eq}+260)\quad\ldots(45)$$

$$C_{eq}=C+0.004Si+0.011Mn+0.02Ni+0.012Cr+0.016Mo+0.006Nb+0.0025V\ldots(46)$$

,

wherein the rate of change is determined with the method described in the description.

6. The heat-treated structural material according to claim 5, wherein the range of the hardening ratio f_M is a range determined so that a work-hardening coefficient E_h calculated on the basis of the rate of change is higher than or equal to a work-hardening coefficient E_h in a case where the hardening ratio f_M is 1.

7. The heat-treated structural material according to claim 5, wherein the heat treatment is performed using a laser.

Patentansprüche

1. Wärmebehandlungsverfahren eines Strukturmaterials (10), das ein Stahlmaterial ist und aufweist: Flachabschnitte (11) mit sich in einer Längsrichtung des Strukturmaterials (10) erstreckenden Flachblechformen, einen Biegeabschnitt (12), der sich in Längsrichtung des Strukturmaterials (10) zwischen den Flachabschnitten (11) erstreckt und eine Biegung in einer Richtung senkrecht zur Längsrichtung hat, und einen hutförmigen Querschnitt mit fünf Flachabschnitten, die so angeordnet sind, dass ihr Querschnitt eine Hutform hat, wobei das Wärmebehandlungsverfahren aufweist:

Bestimmen einer Wirkbreite (e) des Biegeabschnitts (12);
Festlegen eines Wirkbreitengebiets (15) als Gebiet, das den Biegeabschnitt (12) aufweist und dessen Abstand in senkrechter Richtung zur Längsrichtung vom Biegeabschnitt (12) innerhalb der Wirkbreite (e) liegt;
Festlegen eines Verfestigungsverhältnisses f_M als ein Verhältnis zwischen einem Gebiet, das durch eine Wärmebehandlung im Wirkbreitengebiet (15) abschreckgehärtet wird, und dem Wirkbreitengebiet (15),
wobei das Gebiet des gehärteten Gebiets in einem Querschnitt senkrecht zur Längsrichtung gemessen wird und wobei in einem Fall, in dem hinsichtlich chemischer Komponenten, die im Strukturmaterial (10) enthalten sind, ein Massenanteil von Kohlenstoff als C festgelegt ist, ein Massenanteil von Silizium als Si festgelegt ist, ein Massenanteil von Mangan als Mn festgelegt ist, ein Massenanteil von Nickel als Ni festgelegt ist, ein Massenanteil von Chrom als Cr festgelegt ist, ein Massenanteil von Molybdän als Mo festgelegt ist, ein Massenanteil von Niob als Nb festgelegt ist und ein Massenanteil von Vanadium als V festgelegt ist, das durch die Wärmebehandlung gehärtete Gebiet ein Gebiet ist, das eine Härte hat, die gleich oder größer als eine durch die folgenden Ausdrücke (45) und (46) berechnete Vickershärte ist:

$$H_v = 0{,}8(950C_{eq} + 260) \quad \ldots (45),$$

$$C_{eq} = C + 0{,}004Si + 0{,}011Mn + 0{,}02Ni + 0{,}012Cr + 0{,}016Mo + 0{,}006Nb + 0{,}0025V \quad \ldots (46),$$

Bestimmen eines Bereichs des Verfestigungsverhältnisses f_M auf der Grundlage einer Änderungsgeschwindigkeit einer Streckgrenze σ_Y im Hinblick auf das Verfestigungsverhältnis f_M; und
Durchführen der Wärmebehandlung am Wirkbreitengebiet (15) des Strukturmaterials (10), um den Bereich des Verfestigungsverhältnisses f_M zu erfüllen,
wobei das Gebiet in jedem der Flachabschnitte (11), das die Drucklast hauptsächlich aufnimmt, ein Gebiet ist, dessen Abstand in Breitenrichtung vom Biegeabschnitt (12) innerhalb der Wirkbreite (e) liegt, und die Wirkbreite (e) festgelegt ist durch den folgenden Ausdruck (15):

$$e = \frac{1}{2\sigma_{Y0}} \int_0^w \sigma_x dw \quad \ldots (15)$$

bei Festlegung des Mittelwerts der Höhe und der Breite des Kopfabschnitts des Strukturmaterials (10) im hutförmigen Querschnitt als w, einer Streckgrenze in dem Fall, in dem das Verfestigungsverhältnis f_M 0 beträgt, als σ_{Y0} und einer Spannung an jeder Position in Breitenrichtung senkrecht zur Längsrichtung als σ_x, wenn eine Spannung, bei der eine maximale Spannung in Längsrichtung des Strukturmaterials (10) σ_{Y0} beträgt, in Längsrichtung vorliegt,
oder
durch den folgenden Ausdruck (18B)

$$e = \frac{t}{2}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1.90 - \frac{t}{w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad \ldots (18B)$$

bei Festlegung eines Dickenmaßes als t, eines Poissonschen Verhältnisses als v, eines Elastizitätsmoduls als E und einer Streckgrenze in einem Fall, in dem das Verfestigungsverhältnis f_M 0 beträgt, als σ_{Y0},

oder
durch den folgenden Ausdruck (47)
bei Festlegung eines Dickenmaßes als t, eines Elastizitätsmoduls als E und einer Streckgrenze in einem Fall, in dem das Verfestigungsverhältnis f_M 0 beträgt, als σ_{Y0}:

$$e = \frac{t}{1.052}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1 - \frac{0.44t}{1.052w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad \ldots(47)$$,

und
wobei die Änderungsgeschwindigkeit ein Wert in einem Fall ist, in dem ein Wert des Verfestigungsverhältnisses f_M 0 beträgt, und
wobei bei Festlegung einer Differenz zwischen einer Fließspannung, die als Dehngrenze, wenn 5 %ige plastische Dehnung auftritt, in einem Fall festgelegt ist, in dem das Verfestigungsverhältnis f_M 1 beträgt, und einer Fließspannung in dem Fall,
in dem das Verfestigungsverhältnis f_M 0 beträgt, als $\Delta\sigma_h$, einer Differenz zwischen einer Streckgrenze in dem Fall, in dem das Verfestigungsverhältnis f_M 1 beträgt, und einer Streckgrenze in dem Fall, in dem das Verfestigungsverhältnis f_M 0 beträgt, als $\Delta\sigma_Y$, und der Änderungsgeschwindigkeit als b, der Bereich des Verfestigungsverhältnisses f_M gleich oder größer als $f_{M\text{-}min}$, ausgedrückt durch den folgenden Ausdruck (32), und kleiner als 1 ist, und optional der Bereich des Verfestigungsverhältnisses f_M gleich oder kleiner als $f_{M\text{-}max}$, ausgedrückt durch den folgenden Ausdruck (33), ist:

$$f_{M\text{-}min} = \frac{\Delta\sigma_h - \Delta\sigma_Y}{\Delta\sigma_Y - b} \quad \ldots(32)$$,

$$f_{M\text{-}max} = \frac{\Delta\sigma_h - b}{2(\Delta\sigma_Y - b)} \quad \ldots(33)$$,

wobei die Änderungsgeschwindigkeit mit dem in der Beschreibung dargestellten Verfahren bestimmt wird.

2. Wärmebehandlungsverfahren nach Anspruch 1,

wobei ein Grenzverfestigungsverhältnis f_M, bei dem die Änderungsgeschwindigkeit gleich einer Änderungsgeschwindigkeit der Fließspannung σ_h im Hinblick auf das Verfestigungsverhältnis f_M wird, als $f_{M\text{-}max}$ bestimmt wird und der Bereich des Verfestigungsverhältnisses f_M auf der Grundlage von $f_{M\text{-}max}$ bestimmt wird, und wobei optional der Bereich des Verfestigungsverhältnisses f_M in einem Bereich bestimmt wird, der den folgenden Ausdruck (37) erfüllt, oder
wobei optional der Bereich des Verfestigungsverhältnisses f_M so bestimmt wird, dass er gleich oder größer als ein Verfestigungsverhältnis $f_{M\text{-}min}$ ist, wobei das Verfestigungsverhältnis $f_{M\text{-}min}$ ein Verfestigungsverhältnis in einem Fall ist, in dem ein Kaltverfestigungskoeffizient E_h gleich dem Kaltverfestigungskoeffizient E_h, wenn das Verfestigungsverhältnis f_M 1 beträgt, und kleiner als 1 ist:

$$0{,}5f_{M\text{-}max} \leq f_M < 1 \quad \ldots(37).$$

3. Wärmebehandlungsverfahren nach Anspruch 1,
wobei die Wärmebehandlung mit Hilfe eines Lasers durchgeführt wird.

4. Wärmebehandlungsverfahren nach Anspruch 1,
wobei ein Durchgang der Wärmebehandlung über die gesamte Länge der Längsrichtung kontinuierlich durchgeführt wird.

5. Strukturmaterial, das ein Stahlmaterial ist, das gemäß dem Verfahren nach einem der vorstehenden Ansprüche 1

bis 4 wärmebehandelt ist, und aufweist: Flachabschnitte (11) mit sich in Längsrichtung des Strukturmaterials (10) erstreckenden Flachblechformen, einen Biegeabschnitt (12), der sich in Längsrichtung des Strukturmaterials (10) zwischen den Flachabschnitten (11) erstreckt und eine Biegung in einer Richtung senkrecht zur Längsrichtung hat, und einen hutförmigen Querschnitt mit fünf Flachabschnitten, die so angeordnet sind, dass ihr Querschnitt eine Hutform hat,
wobei bei Festlegung eines Gebiets, das den Biegeabschnitt (12) aufweist und dessen Abstand in senkrechter Richtung zur Längsrichtung vom Biegeabschnitt (12) innerhalb einer Wirkbreite (e) liegt, als Wirkbreitengebiet (15) und eines Verhältnisses zwischen einem Gebiet, das durch eine Wärmebehandlung im Wirkbreitengebiet (15) abschreckgehärtet ist, und dem Wirkbreitengebiet als Verfestigungsverhältnis f_M, das Verfestigungsverhältnis f_M kleiner als 1 ist und in einem Bereich des Verfestigungsverhältnisses f_M enthalten ist, der auf der Grundlage einer Änderungsgeschwindigkeit einer Streckgrenze σ_Y im Hinblick auf das Verfestigungsverhältnis f_M bestimmt ist, wobei das Gebiet in jedem der Flachabschnitte (11), das die Drucklast hauptsächlich aufnimmt, ein Gebiet ist, dessen Abstand in Breitenrichtung vom Biegeabschnitt (12) innerhalb der Wirkbreite (e) liegt, und die Wirkbreite (e) festgelegt ist durch den folgenden Ausdruck (15):

$$e = \frac{1}{2\sigma_{Y0}} \int_0^w \sigma_x dw \quad \ldots(15)$$

bei Festlegung des Mittelwerts der Höhe und der Breite des Kopfabschnitts des Strukturmaterials (10) im hutförmigen Querschnitt als w, einer Streckgrenze in dem Fall, in dem das Verfestigungsverhältnis f_M 0 beträgt, als σ_{Y0} und bei Festlegung einer Spannung an jeder Position in Breitenrichtung senkrecht zur Längsrichtung als σ_x, wenn eine Spannung, bei der eine maximale Spannung in Längsrichtung des Strukturmaterials (10) σ_{Y0} beträgt, in Längsrichtung vorliegt,
oder
durch den folgenden Ausdruck (18B)

$$e = \frac{t}{2}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1.90 - \frac{t}{w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad \ldots(18B)$$

bei Festlegung eines Dickenmaßes als t, eines Poissonschen Verhältnisses als v, eines Elastizitätsmoduls als E und einer Streckgrenze in einem Fall, in dem das Verfestigungsverhältnis f_M 0 beträgt, als σ_{Y0}
oder
durch den folgenden Ausdruck (47)

bei Festlegung eines Dickenmaßes als t, eines Elastizitätsmoduls als E und einer Streckgrenze in einem Fall, in dem das Verfestigungsverhältnis f_M 0 beträgt, als σ_{Y0}:

$$e = \frac{t}{1.052}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1 - \frac{0.44t}{1.052w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad \ldots(47)$$

,

und

wobei die Änderungsgeschwindigkeit ein Wert in einem Fall ist, in dem ein Wert des Verfestigungsverhältnisses f_M 0 beträgt, und
wobei bei Festlegung einer Differenz zwischen einer Fließspannung, die als Dehngrenze, wenn 5 %ige plastische Dehnung auftritt, in einem Fall festgelegt ist, in dem das Verfestigungsverhältnis f_M 1 beträgt, und einer Fließspannung in dem Fall, in dem das Verfestigungsverhältnis f_M 0 beträgt, als $\Delta\sigma_h$, einer Differenz zwischen einer Streckgrenze in dem Fall, in dem das Verfestigungsverhältnis f_M 1 beträgt, und einer Streckgrenze in dem Fall, in dem das Verfestigungsverhältnis f_M 0 beträgt, als $\Delta\sigma_Y$, und der Änderungsgeschwindigkeit als b, der Bereich des Verfestigungsverhältnisses f_M gleich oder größer als $f_{M\text{-}min}$, ausgedrückt durch den folgenden

Ausdruck (32), und kleiner als 1 ist, und optional der Bereich des Verfestigungsverhältnisses f_M gleich oder kleiner als $f_{M\text{-}max}$, ausgedrückt durch den folgenden Ausdruck (33), ist:

$$f_{M-\min} = \frac{\Delta\sigma_h - \Delta\sigma_Y}{\Delta\sigma_Y - b} \quad \ldots(32)$$

,

$$f_{M-\max} = \frac{\Delta\sigma_h - b}{2(\Delta\sigma_Y - b)} \quad \ldots(33)$$

,

wobei das Gebiet des gehärteten Gebiets in einem Querschnitt senkrecht zur Längsrichtung gemessen wird und

wobei in einem Fall, in dem hinsichtlich chemischer Komponenten, die im Strukturmaterial (10) enthalten sind, ein Massenanteil von Kohlenstoff als C festgelegt ist, ein Massenanteil von Silizium als Si festgelegt ist, ein Massenanteil von Mangan als Mn festgelegt ist, ein Massenanteil von Nickel als Ni festgelegt ist, ein Massenanteil von Chrom als Cr festgelegt ist, ein Massenanteil von Molybdän als Mo festgelegt ist, ein Massenanteil von Niob als Nb festgelegt ist und ein Massenanteil von Vanadium als V festgelegt ist, das durch die Wärmebehandlung gehärtete Gebiet ein Gebiet ist, das eine Härte hat, die gleich oder größer als eine durch die folgenden Ausdrücke (45) und (46) berechnete Vickershärte ist:

$$H_v = 0{,}8(950C_{eq} + 260) \quad \ldots (45),$$

$$C_{eq} = C + 0{,}004Si + 0{,}011Mn + 0{,}02Ni + 0{,}012Cr + 0{,}016Mo + 0{,}006Nb + 0{,}0025V \quad \ldots (46),$$

wobei die Änderungsgeschwindigkeit mit dem in der Beschreibung dargestellten Verfahren bestimmt wird.

6. Wärmebehandeltes Strukturmaterial nach Anspruch 5,
wobei der Bereich des Verfestigungsverhältnisses f_M ein Bereich ist, der so bestimmt ist, dass ein auf der Grundlage der Änderungsgeschwindigkeit berechneter Kaltverfestigungskoeffizient E_h gleich oder größer als ein Kaltverfestigungskoeffizient E_h in einem Fall ist, in dem das Verfestigungsverhältnis f_M 1 beträgt.

7. Wärmebehandeltes Strukturmaterial nach Anspruch 5,
wobei die Wärmebehandlung mit Hilfe eines Lasers durchgeführt ist.

Revendications

1. Procédé de traitement thermique d'un matériau structurel (10) qui est un matériau en acier, comprend des portions planes (11) ayant des formes de feuilles planes s'étendant dans une direction longitudinale du matériau structurel (10), une portion courbée (12) qui s'étend dans la direction longitudinale du matériau structurel (10) entre les portions planes (11) et présente une courbure dans une direction perpendiculaire à la direction longitudinale, et une section transversale en forme de chapeau incluant cinq portions planes qui sont disposées de sorte que la section transversale de celles-ci présente une forme de chapeau, le procédé de traitement thermique comprenant :

la détermination d'une largeur effective (e) de la portion courbée (12) ;
la définition d'une surface de largeur effective (15) comme une surface qui inclut la portion courbée (12) et dont une distance dans la direction perpendiculaire à la direction longitudinale à partir de la portion courbée (12) se trouve dans la largeur effective (e) ;
la définition d'un taux de durcissement f_M comme un taux entre une surface qui est durcie par trempe par un traitement thermique dans la surface de largeur effective (15) et la surface de largeur effective (15),
dans lequel la surface de la surface durcie est mesurée dans une section transversale perpendiculaire à la

direction longitudinale, et
dans lequel, dans un cas où, en considérant les constituants chimiques contenus dans le matériau structurel (10), un pourcentage en masse de carbone est défini par C, un pourcentage en masse de silicium est défini par Si, un pourcentage en masse de manganèse est défini par Mn, un pourcentage en masse de nickel est défini par Ni, un pourcentage en masse de chrome est défini par Cr, un pourcentage en masse de molybdène est défini par Mo, un pourcentage en masse de niobium est défini par Nb, et un pourcentage en masse de vanadium est défini par V, la surface durcie par le traitement thermique est une surface qui présente une dureté supérieure ou égale à une dureté Vickers calculée par les expressions (45) et (46) suivantes,

$$Hv = 0{,}8\ (950C_{eq} + 260)\ ...\ (45)$$

$$C_{eq} = C+0{,}004Si+0{,}011Mn+0{,}02Ni+0{,}012Cr+0{,}016Mo+0{,}006Nb+0{,}0025V...\ (46)$$

la détermination d'un intervalle du taux de durcissement f_M sur la base d'un taux de variation dans une limite d'élasticité σ_Y par rapport au taux de durcissement f_M ; et
la réalisation du traitement thermique sur la surface de largeur effective (15) du matériau structurel (10) pour satisfaire l'intervalle du taux de durcissement f_M,
dans lequel la surface dans chacune des portions planes (11) qui reçoit principalement la charge compressive est une surface dont la distance dans la direction de largeur à partir de la portion courbée (12) se trouve dans la largeur effective (e) et la largeur effective (e) est définie par l'expression (15) suivante,

$$e=\frac{1}{2\sigma_{Y0}}\int_0^w \sigma_x dw \quad ...(15)$$

lorsque la valeur moyenne de la hauteur et la largeur de la portion de haut du matériau structurel (10) dans la section transversale en forme de chapeau est définie par w, une limite d'élasticité dans le cas où le taux de durcissement f_M est égal à 0 est définie par σ_{Y0}, et une contrainte à chaque position dans une direction de largeur perpendiculaire à la direction longitudinale lorsqu'une contrainte à laquelle une contrainte maximale dans la direction longitudinale du matériau structurel (10) est σ_{Y0} est donnée dans la direction longitudinale est définie par σ_x,
ou
par l'Expression (18B) suivante,

$$e=\frac{t}{2}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1.90-\frac{t}{w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad ...(18B)$$

lorsqu'une dimension d'épaisseur est définie par t, un coefficient de Poisson est défini par v, un module élastique est défini par E, et une limite d'élasticité dans un cas où le taux de durcissement f_M est égal à 0 est définie par σ_{Y0},
ou
par l'Expression (47) suivante,
lorsqu'une dimension d'épaisseur est définie par t, un module élastique est défini par E, et une limite d'élasticité dans un cas où le taux de durcissement f_M est égal à 0 est défini par σ_{Y0},

$$e=\frac{t}{1.052}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1-\frac{0.44t}{1.052w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad ...(47)$$

,

et

dans lequel le taux de variation est une valeur dans un cas où une valeur du taux de durcissement f_M est égale à 0, et

dans lequel, lorsqu'une différence entre une contrainte d'écoulement, qui est définie comme la limite apparente d'élasticité qui existe lorsqu'une contrainte plastique de 5 % apparaît, dans un cas où le taux de durcissement f_M est égal à 1 et une contrainte d'écoulement dans le cas où le taux de durcissement f_M est égal à 0 est définie par $\Delta\sigma_h$, une différence entre une limite d'élasticité dans le cas où le taux de durcissement f_M est égal à 1 et une limite d'élasticité dans le cas où le taux de durcissement f_M est égal à 0 est définie par $\Delta\sigma_Y$, et le taux de variation est défini par b, l'intervalle du taux de durcissement f_M est supérieur ou égal à $f_{M\text{-}min}$ exprimé par l'Expression (32) suivante et inférieur à 1, et l'intervalle du taux de durcissement f_M est éventuellement inférieur ou égal à $f_{M\text{-}max}$ exprimé par l'Expression (33) suivante,

$$f_{M-\min} = \frac{\Delta\sigma_h - \Delta\sigma_Y}{\Delta\sigma_Y - b} \quad \ldots(32)$$

$$f_{M-\max} = \frac{\Delta\sigma_h - b}{2(\Delta\sigma_Y - b)} \quad \ldots(33)$$

dans lequel le taux de variation est déterminé avec le procédé décrit dans la description.

2. Procédé de traitement thermique selon la revendication 1,

dans lequel un taux de durcissement limite f_M auquel le taux de variation devient égal à un taux de variation dans la contrainte d'écoulement σ_h par rapport au taux de durcissement f_M est déterminé par $f_{M\text{-}max}$, et l'intervalle du taux de durcissement f_M est déterminé sur la base du $f_{M\text{-}max}$, et éventuellement

dans lequel l'intervalle du taux de durcissement f_M est déterminé dans un intervalle qui satisfait l'Expression (37) suivante, ou éventuellement

dans lequel l'intervalle du taux de durcissement f_M est déterminé pour être supérieur ou égal à un taux de durcissement $f_{M\text{-}min}$, dans lequel le taux de durcissement $f_{M\text{-}min}$ est un taux de durcissement dans un cas où un coefficient d'écrouissage E_h est égal au coefficient d'écrouissage E_h lorsque le taux de durcissement f_M est égal à 1, et inférieur à 1,

$$0{,}5 f_{M\text{-}max} \leq f_M < 1 \ \ldots \ (37).$$

3. Procédé de traitement thermique selon la revendication 1, dans lequel le traitement thermique est réalisé en utilisant un laser.

4. Procédé de traitement thermique selon la revendication 1, dans lequel un passage du traitement thermique est réalisé en continu sur la longueur entière de la direction longitudinale.

5. Matériau structurel qui est un matériau en acier traité thermiquement selon le procédé selon l'une quelconque des revendications 1 à 4 précédentes comprenant :

des portions planes (11) ayant des formes de feuilles planes s'étendant dans une direction longitudinale du matériau structurel (10), une portion courbée (12) qui s'étend dans la direction longitudinale du matériau structurel (10) entre les portions planes (11) et présente une courbure dans une direction perpendiculaire à la direction longitudinale, et une section transversale en forme de chapeau incluant cinq portions planes qui sont disposées de sorte que la section transversale de celles-ci présente une forme de chapeau,

dans lequel, dans un cas où une surface qui inclut la portion courbée (12) et dont une distance dans une direction perpendiculaire à la direction longitudinale à partir de la portion courbée (12) se trouve dans une largeur effective

(e) est définie comme une surface de largeur effective (15) et un taux entre une surface qui est durcie par trempe par un traitement thermique dans la surface de largeur effective (15) et la surface de largeur effective est définie comme un taux de durcissement f_M, le taux de durcissement f_M est inférieur à 1 et est contenu dans un intervalle du taux de durcissement f_M déterminé sur la base d'un taux de variation dans une limite d'élasticité σ_Y par rapport au taux de durcissement f_M, dans lequel la surface dans chacune des portions planes (11) qui reçoit principalement la charge compressive est une surface dont la distance dans la direction de largeur à partir de la portion courbée (12) se trouve dans la largeur effective (e) et la largeur effective (e) est définie par l'Expression (15) suivante,

$$e=\frac{1}{2\sigma_{Y0}}\int_0^w \sigma_x dw \quad ...(15)$$

lorsque la valeur moyenne de la hauteur et la largeur de la portion de haut du matériau structurel (10) dans la section transversale en forme de chapeau est définie par w, une limite d'élasticité dans le cas où le taux de durcissement f_M est égal à 0 est définie par σ_{Y0}, et une contrainte à chaque position dans une direction de largeur perpendiculaire à la direction longitudinale lorsqu'une contrainte à laquelle une contrainte maximale dans la direction longitudinale du matériau structurel (10) est σ_{Y0} est donnée dans la direction longitudinale est définie par σ_x,

ou

par l'Expression (18B) suivante,

$$e=\frac{t}{2}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1.90-\frac{t}{w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad ...(18B)$$

lorsqu'une dimension d'épaisseur est définie par t, un coefficient de Poisson est défini par v, un module élastique est défini par E, et une limite d'élasticité dans un cas où le taux de durcissement f_M est égal à 0 est définie par σ_{Y0},

ou

par l'Expression (47) suivante,

lorsqu'une dimension d'épaisseur est définie par t, un module élastique est défini par E, et une limite d'élasticité dans un cas où le taux de durcissement f_M est égal à 0 est définie par σ_{Y0},

$$e=\frac{t}{1.052}\sqrt{\frac{E}{\sigma_{Y0}}}\left(1-\frac{0.44t}{1.052w}\sqrt{\frac{E}{\sigma_{Y0}}}\right) \quad ...(47)$$

et

dans lequel le taux de variation est une valeur dans un cas où une valeur du taux de durcissement f_M est égale à 0, et

dans lequel, lorsqu'une différence entre une contrainte d'écoulement, qui est définie comme la limite apparente d'élasticité qui existe lorsqu'une contrainte plastique de 5 % apparaît, dans un cas où le taux de durcissement f_M est égal à 1 et une contrainte d'écoulement dans le cas où le taux de durcissement f_M est égal à 0 est définie par $\Delta\sigma_h$, une différence entre une limite d'élasticité dans le cas où le taux de durcissement f_M est égal à 1 et une limite d'élasticité dans le cas où le taux de durcissement f_M est égal à 0 est définie par $\Delta\sigma_Y$, et le taux de variation est défini par b, l'intervalle du taux de durcissement f_M est supérieur ou égal à $f_{M\text{-}min}$ exprimé par l'Expression (32) suivante et inférieur à 1, et l'intervalle du taux de durcissement f_M est éventuellement inférieur ou égal à $f_{M\text{-}max}$ exprimé par l'Expression (33) suivante,

$$f_{M\text{-}min} = \frac{\Delta\sigma_h - \Delta\sigma_Y}{\Delta\sigma_Y - b} \quad ...(32)$$

$$f_{M\text{-}max} = \frac{\Delta\sigma_h - b}{2(\Delta\sigma_Y - b)} \quad ...(33)$$

dans lequel la surface de la surface durcie est mesurée dans une section transversale perpendiculaire à la direction longitudinale, et
dans lequel, dans un cas où, en considérant les constituants chimiques contenus dans le matériau structurel (10), un pourcentage en masse de carbone est défini par C, un pourcentage en masse de silicium est défini par Si, un pourcentage en masse de manganèse est défini par Mn, un pourcentage en masse de nickel est défini par Ni, un pourcentage en masse de chrome est défini par Cr, un pourcentage en masse de molybdène est défini par Mo, un pourcentage en masse de niobium est défini par Nb, et un pourcentage en masse de vanadium est défini par V, la surface durcie par le traitement thermique est une surface qui présente une dureté supérieure ou égale à une dureté Vickers calculée par les expressions (45) et (46) suivantes,

$$H\nu = 0{,}8\ (950C_{eq} + 260)\ ...\ (45)$$

$$C_{eq} = C+0{,}004Si+0{,}011Mn+0{,}02Ni+0{,}012Cr+0{,}016Mo+0{,}006Nb+0{,}0025V...\ (46)$$

dans lequel le taux de variation est déterminé avec le procédé décrit dans la description.

6. Matériau structurel traité thermiquement selon la revendication 5,
dans lequel l'intervalle du taux de durcissement f_M se trouve dans un intervalle déterminé de sorte qu'un coefficient d'écrouissage E_h calculé sur la base du taux de variation est supérieur ou égal à un coefficient d'écrouissage E_h dans un cas où le taux de durcissement f_M est égal à 1.

7. Matériau structurel traité thermiquement selon la revendication 5,
dans lequel le traitement thermique est réalisé en utilisant un laser.

FIG. 1

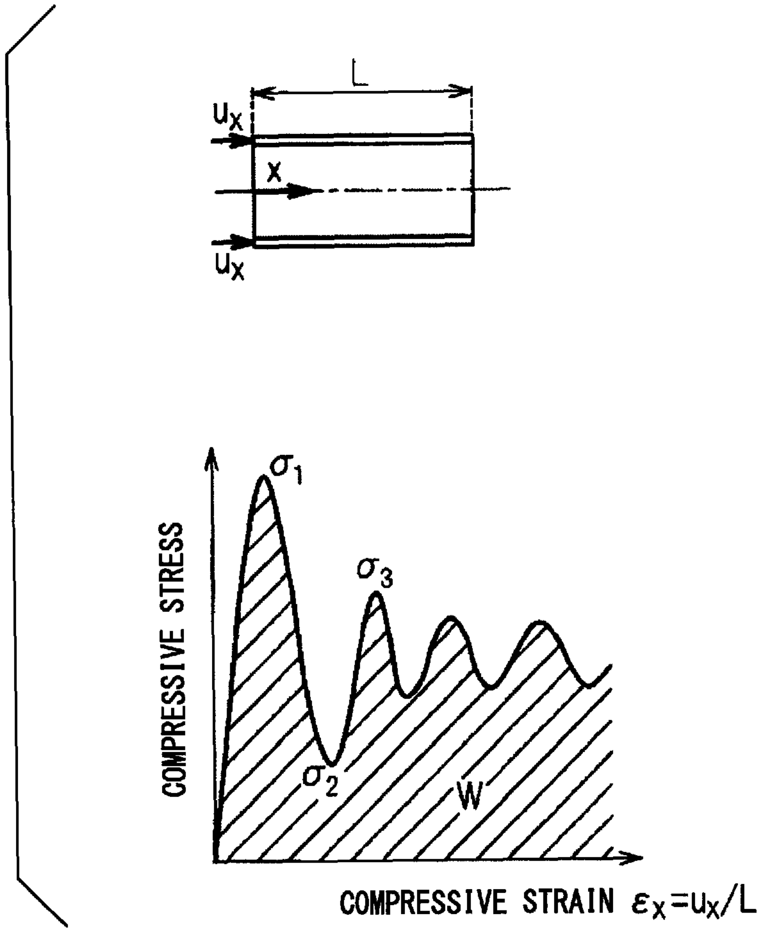

L
ux
x
ux
σ1
σ3
σ2
W
COMPRESSIVE STRESS
COMPRESSIVE STRAIN εx=ux/L

FIG. 2

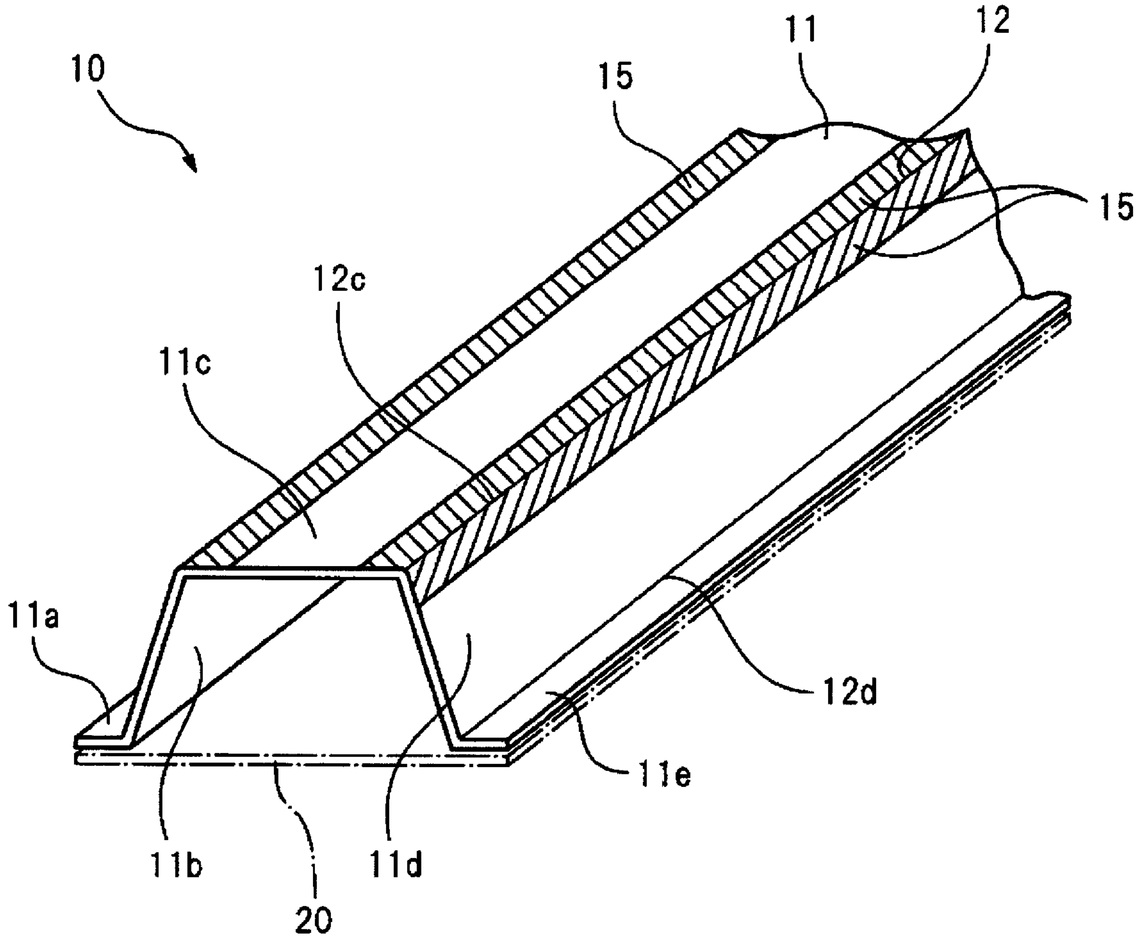


FIG. 3

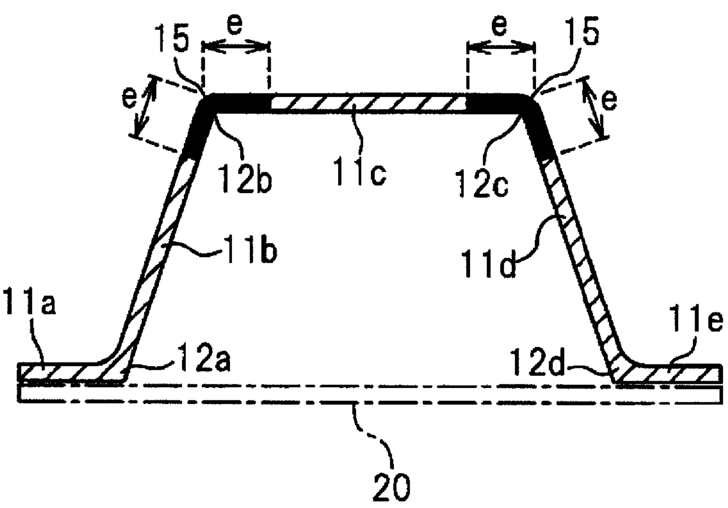


FIG. 4A

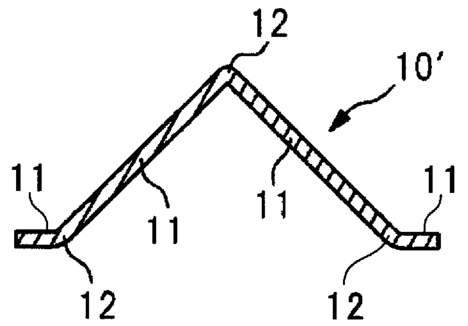


FIG. 4B

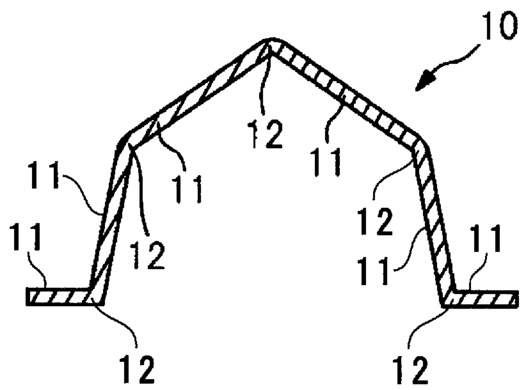


FIG. 4C

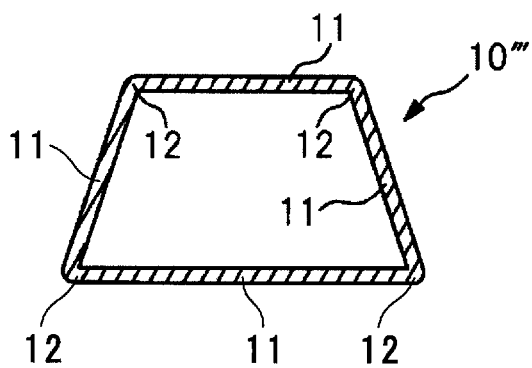


FIG. 5

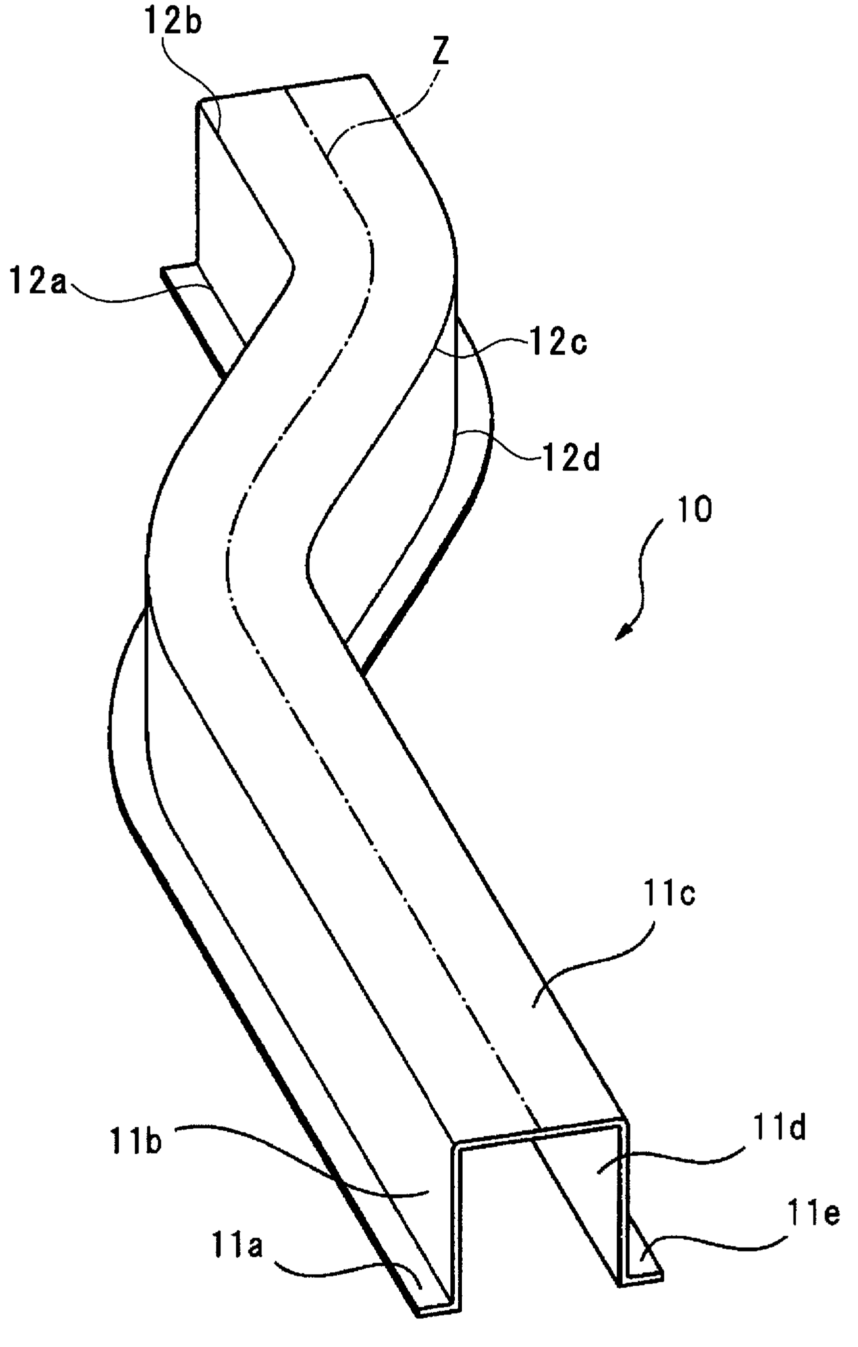


FIG. 6A

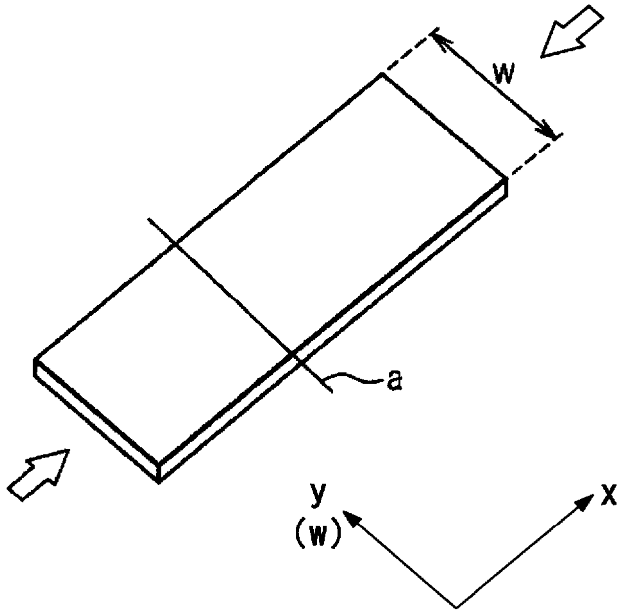


FIG. 6B

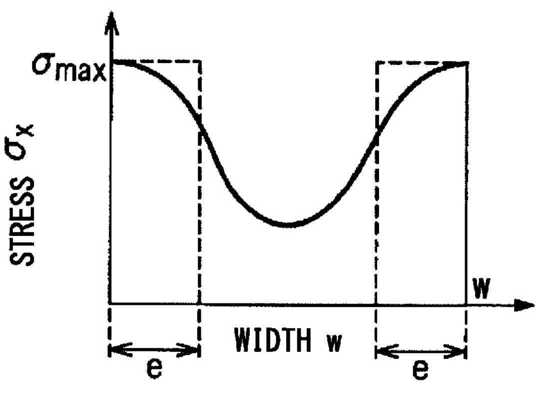


FIG. 7

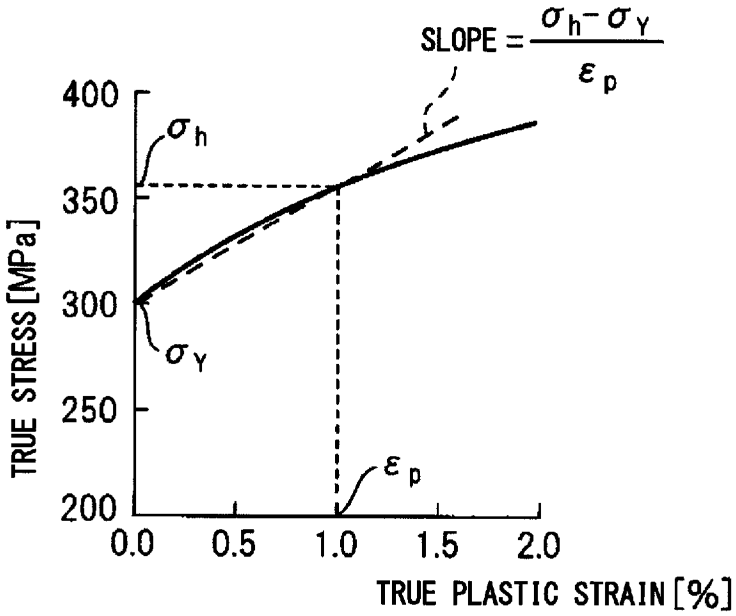

SLOPE = (σh − σY) / εp
400
350
300
250
200
σh
σY
εp
TRUE STRESS [MPa]
0.0
0.5
1.0
1.5
2.0
TRUE PLASTIC STRAIN [%]

FIG. 8

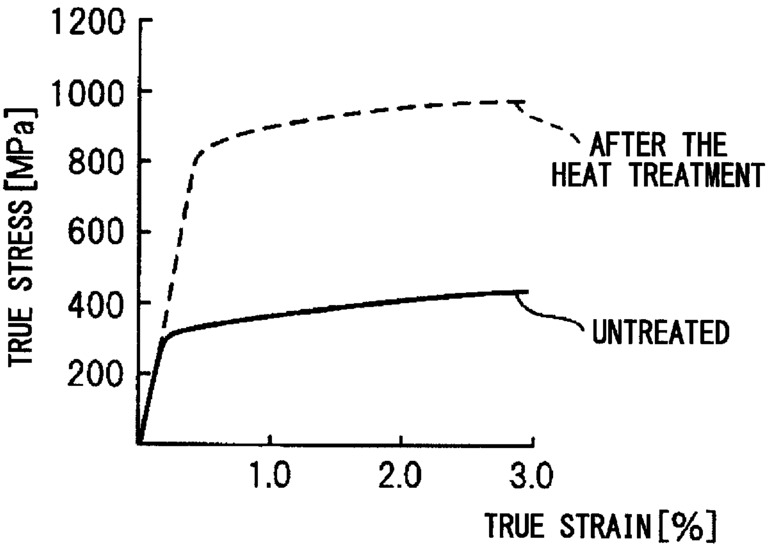
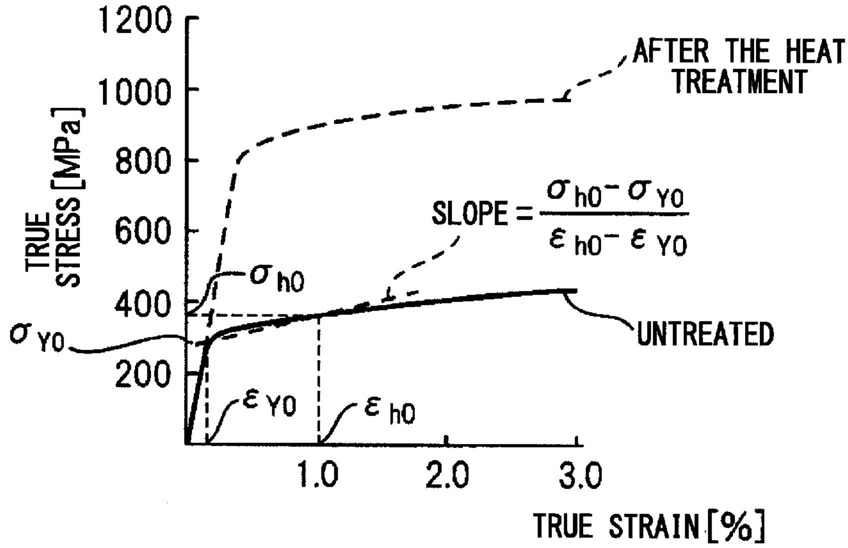
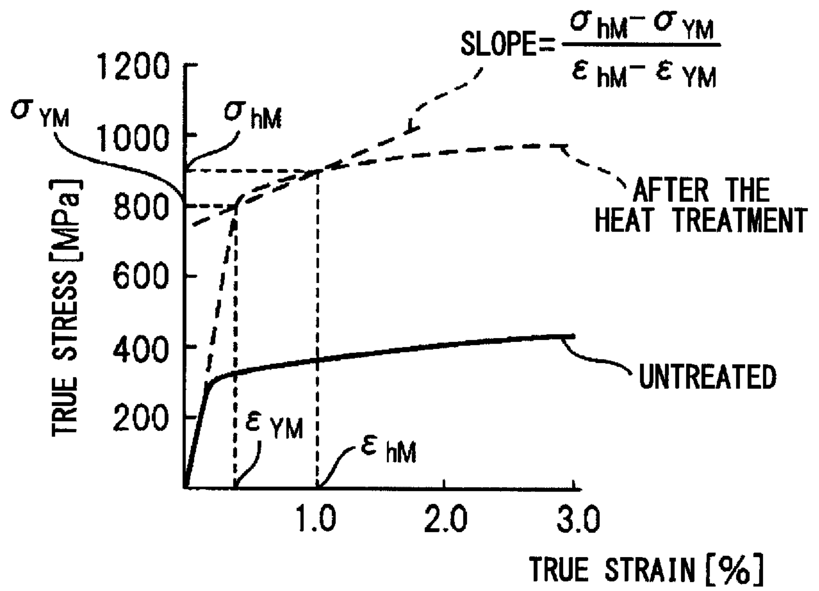

1200
1000
800
600
400
200
TRUE STRESS [MPa]
AFTER THE
HEAT TREATMENT
UNTREATED
1.0
2.0
3.0
TRUE STRAIN [%]

FIG. 9A



AFTER THE HEAT TREATMENT
SLOPE = $\frac{\sigma_{h0} - \sigma_{Y0}}{\varepsilon_{h0} - \varepsilon_{Y0}}$
σ_{h0}
σ_{Y0}
UNTREATED
ε_{Y0}
ε_{h0}
TRUE STRESS [MPa]
1200
1000
800
600
400
200
1.0
2.0
3.0
TRUE STRAIN [%]

FIG. 9B



SLOPE= $\frac{\sigma_{hM} - \sigma_{YM}}{\varepsilon_{hM} - \varepsilon_{YM}}$
σ_{YM}
σ_{hM}
AFTER THE HEAT TREATMENT
UNTREATED
ε_{YM}
ε_{hM}
TRUE STRESS [MPa]
1200
1000
800
600
400
200
1.0
2.0
3.0
TRUE STRAIN [%]

FIG. 10

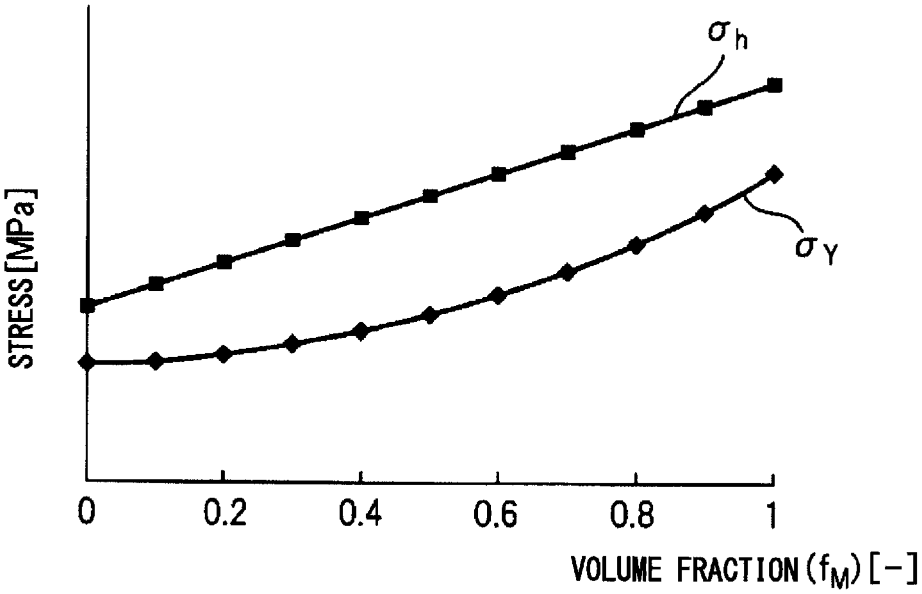

σh
σY
STRESS [MPa]
0
0.2
0.4
0.6
0.8
1
VOLUME FRACTION (fM) [-]

FIG. 11

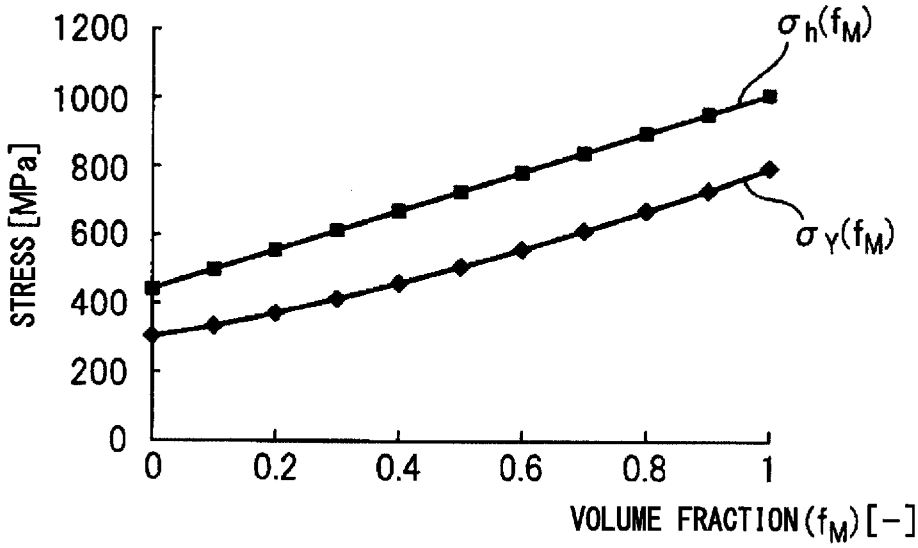

1200
1000
800
600
400
200
0
STRESS [MPa]
σh(fM)
σY(fM)
0
0.2
0.4
0.6
0.8
1
VOLUME FRACTION (fM) [-]

FIG. 12

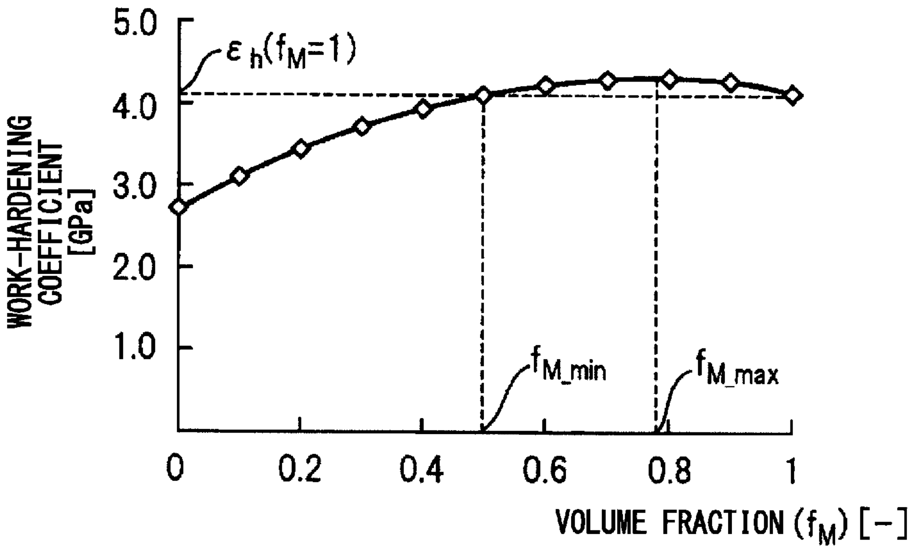

5.0
4.0
3.0
2.0
1.0
ε h(fM=1)
WORK-HARDENING COEFFICIENT [GPa]
fM_min
fM_max
0
0.2
0.4
0.6
0.8
1
VOLUME FRACTION (fM) [-]

FIG. 13A

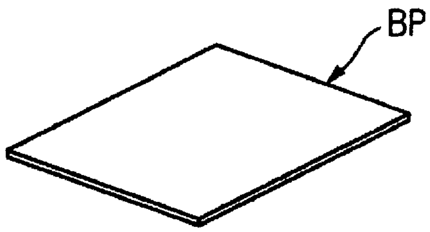


FIG. 13B

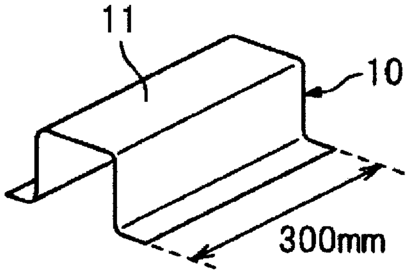


FIG. 13C

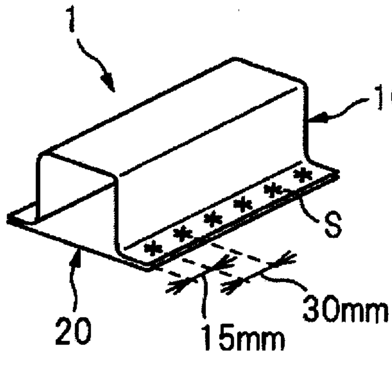


FIG. 14

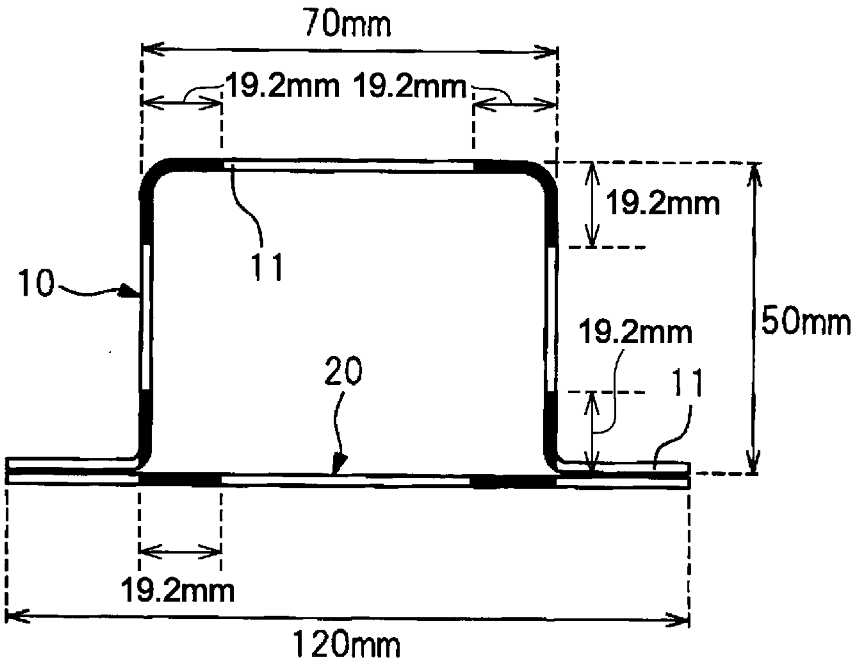


FIG. 15

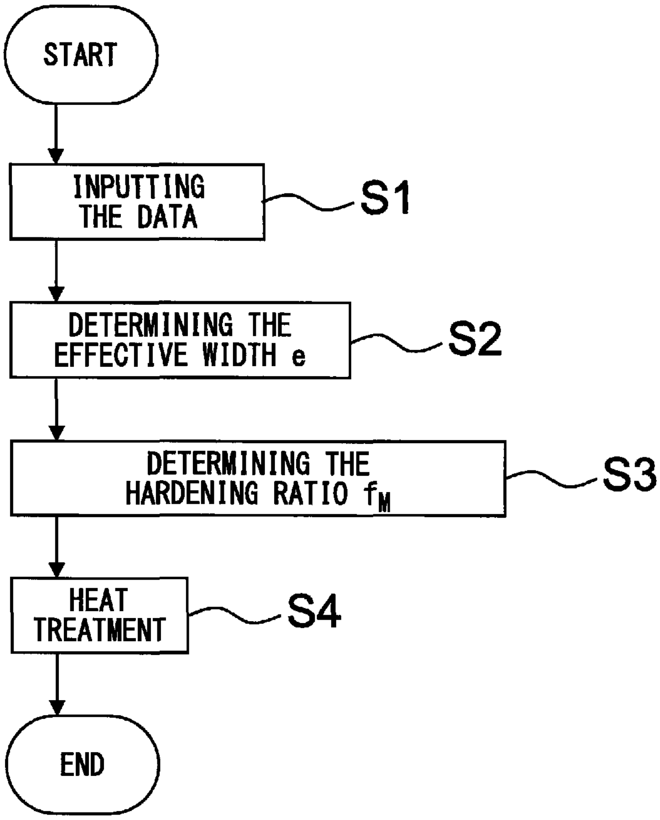

START
INPUTTING THE DATA
S1
DETERMINING THE EFFECTIVE WIDTH e
S2
DETERMINING THE HARDENING RATIO f_M
S3
HEAT TREATMENT
S4
END

FIG. 16

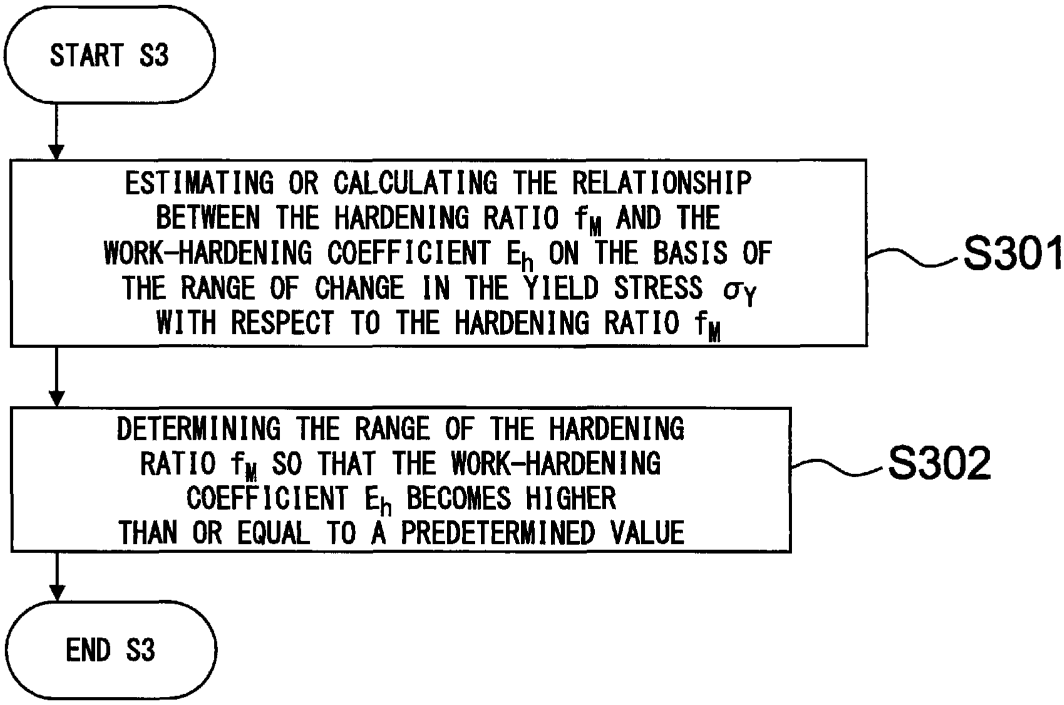

START S3
ESTIMATING OR CALCULATING THE RELATIONSHIP BETWEEN THE HARDENING RATIO f_M AND THE WORK-HARDENING COEFFICIENT E_h ON THE BASIS OF THE RANGE OF CHANGE IN THE YIELD STRESS σ_Y WITH RESPECT TO THE HARDENING RATIO f_M
S301
DETERMINING THE RANGE OF THE HARDENING RATIO f_M SO THAT THE WORK-HARDENING COEFFICIENT E_h BECOMES HIGHER THAN OR EQUAL TO A PREDETERMINED VALUE
S302
END S3

FIG. 17

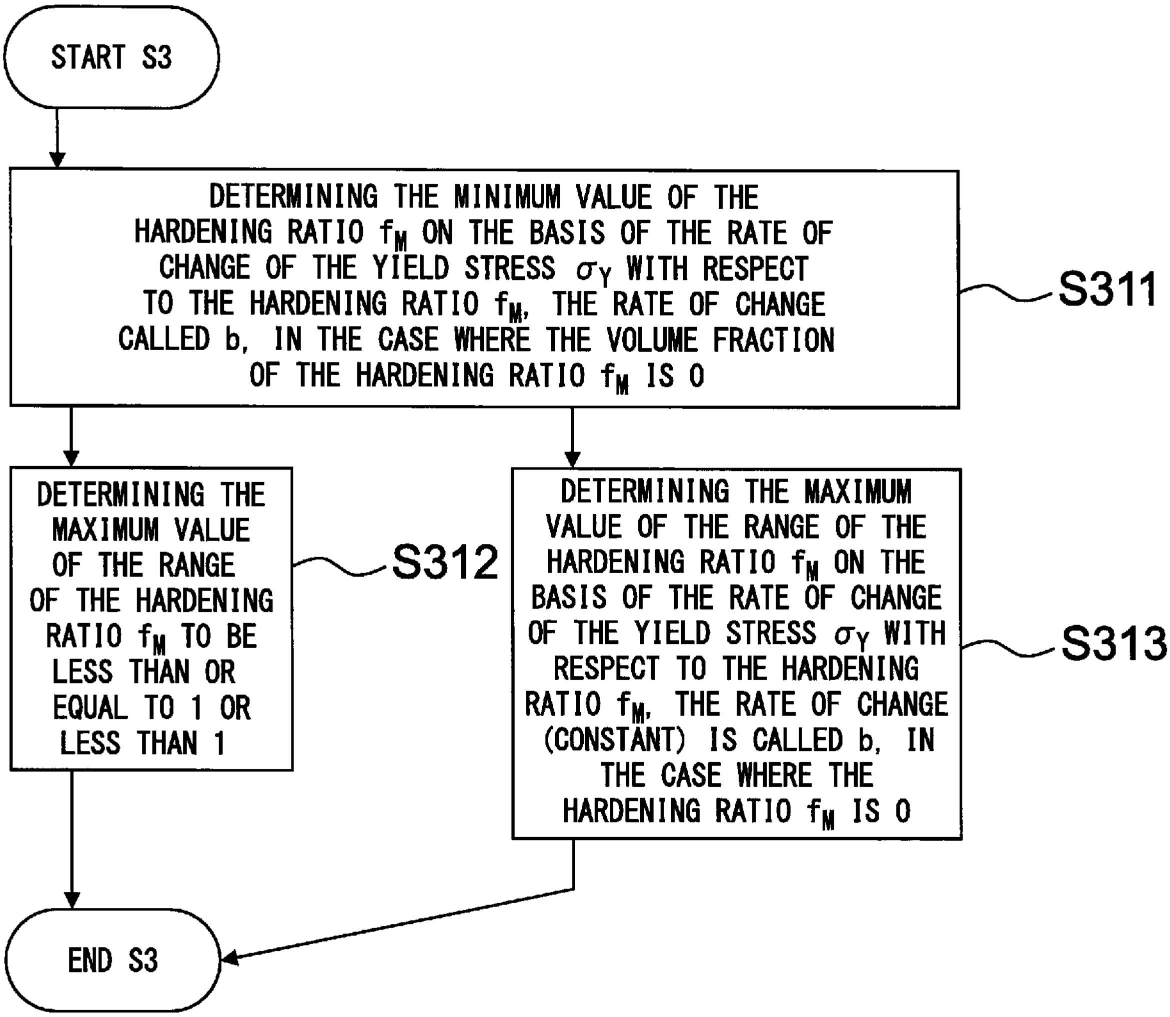
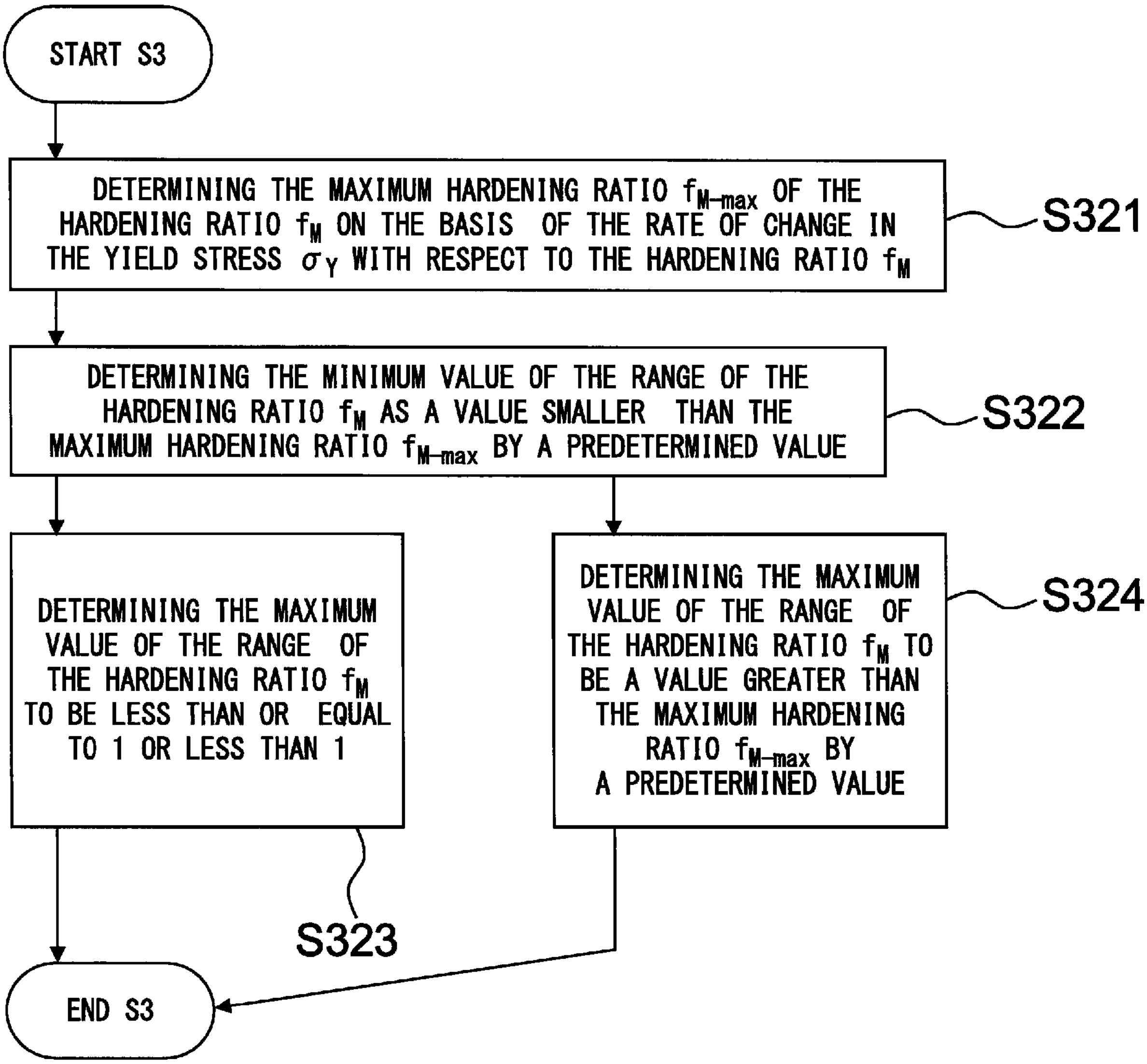

START S3
DETERMINING THE MINIMUM VALUE OF THE HARDENING RATIO f_M ON THE BASIS OF THE RATE OF CHANGE OF THE YIELD STRESS σ_Y WITH RESPECT TO THE HARDENING RATIO f_M, THE RATE OF CHANGE CALLED b, IN THE CASE WHERE THE VOLUME FRACTION OF THE HARDENING RATIO f_M IS 0
S311
DETERMINING THE MAXIMUM VALUE OF THE RANGE OF THE HARDENING RATIO f_M TO BE LESS THAN OR EQUAL TO 1 OR LESS THAN 1
S312
DETERMINING THE MAXIMUM VALUE OF THE RANGE OF THE HARDENING RATIO f_M ON THE BASIS OF THE RATE OF CHANGE OF THE YIELD STRESS σ_Y WITH RESPECT TO THE HARDENING RATIO f_M, THE RATE OF CHANGE (CONSTANT) IS CALLED b, IN THE CASE WHERE THE HARDENING RATIO f_M IS 0
S313
END S3

FIG. 18


START S3
DETERMINING THE MAXIMUM HARDENING RATIO f_M-max OF THE HARDENING RATIO f_M ON THE BASIS OF THE RATE OF CHANGE IN THE YIELD STRESS σ_Y WITH RESPECT TO THE HARDENING RATIO f_M
S321
DETERMINING THE MINIMUM VALUE OF THE RANGE OF THE HARDENING RATIO f_M AS A VALUE SMALLER THAN THE MAXIMUM HARDENING RATIO f_M-max BY A PREDETERMINED VALUE
S322
DETERMINING THE MAXIMUM VALUE OF THE RANGE OF THE HARDENING RATIO f_M TO BE LESS THAN OR EQUAL TO 1 OR LESS THAN 1
S323
DETERMINING THE MAXIMUM VALUE OF THE RANGE OF THE HARDENING RATIO f_M TO BE A VALUE GREATER THAN THE MAXIMUM HARDENING RATIO f_M-max BY A PREDETERMINED VALUE
S324
END S3

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- JP 61099629 A **[0004] [0005] [0009] [0016]**
- JP H472010 A **[0004] [0006] [0009] [0016]**
- JP H673439 A **[0004] [0007] [0009] [0016]**
- JP 2004108541 A **[0004] [0008] [0009] [0016]**
- JP H07119892 A **[0010]**
- JP 2004114912 A **[0011]**
- FR 2849059 A1 **[0012]**