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CA 2278841 C 2007/05/01

(11)(21) 2 278 841

(12) BREVET CANADIEN
CANADIAN PATENT

(13) C

(86) Date de dépôt PCT/PCT Filing Date: 1998/01/23
(87) Date publication PCT/PCT Publication Date: 1998/07/30
(45) Date de délivrance/Issue Date: 2007/05/01
(85) Entrée phase nationale/National Entry: 1999/07/27
(86) N° demande PCT/PCT Application No.: JP 1998/000272
(87) N° publication PCT/PCT Publication No.: 1998/032889
(30) Priorités/Priorities: 1997/01/29 (JP9-28296);
1997/07/15 (JP9-190298); 1997/07/15 (JP9-190297);
1997/08/06 (JP9-223005); 1997/09/24 (JP9-258834);
1997/09/24 (JP9-258887); 1997/09/24 (JP9-258865);
1997/09/24 (JP9-258939); 1997/09/24 (JP9-258928)

(51) Cl.Int./Int.Cl. *C22C 38/00* (2006.01),
C21D 8/02 (2006.01), *C21D 8/04* (2006.01),
C22C 38/04 (2006.01)

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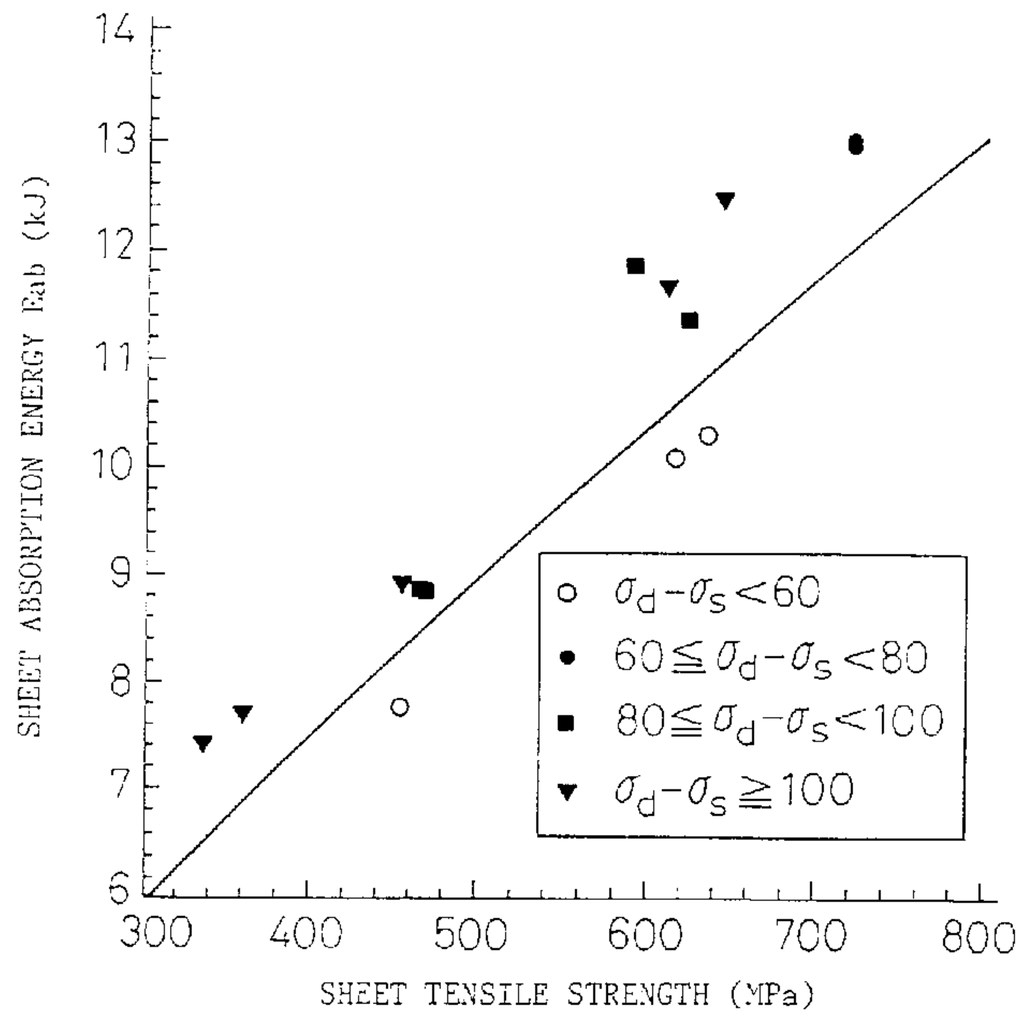
(54) Titre : ACIERS A HAUTE RESISTANCE A FORMABILITE EXCELLENTE ET A PROPRIETES D'ABSORPTION D'ENERGIE A RENDEMENT ELEVE, ET METHODE DE FABRICATION CONNEXE

(54) Title: HIGH STRENGTH STEELS HAVING EXCELLENT FORMABILITY AND HIGH IMPACT ENERGY ABSORPTION PROPERTIES, AND A METHOD FOR PRODUCING THE SAME



(57) Abrégé/Abstract:
The object of the present invention is to provide high-strength steel sheets exhibiting high impact energy absorption properties, as steel sheets to be used for shaping and working into such parts to front side members which absorb impact energy upon collision, as well as a method for their production. The high-strength steel sheets of the invention which exhibit high impact energy absorption properties are press formable high-strength steel sheets with high flow stress during dynamic deformation characterized in that the microstructure of the steel sheets in their final form is a composite microstructure of a mixture of ferrite and/or bainite, either of which is the dominant phase, and a third phase including retained austenite at a volume fraction between 3% and 50%, wherein the difference between the static tensile strength σs when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10%, and the dynamic tensile strength σd when deformed at a strain rate of $5 \times 10^{2} \sim 5 \times 10^{3}$ (1/sec) after the pre-deformation, i.e. σd - σs, is at least 60 MPa, and the work hardening coefficient between 5% and 10% of a strain is at least 0.130.

CA 2278841 C 2007/05/01

(11)(21) 2 278 841

(13) C

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SUMMARY

The object of the present invention is to provide high-strength steel sheets exhibiting high impact energy absorption properties, as steel sheets to be used for shaping and working into such parts to front side members which absorb impact energy upon collision, as well as a method for their production. The high-strength steel sheets of the invention which exhibit high impact energy absorption properties are press formable high-strength steel sheets with high flow stress during dynamic deformation characterized in that the microstructure of the steel sheets in their final form is a composite microstructure of a mixture of ferrite and/or bainite, either of which is the dominant phase, and a third phase including retained austenite at a volume fraction between 3% and 50%, wherein the difference between the static tensile strength σs when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10%, and the dynamic tensile strength σd when deformed at a strain rate of $5 \times 10^{2} \sim 5 \times 10^{3}$ (1/sec) after the pre-deformation, i.e. σd - σs, is at least 60 MPa, and the work hardening coefficient between 5% and 10% of a strain is at least 0.130.

DESCRIPTION

HIGH STRENGTH STEELS HAVING EXCELLENT FORMABILITY AND HIGH IMPACT ENERGY ABSORPTION PROPERTIES, AND A METHOD FOR PRODUCING THE SAME

Technical Field

The present invention relates to press formable, high strength hot rolled and cold rolled steel sheets having high flow stress during dynamic deformation, which can be used for automobile members and the like to provide assurance of safety for passengers by efficiently absorbing the impact energy of a collision, as well as a method for producing the same.

Background Art

In recent years, protection of passengers from automobile collisions has been acknowledged as an aspect of utmost importance for automobiles, and hopes are increasing for suitable materials exhibiting excellent high-speed deformation resistance. For example, by applying such materials to front side members of automobiles, the energy of frontal collisions may be absorbed as the materials are crushed, thus alleviating the impact on passengers.

Since the strain rate for deformation undergone by each section of an automobile upon collision reaches about 10^3 (1/s), consideration of the impact absorption performance of a material requires knowledge of its dynamic deformation properties in a high strain rate range. Because it is also essential to consider at the same time such factors as energy savings and CO_2 exhaust reduction, as well as weight reduction of the automobile, requirements for effective high-strength steel sheets are therefore increasing.

For example, in CAMP-ISIJ Vol. 9 (1996), pp.1112-1115 the present inventors have reported on the high-

speed deformation properties and impact energy absorption of high-strength thin steel sheets, and in that article it was reported that the dynamic strength in the high strain rate range of about 10^3 (1/s) is drastically increased in comparison to the static strength in the low strain rate of 10^{-3} (1/s), that the strain rate dependence for deformation resistance varies based on the strengthening mechanism for the material, and that TRIP (transformation induced plasticity) steel sheets and DP (ferrite/martensite dual phase) steel sheets possess both excellent formability and impact absorption properties compared to other high strength steel sheets.

Furthermore, Japanese Unexamined Patent Publication No. 7-18372, which provides retained austenite-containing high strength steel sheets with excellent impact resistance and a method for their production, discloses a solution for impact absorption simply by increasing the yield stress brought about by a higher deformation rate; however, it has not been demonstrated what other aspects of the retained austenite should be controlled, apart from the amount of retained austenite, in order to improve impact absorption.

Thus, although understanding continues to improve with regard to the dynamic deformation properties of member constituent materials affecting absorption of impact energy in automobile collisions, it is still not fully understood what properties should be maximized to obtain steel materials for automotive members with more excellent impact energy absorption properties, and on what criteria the selection of materials should be based.

Steel materials for automotive members are formed into the required part shapes by press molding and, after usually undergoing painting and baking, are then incorporated into automobiles and subjected to actual instances of impact. However, it is still not clear what steel-strengthening mechanisms are suitable for improving

the impact energy absorption of steel materials against collisions subsequent to such pre-deformation and baking treatment.

Disclosure of the Invention

It is an object of the present invention to provide high-strength steel sheets with high impact energy absorption properties as steel materials for shaping and forming into such parts as front side members which absorb impact energy upon collision, as well as a method for their production. First, the high-strength steel sheets exhibiting high impact energy absorption properties according to the present invention include:

(1) The press formable high-strength steel sheets with high flow stress during dynamic deformation, characterized in that the microstructure of the steel sheets in their final form is a composite microstructure of a mixture of ferrite and/or bainite, either of which is the dominant phase, and a third phase including retained austenite at a volume fraction between 3% and 50%, wherein the difference between the static tensile strength σs when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10%, and the tensile deformation strength σd when deformed at a strain rate of $5 \times 10^{2} \sim 5 \times 10^{3}$ (1/s) after the aforementioned pre-deformation, i.e. σd - σs, is at least 60 MPa, and the work hardening coefficient between 5% and 10% of a strain is at least 0.130; and

(2) The press formable high-strength steel sheets with high flow stress during dynamic deformation, characterized in that the microstructure of the steel sheets in their final form is a composite microstructure of a mixture of ferrite and/or bainite, either of which is the dominant phase, and a third phase including retained austenite at a volume fraction between 3% and 50%, wherein the difference between the static tensile

strength σs when deformed in a strain rate range of 5 x 10^{-4} ~ 5 x 10^{-3} (1/s) after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10%, and the dynamic tensile strength σd when deformed at a strain rate of 5 x 10^{2} ~ 5 x 10^{3} (1/s) after the aforementioned pre-deformation, i.e. σd - σs, is at least 60 MPa, the difference between the average value σdyn (MPa) of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range of 5 x 10^{2} ~ 5 x 10^{3} (1/s) and the average value σst (MPa) of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range of 5 x 10^{-4} ~ 5 x 10^{-3} (1/s) satisfies the inequality: (σdyn - σst) ≥ -0.272 x TS + 300 as expressed in terms of the maximum stress TS (MPa) in the static tensile test as measured in a strain rate range of 5 x 10^{-4} 2 ~ 5 x 10^{-3} (1/s), and the work hardening coefficient between 5% and 10% of a strain is at least 0.130.

They further include:

(3) The press formable high-strength steel sheets with high flow stress during dynamic deformation, characterized in that the microstructure of the steel sheets in their final form is a composite microstructure of a mixture of ferrite and/or bainite, either of which is the dominant phase, and a third phase including retained austenite at a volume fraction between 3% and 50%, wherein the difference between the static tensile strength σs when deformed in a strain rate range of 5 x 10^{-4} ~ 5 x 10^{-3} (1/s) after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10%, and the dynamic tensile strength σd when deformed at a strain rate of 5 x 10^{2} ~ 5 x 10^{3} (1/s) after the aforementioned pre-deformation, i.e. σd - σs, is at least 60 MPa, the difference between the average value σdyn (MPa) of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range

of $5 \times 10^2 \sim 5 \times 10^3$ (1/s) and the average value σst (MPa) of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) satisfies the inequality: (σdyn - σst) ≥ -0.272 x TS + 300 as expressed in terms of the maximum stress TS (MPa) in the static tensile test as measured in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s), the value (M) determined by the solid solution [C] in the retained austenite and the average Mn equivalents of the steel material {Mn eq = Mn + (Ni + Cr + Cu + Mo)/2}, defined by the equation M = 678 - 428 x [C] - 33 Mn eq is at least -140 and less than 70, the retained austenite volume fraction of the steel material after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10% is at least 2.5%, the ratio between the initial volume fraction of the retained austenite V(0) and the volume fraction of the retained austenite after pre-deformation at an equivalent strain of 10% V(10), i.e. V(10)/V(0) is at least 0.3, and the work hardening coefficient between 5% and 10% of a strain is at least 0.130.

They still further include:

(4) The high-strength steel sheets with high flow stress during dynamic deformation according to any of (1)-(3) above wherein any of the following conditions are satisfied: the average grain diameter of the retained austenite is no greater than 5 μm; the ratio of the average grain diameter of the retained austenite and the average grain diameter of the ferrite or bainite in the dominant phase is no greater than 0.6 while the average grain diamter of the dominant phase is no greater than 10 μm and preferably no greater than 6 μm; the volume fraction of the martensite is 3~30% while the average grain diameter of the martensite is no greater than 10 μm and preferably no greater than 5 μm; and the volume fraction of the ferrite is at least 40% while the value

of the tensile strength x total elongation is at least 20,000.

(5) The high-strength steel sheets of the present invention are also high-strength steel sheets containing, in terms of weight percentage, C at from 0.03% to 0.3%, either or both Si and Al at a total of from 0.5% to 3.0% and if necessary one or more from among Mn, Ni, Cr, Cu and Mo at a total of from 0.5% to 3.5%, with the remainder Fe as the primary component, or they are high-strength steel sheets with high flow stress during dynamic deformation obtained by further addition if necessary to the aforementioned high-strength steel sheets, one or more from among Nb, Ti, V, P, B, Ca and REM, with one or more from among Nb, Ti and V at a total of no greater than 0.3%, P at no greater than 0.3%, B at no greater than 0.01%, Ca at from 0.0005% to 0.01% and REM at from 0.005% to 0.05%, with the remainder Fe as the primary component.

(6) The method for producing high-strength hot-rolled steel sheets with high flow stress during dynamic deformation according to the present invention, for press formable high-strength steel sheets with high flow stress during dynamic deformation where the microstructure of the hot-rolled steel sheets is a composite microstructure of a mixture of ferrite and/or bainite, either of which is the dominant phase, and a third phase including retained austenite of the volume fraction between 3% and 50%, wherein the difference between the static tensile strength σs when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10%, and the dynamic tensile strength σd when deformed at a strain rate of $5 \times 10^{2} \sim 5 \times 10^{3}$ (1/s) after the aforementioned pre-deformation, i.e. $\sigma d - \sigma s$, is at least 60 MPa, the difference between the average value σdyn (MPa) of the flow stress at an equivalent strain in

the range of 3-10% when deformed in a strain rate range of $5 \times 10^2 \sim 5 \times 10^3$ (1/s) and the average value σst (MPa) of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) satisfies the inequality: (σdyn - σst) ≥ -0.272 x TS + 300 as expressed in terms of the maximum stress TS (MPa) in the static tensile test as measured in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s), and the work hardening coefficient between 5% and 10% of a strain is at least 0.130, is characterized in that a continuous cast slab having the component composition of (5) above is fed directly from casting to a hot rolling step, or is hot rolled after reheating, the hot rolling is completed at a finishing temperature of Ar_3 - 50°C to Ar_3 + 120°C, and after cooling at an average cooling rate of 5°C/sec in a cooling process following the hot rolling, the slab is coiled at a temperature of no greater than 500°C.

(7) The method of producing high-strength hot-rolled steel sheets with high flow stress during dynamic deformation is also that described in (6) above, wherein at the finishing temperature for hot-rolling in a range of Ar_3 - 50°C to Ar_3 + 120°C, the hot rolling is carried out so that the metallurgy parameter: A satisfies inequalities (1) and (2) below, the subsequent average cooling rate in the run-out table is at least 5°C/sec, and the coiling is accomplished so that the relationship between the above-mentioned metallurgy parameter: A and the coiling temperature (CT) satisfies inequality (3) below.

$$9 \leq \log A \leq 18 \quad (1)$$

$$\Delta T \leq 21 \times \log A - 178 \quad (2)$$

$$6 \times \log A + 312 \leq CT \leq 6 \times \log A + 392 \quad (3)$$

(8) The method for producing high-strength cold-rolled steel sheets with high flow stress during dynamic deformation according to the present invention, for press formable high-strength steel sheets with high flow stress

during dynamic deformation where the microstructure of the cold-rolled steel sheets is a composite microstructure of a mixture of ferrite and/or bainite, either of which is the dominant phase, and a third phase including retained austenite of the volume fraction between 3% and 50%, wherein the difference between the static tensile strength σs when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10%, and the dynamic tensile strength σd when deformed at a strain rate of $5 \times 10^{2} \sim 5 \times 10^{3}$ (1/s) after the aforementioned pre-deformation, i.e. σd - σs, is at least 60 MPa, the difference between the average value σdyn (MPa) of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range of $5 \times 10^{2} \sim 5 \times 10^{3}$ (1/s) and the average value σst (MPa) of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) satisfies the inequality: (σdyn - σst) ≥ -0.272 x TS + 300 as expressed in terms of the maximum stress TS (MPa) in the static tensile test as measured in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s), and the work hardening coefficient between 5% and 10% of a strain is at least 0.130, is characterized in that a continuous cast slab having the component composition of (5) above is fed directly from casting to a hot rolling step, or is hot rolled after reheating, the coiled hot-rolled steel sheets after hot rolling is subjected to acid pickling and then cold-rolled, and during annealing in a continuous annealing step for preparation of the final product, annealing for 10 seconds to 3 minutes at a temperature of from $0.1 \times (Ac_3 - Ac_1) + Ac_1$ °C to Ac_3 + 50°C is followed by cooling to a primary cooling stop temperature in the range of 550~720°C at a primary cooling rate of 1~10°C/sec and then by cooling to a secondary cooling stop temperature in the range of

200~450°C at a secondary cooling rate of 10~200°C/sec, after which the temperature is held in a range of 200~500°C for 15 seconds to 20 minutes prior to cooling to room temperature; or

(9) The method described in (8) above for press formable high-strength steel sheets with high flow stress during dynamic deformation where the microstructure of the cold-rolled steel sheets in their final form is a composite microstructure of a mixture of ferrite and/or bainite, either of which is the dominant phase, and a third phase including retained austenite of the volume fraction between 3% and 50%, wherein the difference between the static tensile strength σs when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10%, and the dynamic tensile strength σd when deformed at a strain rate of $5 \times 10^{2} \sim 5 \times 10^{3}$ (1/s) after the aforementioned pre-deformation, i.e. σd - σs, is at least 60 MPa, the difference between the average value σdyn (MPa) of the flow stress at an equivalent strain in the range of 3-10% when deformed in a strain rate range of $5 \times 10^{2} \sim 5 \times 10^{3}$ (1/s) and the average value σst (MPa) of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) satisfies the inequality: $(\sigma dyn - \sigma st) \geq -0.272 \times TS + 300$ as expressed in terms of the maximum stress TS (MPa) in the static tensile test as measured in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s), and the work hardening coefficient between 5% and 10% of a strain is at least 0.130, characterized in that during annealing in the continuous annealing step for preparation of the final product, annealing for 10 seconds to 3 minutes at a temperature of from $0.1 \times (Ac_3 - Ac_1) + Ac_1$ °C to Ac_3 + 50°C is followed by cooling to a secondary cooling start temperature Tq in the range of 550~720°C at the primary

cooling rate of 1~10°C/sec and then by cooling to a secondary cooling stop temperature Te in the range from the temperature Tem determined by the component and annealing temperature To to 500°C at the secondary cooling rate of 10~200°C/sec, after which the temperature Toa is held in a range of Te - 50°C to 500°C for 15 seconds to 20 minutes prior to cooling to room temperature.

Brief Description of the Drawings

Fig. 1 is a graph showing the relationship between member absorption energy and TS according to the invention.

Fig. 2 is an illustration of a shaped member for measurement of member absorption energy for Fig. 1.

Fig. 3 is a graph showing the relationship between the work hardening coefficient and dynamic energy absorption (J) for a steel sheet strain of 5-10%.

Fig. 4a is a perspective view of a part (hat-shaped model) used for an impact crush test for measurement of dynamic energy absorption in Fig. 3.

Fig. 4b is a cross-sectional view of the test piece used in Fig. 4a.

Fig. 4c is a schematic view of the impact crush test method.

Fig. 5 is a graph showing the relationship between TS and the difference (σdyn - σst) between the average value σdyn of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range of $5 \times 10^2 \sim 5 \times 10^3$ (1/s) and the average value σst of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s), as an index of the impact energy absorption property according to the invention.

Fig. 6 is a graph showing the relationship between work hardening coefficient between 5% and 10% of a strain and the tensile strength (TS) x total elongation (T•El).

Fig. 7 is a graph showing the relationship between ΔT and the metallurgy parameter A for the hot-rolling step according to the invention.

Fig. 8 is a graph showing the relationship between the coiling temperature and the metallurgy parameter A for the hot-rolling step according to the invention.

Fig. 9 is an illustration of the annealing cycle in a continuous annealing step according to the invention.

Fig. 10 is a graph showing the relationship between the secondary cooling stop temperature (Te) and the subsequent holding temperature (Toa) in a continuous annealing step according to the invention.

Best Mode for Carrying Out the Invention

Collision impact absorbing members such as front side members in automobiles and the like are produced by subjecting steel sheets to a bending or press forming step. After being worked in this manner they are usually subjected to impact by automobile collision following painting and baking. The steel sheets, therefore, are required to exhibit high impact energy absorption properties after their working into members, painting and baking. At the present time, however, no attempts have been made to obtain steel sheets with excellent impact absorption properties as actual members, while simultaneously considering both increased deformation stress due to forming and increased flow stress due to higher strain rates.

As a result of years of research on high-strength steel sheets as impact absorbing members satisfying the above-mentioned demands, the present inventors have found that inclusion of appropriate amounts of retained austenite in steel sheets for such press-formed members is an effective means for obtaining high-strength steel sheets which exhibit excellent impact absorption properties. Specifically, it has been found that high flow stress during dynamic deformation is exhibited when the ideal microstructure is a composite structure

including ferrite and/or bainite which are readily solid-solution strengthened by various substitutional elements, either of which as the dominant phase, and a third phase containing a 3-50% volume fraction of retained austenite which is transformed into hard martensite during deformation. In addition, it has been found that press formable high-strength steel sheets with high flow stress during dynamic deformation can also be obtained with a composite structure wherein martensite is present in the third phase of the initial microstructure, provided that specific conditions are satisfied.

As a result of further experimentation and study based on these findings, the present inventors then discovered that the amount of pre-deformation corresponding to press forming of impact absorbing members such as front side members sometimes reaches a maximum of over 20% depending on the section, but that the majority of the sections undergo equivalent strain of greater than 0% and less than or equal to 10%, and thus, upon determining the effect of the pre-deformation within that range, it is possible to estimate the behavior of the member as a whole after the pre-deformation. Consequently, according to the present invention, deformation at an equivalent strain of greater than 0% and less than or equal to 10% was selected as the amount of pre-deformation to be applied to members during their working.

Fig. 1 is a graph showing the relationship between collision absorption energy Eab of a shaped member with various steel materials described later, and the material strength S (TS). The absorption energy Eab of the member is the absorption energy upon colliding a weight with a mass of 400 Kg at a speed of 15 m/sec against a formed member such as shown in Fig. 2 in its lengthwise direction (direction of the arrow) to a crushing degree of 100 mm. The formed member in Fig. 2 was prepared from a hat-shaped part 1 shaped from a 2.0 mm-thick steel

sheet, to which a steel sheet 2 made of the same type of steel with the same thickness was attached by spot welding, and the corner radius of the hat-shaped part 1 was 2 mm. Numeral 3 indicates the spot-welded sections. Fig. 1 shows that the member absorption energy Eab tends to increase with higher tensile strength (TS) determined by normal tensile test, although the variation is wide. Each of the materials shown in Fig. 1 were measured for the static tensile strength σs when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10%, and for the dynamic tensile strength σd when deformed at a strain rate of $5 \times 10^{2} \sim 5 \times 10^{3}$ (1/s).

Classification was therefore possible on the basis of (σd - σs). The symbols plotted in Fig. 1 are as follows: ○ represents cases where (σd - σs) < 60 MPa with pre-deformation anywhere within a range of greater than 0% and less than or equal to 10%, ● represents cases where 60 MPa ≤ (σd - σs) with pre-deformation all throughout the above-mentioned range and where 60 MPa ≤ (σd - σs) < 80 MPa when the pre-deformation was 5%, ■ represents cases where 60 MPa ≥ (σd - σs) with pre-deformation all throughout the above-mentioned range and where 80 MPa ≤ (σd - σs) < 100 MPa when the pre-deformation was 5%, and ▲ represents cases where 60 MPa ≤ (σd - σs) with pre-deformation all throughout the above-mentioned range and 100 MPa ≤ (σd - σs) when the pre-deformation was 5%.

Also, in cases where 60 MPa ≤ (σd - σs) with pre-deformation all throughout the range of greater than 0% and less than or equal to 10%, the member absorption energy Eab upon collision was greater than the value predicted from the material strength S (TS), and those steel sheets therefore had excellent dynamic deformation properties as collision impact absorbing members. The

predicted values are the values indicated by the curve in Fig. 1, where Eab = 0.062 $S^{0.8}$. Thus, according to the invention (σd - σs) was 60 MPa or greater.

The dynamic tensile strength is commonly expressed in the form of the power of the static tensile strength (TS), and the difference between the dynamic tensile strength and the static tensile strength decreases as the static tensile strength (TS) increases. However, from the standpoint of weight reduction with high reinforcement of materials, a smaller difference between the dynamic tensile strength and the static tensile strength (TS) reduces the prospect of a notable improvement in the impact absorbing property by material substitution, thus making weight reduction more difficult to achieve.

Furthermore, impact absorbing members such as front side members typically have a hat-shaped cross-section, and as a result of analysis of deformation of such members upon crushing by high-speed collision, the present inventors have found that despite deformation proceeding up to a high maximum strain of over 40%, at least 70% of the total absorption energy is absorbed in a strain range of 10% or lower in a high-speed stress-strain diagram. Therefore, the flow stress during dynamic deformation with high-speed deformation at 10% or lower was used as the index of the high-speed collision energy absorption property. In particular, since the amount of strain in the range of 3~10% is most important, the index used for the impact energy absorption property was the average stress σdyn at an equivalent strain in the range of 3~10% when deformed in a strain rate range of $5 \times 10^2 \sim 5 \times 10^3$ (1/s) high-speed deformation.

The average stress σdyn of 3~10% upon high-speed deformation generally increases with increasing static tensile strength {maximum stress: TS (MPa) in a static tensile test measured in a stress rate range of $5 \times 10^{-4} \sim$

5×10^{-3} (1/s)} of the steel sheet prior to pre-deformation or baking treatment. Consequently, increasing the static tensile strength (TS) of the steel sheet directly contributes to improved impact energy absorption property of the member. However, increased strength of the steel sheet results in poorer formability into members, making it difficult to obtain members with the necessary shapes. Consequently, steel sheet having a high σdyn with the same tensile strength (TS) are preferred. In particular, because the strain level during forming into members is generally 10% or lower, it is important from the standpoint of improved formability for the stress to be low in the low strain region, which is the index of formability, e.g. press formability, during shaping into members. Thus, it may be said that a greater difference between σdyn (MPa) and the average value σst (MPa) of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) will result in superior formability from a static standpoint, and will give higher impact energy absorption properties from a dynamic standpoint. It was found that, based on this relationship, steel sheets particularly satisfying the relationship $(\sigma dyn - \sigma st) \geq -0.272 \times TS + 300$ as shown in Fig. 5 have higher impact energy absorption properties as actual members compared to other steel sheets, and that the impact energy absorption property is improved without increasing the overall weight of the member, making it possible to provide high-strength steel sheets with high flow stress during dynamic deformation.

The present inventors have also discovered that for improved anti-collision safety, the work hardening coefficient after press forming of steel sheets may be increased for a higher σd - σs. That is to say, the anti-collision safety may be increased by controlling the microstructure of the steel sheets as explained above so

that the work hardening coefficient between 5% and 10% of a stain is at least 0.130, and preferably at least 0.16. In other words, by viewing the relationship between the dynamic energy absorption, which is an indicator of the anti-collision safety of automobile members, and the work hardening coefficient of the steel sheets as shown in Fig. 3, it can be seen that the dynamic energy absorption improves as the values increase, suggesting that a proper evaluation can be made based on the work hardening coefficient of the steel sheets as an indicator of anti-collision safety of automobile members, so long as the yield strength level is the same. An increase in the work hardening coefficient inhibits necking of the steel sheet, and improves the formability as represented by the tensile strength x the total elongation.

As shown in Fig. 6, the dynamic energy absorption of Fig. 3 was determined in the following manner by the impact crush test method. Specifically, a steel sheet is shaped into a test piece such as shown in Fig. 4b, and spot welded 3 with a 35 mm pitch at a current of 0.9 times the expulsion current using an electrode with a tip radius of 5.5 mm, to make a part (hat-shaped model) with the test piece 2 set between two worktops 1 as shown in Fig. 4a, and then after baking and painting treatment at 170°C x 20 minutes, a weight 4 of approximately 150 Kg as shown in Fig. 4c is dropped from a height of about 10 m, the part placed on a frame 5 provided with a stopper 6 is crushed in the lengthwise direction, and the deformation work at displacement = 0~150 mm is calculated from the area of the corresponding load displacement diagram to determine the dynamic energy absorption.

The work hardening coefficient of the steel sheet may be calculated as the work hardening coefficient (n value for strain of 5~10%) upon working of a steel sheet into a JIS-5 test piece (gauge length: 50 mm, parallel part width: 25 mm) and a tensile test at a strain rate of 0.001/s.

The microstructure of steel sheets according to the invention will now be described.

When a suitable amount of retained austenite is present in a steel sheet, the strain undergone during deformation (shaping) results in its transformation into extremely hard martensite, and thus has the effect of increasing the work hardening coefficient and improving the formability by controlling necking. A suitable amount of retained austenite is preferably 3% to 50%. Specifically, if the volume fraction of the retained austenite is less than 3%, the shaped member cannot exhibit its excellent work hardening property upon undergoing collision deformation, the deformation load remains at a low level resulting in a low deformation work and therefore the dynamic energy absorption is lower making it impossible to achieve improved anti-collision safety, and the anti-necking effect is also insufficient, making it impossible to obtain a high tensile strength x total elongation. On the other hand, if the volume fraction of the retained austenite is greater than 50%, working-induced martensite transformation occurs in a concatenated fashion with only slight press forming strain, and no improvement in the tensile strength x total elongation can be expected since the hollow extension ratio instead deteriorates as a result of notable hardening which occurs during punching, while even if press forming of the member is possible, the press formed member cannot exhibit its excellent work hardening property upon undergoing collision deformation; the above-mentioned range for the retained austenite content is determined from this viewpoint.

In addition to the aforementioned condition of a retained austenite volume fraction of 3~50%, another desired condition is that the average gain diameter of the retained austenite should be no greater than 5 μm, and preferably no greater than 3 μm. Even if the retained austenite volume fraction of 3~50% is satisfied,

an average grain diameter of greater than 5 μm is not preferred because this will prevent fine dispersion of the retained austenite in the steel sheets, locally inhibiting the improving effect by the characteristics of the retained austenite. Furthermore, it was shown that excellent anti-collision safety and formability are exhibited when the microstructure is such that the ratio of the aforementioned average grain diameter of the retained austenite to the average grain diameter of the ferrite or bainite of the dominant phase is no greater than 0.6, and the average grain diameter of the dominant phase is no greater than 10 μm, and preferably no greater than 6 μm.

The present inventors have further discovered that the aforementioned difference in the average stress: σdyn - σst at an equivalent strain range of 3~10%, with the same level of tensile strength (TS: MPa), varies according to the solid solution carbon content: [C] in the retained austenite contained in the steel sheets prior to its working into a member (wt%), and the average Mn equivalents of the steel sheets (Mn eq) as expressed by Mn eq = Mn + (Ni + Cr + Cu + Mo)/2. The carbon concentration in the retained austenite can be experimentally determined by X-ray diffraction and Mossbauer spectrometry, and for example, it can be calculated by the method indicated in the Journal of The Iron and Steel Institute, 206(1968), p60, utilizing the integrated reflection intensity of the (200) plane, (211) plane of the ferrite and the (200) plane, (220) plane and (311) plane of the austenite, with X-ray diffraction using Mo Kα rays. Based on experimental results obtained by the present inventors, it was also found that when the value: M as defined by M = 678 - 428 x [C] - 33 Mn eq is at least -140 and less than 70, by calculation using the solid solution carbon content [C] in the retained austenite and Mn eq determined from the substitutional alloy elements added to the steel sheets, both obtained

in the manner described earlier, the retained austenite volume fraction of the steel sheets after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10% is at least 2.5%, and the ratio between the volume fraction of the retained austenite after pre-deformation at an equivalent strain of 10% V(10) and the initial volume fraction of the retained austenite V(0), i.e. V(10)/V(0) is at least 0.3, then a large (σdyn - σst) is exhibited at the same static tensile strength (TS). In such cases, since the retained austenite is transformed into hard martensite in the low strain range when M > 70, this also increases the static stress in the low strain region which is responsible for formability, resulting not only in poorer formability, e.g. press formability, but also in a smaller value for (σdyn - σst), and making it impossible to achieve both satisfactory or high formability and a high impact energy absorbing property; M was therefore set to be less than 70. Furthermore, when M is less than -140, transformation of the retained austenite is limited to the high strain region, no effect is achieved by increasing (σdyn - σst), despite the satisfactory formability; the lower limit for M was therefore set to be -140.

In regard to the location of the retained austenite, since soft ferrite usually receives the strain of deformation, the retained γ (austenite) which is not adjacent to ferrite tends to escape the strain and thus fails to be transformed into martensite with deformation of about 5~10%; because of this lessened effect, it is preferred for the retained austenite to be adjacent to the ferrite. For this reason, the volume fraction of the ferrite is desired to be at least 40%, and preferably at least 60%. As explained above, since ferrite is the softest substance in the constituent composition, it is an important factor in determining the formability. The volume fraction should preferably be within the

prescribed values. In addition, increasing the volume fraction and fineness of the ferrite is effective for raising the carbon concentration of the untransformed austenite and finely dispersing it, thus increasing the volume faction and fineness of the retained austenite, and this will contribute to improved anti-collision and formability.

The chemical components and their content restrictions of high-strength steel sheets which exhibit the aforementioned microstructure and various characteristics will now be explained. The high-strength steel sheets used according to the invention are high-strength steel sheets containing, in terms of weight percentage, C at from 0.03% to 0.3%, either or both Si and Al at a total of from 0.5% to 3.0% and if necessary one or more from among Mn, Ni, Cr, Cu and Mo at a total of from 0.5% to 3.5%, with the remainder Fe as the primary component, or they are high-strength steel sheets with high dynamic deformation resistance obtained by further addition, if necessary, to the aforementioned high-strength steel plates, of one or more from among Nb, Ti, V, P, B, Ca and REM, with one or more from among Nb, Ti and V at a total of no greater than 0.3%, P at no greater than 0.3%, B at no greater than 0.01%, Ca at from 0.0005% to 0.01% and REM at from 0.005% to 0.05%, with the remainder Fe as the primary component. These chemical components and their contents (all in weight percentages) will now be discussed.

C: C is the most inexpensive element for stabilizing austenite at room temperature and thus contributing to the necessary stabilization of austenite for its retention, and therefore it may be considered the most essential element according to the invention. The average C content in the steel sheets not only affects the retained austenite volume fraction which can be ensured at room temperature, but by increasing the concentration in the untransformed austenite during the

working at the heat treatment of production, it is possible to improve the stability of the retained austenite for working. If the content is less than 0.03%, however, a final retained austenite volume fraction of at least 3% cannot be ensured, and therefore 0.03% is the lower limit. On the other hand, as the average C content of the steel sheets increases the ensurable retained austenite volume fraction also increases, allowing the stability of the retained austenite to be ensured by ensuring the retained austenite volume fraction. Nevertheless, if the C content of the steel sheets is too great, not only does the strength of the steel sheets exceed the necessary level thus impairing the formability for press working and the like, but the dynamic stress increase is also inhibited with respect to the static strength increase, while the reduced weldability limits the use of the steel sheets as a member; the upper limit for the C content was therefore determined to be 0.3%.

Si, Al: Si and Al are both ferrite-stabilizing elements, and they serve to increase the ferrite volume fraction for improved workability of the steel sheets. In addition, Si and Al both inhibit production of cementite, allowing C to be effectively concentrated in the austenite, and therefore addition of these elements is essential for retention of austenite at a suitable volume fraction at room temperature. Other elements whose addition has this effect of suppressing production of cementite include, in addition to Si and Al, also P, Cu, Cr, Mo, etc. A similar effect can be expected by appropriate addition of these elements as well. However, if the total amount of either or both Si and Al is less than 0.5%, the cementite production-inhibiting effect will be insufficient, thus wasting as carbides most of the added C which is the most effective component for stabilizing the austenite, and this will either render it impossible to ensure the retained austenite volume

fraction required for the invention, or else the production conditions necessary for ensuring the retained austenite will fail to satisfy the conditions for volume production processes; the lower limit was therefore determined to be 0.5%. Also, if the total of either or both Si and Al exceeds 3.0%, the primary phase of ferrite or bainite will tend to become hardened and brittle, not only inhibiting increased flow stress from the increased strain rate, but also leading to lower workability and lower toughness of the steel sheets, increased cost of the steel sheets, and much poorer surface treatment characteristics for chemical treatment and the like; the upper limit was therefore determined to be 3.0%. In cases where particularly superior surface properties are demanded, Si scaling may be avoided by having Si ≤ 0.1% or conversely Si scaling may be generated over the entire surface to be rendered less conspicuous by having Si ≥ 1.0%.

Mn, Ni, Cr, Cu, Mo: Mn, Ni, Cr, Cu and Mo are all austenite-stabilizing elements, and are effective elements for stabilizing austenite at room temperature. In particular, when the C content is restricted from the standpoint of weldability, the addition of appropriate amounts of these austenite-stabilizing elements can effectively promote retention of austenite. These elements also have an effect of inhibiting production of cementite, although to a lesser degree than Al and Si, and act as aids for concentration of C in the austenite. Furthermore, these elements cause solid-solution strengthening of the ferrite and bainite matrix together with Al and Si, thus also acting to increase the flow stress during dynamic deformation at high speeds. However, if the total content of any or more than one of these elements is less than 0.5%, it will become impossible to ensure the necessary retained austenite, while the strength of the steel sheets will be lowered, thus impeding efforts to achieve effective vehicle weight

reduction; the lower limit was therefore determined to be 0.5%. On the other hand, if the total exceeds 3.5%, the primary phase of ferrite or bainite will tend to be hardened, not only inhibiting increased flow stress from the increased strain rate, but also leading to lower workability and lower toughness of the steel sheets, and increased cost of the steel sheets; the upper limit was therefore determined to be 3.5%.

Nb, Ti or V which are added as necessary can promote higher strength of the steel sheets by forming carbides, nitrides or carbonitrides, but if their total exceeds 0.3%, excess amounts of the nitrides, carbides or carbonitrides will precipitate in the particles or at the grain boundaries of the ferrite or bainite primary phase, becoming a source of mobile transfer during high-speed deformation and making it impossible to achieve high flow stress during dynamic deformation. In addition, production of carbides inhibits concentration of C in the retained austenite which is the most essential aspect of the present invention, thus wasting the C content; the upper limit was therefore determined to be 0.3%.

B or P are also added as necessary. B is effective for strengthening of the grain boundaries and high strengthening of the steel sheets, but if it is added at greater than 0.01% its effect will be saturated and the steel sheets will be strengthened to a greater degree than necessary, thus inhibiting increased flow stress against high-speed deformation and lowering its workability into parts; the upper limit was therefore determined to be 0.01%. Also, P is effective for ensuring high strength and retained austenite for the steel sheets, but if it is added at greater than 0.2% the cost of the steel sheets will tend to increase, while the flow stress of the dominant phase of ferrite or bainite will be increased to a higher degree than necessary, thus inhibiting increased flow stress against high-speed deformation and resulting in poorer season cracking

resistance and poorer fatigue characteristics and tenacity; the upper limit was therefore determined to be 0.2%. From the standpoint of preventing reduction in the secondary workability, tenacity, spot weldability and recyclability, the upper limit is more desirably 0.02%. Also, with regard to the S content as an unavoidable impurity, the upper limit is more desirably 0.01% from the standpoint of preventing reduction in formability (especially the hollow extension ratio) and spot weldability due to sulfide-based inclusions.

Ca is added to at least 0.0005% for improved formability (especially hollow extension ratio) by shape control (spheroidization) of sulfide-based inclusions, and its upper limit was determined to be 0.01% in consideration of effect saturation and the adverse effect due to increase in the aforementioned inclusions (reduced hollow extension ratio). In addition, since REM has a similar effect as Ca, its added content was also determined to be from 0.005% to 0.05%.

Production methods for obtaining high-strength steel sheets according to the invention will now be explained in detail, with respect to hot-rolled steel sheets and cold-rolled steel sheets.

As the production method for both high-strength hot-rolled steel sheets and cold-rolled steel sheets with high flow stress during dynamic deformation according to the invention, a continuous cast slab having the component composition described above is fed directly from casting to a hot rolling step, or is hot rolled after reheating. Continuous casting for thin gauge strip and hot rolling by the continuous hot-rolling techniques (endless rolling) may be applied for the hot rolling in addition to normal continuous casting, but in order to avoid a lower ferrite volume fraction and a coarser average grain diameter of the thin steel sheet microstructure, the steel sheet thickness at the hot rolling approach side (the initial steel slab thickness)

is preferred to be at least 25 mm. Also, the final pass rolling speed for the hot rolling is preferred to be at least 500 mpm and more preferably at least 600 mpm, in light of the problems described above.

In particular, the finishing temperature for the hot rolling during production of the high-strength hot-rolled steel sheets is preferably in a temperature range of Ar_3 - 50°C to Ar_3 + 120°C as determined by the chemical components of the steel sheets. At lower than Ar_3 - 50°C, deformed ferrite is produced, and σd - σs, σdyn - σst, the 5~10% work hardening property and the formability are inferior. At higher than Ar_3 + 120°C, σd - σs, σdyn - σst and the 5~10% work hardening property are inferior because of a coarser steel sheet microstructure, while it is also not preferred from the viewpoint of scale defects. The steel sheet which has been hot-rolled in the manner described above is subjected to a coiling step after being cooled on a run-out table. The average cooling rate here is at least 5°C/sec. The cooling rate is decided from the standpoint of ensuring the volume fraction of the retained austenite. The cooling method may be carried out at a constant cooling rate, or with a combination of different cooling rates which include a low cooling rate range during the procedure.

The hot-rolled steel sheet is then subjected to a coiling step, where it is coiled up at a coiling temperature of 500°C or below. A coiling temperature of higher than 500°C will result in a lower retained austenite volume fraction. As will be explained hereunder, there is no particular coiling temperature restriction for steel sheets which are provided as cold-rolled steel sheets which have been further cold rolled and subjected to annealing, and there are no problems with the common conditions for coiling.

According to the invention, it was found

particularly that a correlation exists between the finishing temperature in the hot-rolling step, the finishing approach temperature and the coiling temperature. That is, as shown in Fig. 7 and Fig. 8, specific conditions exist which are determined in the major sense by the finishing temperature, finishing approach temperature and the coiling temperature. In other words, the hot-rolling is carried out so that when the finishing temperature for hot rolling is in the range of Ar_3 - 50°C to Ar_3 + 120°C, the metallurgy parameter: A satisfies inequalities (1) and (2). The above-mentioned metallurgy parameter: A may be expressed by the following equation.

$$A = \varepsilon^* \times \exp\{(75282 - 42745 \times C_{eq})/[1.978 \times (FT + 273)]\}$$

where FT: finishing temperature (°C)

Ceq: carbon equivalents = $C + Mn_{eq}/6$ (%)

Mn_{eq}: manganese equivalents = Mn + (Ni + Cr + Cu + Mo)/2 (%)

ε^*: final pass strain rate (s^{-1})

$\varepsilon^* = (v/\sqrt{Rxh_1} \times (1/\sqrt{r} \times \ln\{1/(1-4)\}$

h_1: final pass approach sheet thickness

h_2: final pass exit sheet thickness

$r : (h_1 - h_2)/h_1$

R : roll radius

v : final pass exit speed

ΔT: finishing temperature (finishing final pass exit temperature) - finishing approach temperature (finishing first pass approach temperature)

Ar_3: 901 - 325 C% + 33 Si% - 92 Mn_{eq}

Thereafter, the average cooling rate on the run-out table is 5°C/sec, and the coiling is preferably carried out under conditions such that the relationship between the metallurgy parameter: A and the coiling temperature (CT) satisfies inequality (3).

$$9 \leq \log A \leq 18 \qquad (1)$$

$$\Delta T \leq 21 \times \log A - 178 \quad (2)$$

$$6 \times \log A + 312 \leq CT \leq 6 \times \log A + 392 \quad (3)$$

In inequality (1) above, a logA of less than 9 is unacceptable from the viewpoint of production of retained γ and fineness of the microstructure, while it will also result in inferior σd - σs, σdyn - σst and work hardening coefficient between 5% and 10%

Also, if logA is to be greater than 18, massive equipment will be required to achieve it.

If inequality (2) is not satisfied, the retained γ will be excessively unstable, causing the retained γ to be transformed into hard martensite in the low strain region, and resulting in inferior shapeability, σd - σs, σdyn - σst and 5~10% work hardening property. The upper limit for ΔT is more flexible with increasing logA.

If the upper limit for the coiling temperature in inequality (3) is not satisfied, adverse effects may result such as reduction in the amount of retained γ. If the lower limit of inequality (3) is not satisfied, the retained γ will be excessively unstable, causing the retained γ to be transformed into hard martensite in the low strain region, and resulting in an inferior formability, σd - σs, σdyn - σst and 5~10% work hardening property. The upper and lower limits for the coiling temperature are more flexible with increasing logA.

The cold-rolled steel sheet according to the invention is then subjected to the different steps following hot-rolling and coiling and is cold-rolled at a reduction ratio of 40% or greater, after which the cold-rolled steel sheet is subjected to annealing. The annealing is ideally continuous annealing through an annealing cycle such as shown in Fig. 9, and during the annealing of the continuous annealing step to prepare the final product, annealing for 10 seconds to 3 minutes at a temperature of from $0.1 \times (Ac_3 - Ac_1) + Ac_1$ °C to Ac_3 + 50°C is followed by cooling to a primary cooling stop

temperature in the range of 550~720°C at a primary cooling rate of 1~10°C/sec and then by cooling to a secondary cooling stop temperature in the range of 200~450°C at a secondary cooling rate of 10~200°C/sec, after which the temperature is held in a range of 200~500°C for 15 seconds to 20 minutes prior to cooling to room temperature. If the aforementioned annealing temperature is less than 0.1 x (Ac_3 - Ac_1) + Ac_1 °C in terms of the Ac_1 and Ac_3 temperatures determined based on the chemical components of the steel sheet (see, for example, "Iron & Steel Material Science": W.C. Leslie, Maruzen, p.273), the amount of austenite obtained at the annealing temperature will be too low, making it impossible to leave stably retained austenite in the final steel sheet; the lower limit was therefore determined to be 0.1 x (Ac_3 - Ac_1) + Ac_1 °C. Also, since no improvement in characteristics of the steel sheet is achieved even if the annealing temperature exceeds Ac_3 + 50°C and the cost merely increases, the upper limit for the annealing temperature was determined to be Ac_3 + 50°C. The required annealing time at this temperature is a minimum of 10 seconds in order to ensure a uniform temperature and an appropriate amount of austenite for the steel sheet, but if the time exceeds 3 minutes the effect described above becomes saturated and costs will thus be increased.

Primary cooling is important for the purpose of promoting transformation of the austenite to ferrite and concentrating the C in the untransformed austenite to stabilize the austenite. If the cooling rate is less than 1°C/sec a longer production line will be necessary, and therefore from the standpoint of avoiding reduced productivity the lower limit is 1°C/sec. On the other hand if the cooling rate exceeds 10°C/sec, ferrite transformation does not occur to a sufficient degree, and it becomes difficult to ensure the retained austenite in

the final steel sheet; the upper limit was therefore determined to be 10°C/sec. If the primary cooling is carried out to lower than 550°C, pearlite is produced during the cooling, the austenite-stabilizing element C is wasted, and the final sufficient amount of retained austenite cannot be achieved. Also, if the cooling is carried out to no lower than 720°C, ferrite transformation does not proceed to a sufficient degree.

The rapid cooling of the subsequent secondary cooling must be carried out at a cooling rate of at least 10°C/sec so as not to cause pearlite transformation or precipitation of iron carbides during the cooling, but cooling carried out at greater than 200°C/sec will create a burden on the facility. Also, if the cooling stop temperature in the secondary cooling is lower than 200°C, virtually all of the remaining austenite prior to cooling will be transformed into martensite, making it impossible to ensure the final retained austenite. Conversely, if the cooling stop temperature is higher than 450°C the final $\sigma d - \sigma s$ and $\sigma dyn - \sigma st$ will be lowered.

For room temperature stabilization of the austenite retained in the steel sheet, a portion thereof is preferably transformed to bainite to further increase the carbon concentration in the austenite. If the secondary cooling stop temperature is lower than the temperature maintained for bainite transformation it is heated to the maintained temperature. The final characteristics of the steel sheet will not be impaired so long as this heating rate is from 5°C/sec to 50°C/sec. Conversely, if the secondary cooling stop temperature is higher than the bainite processing temperature, the final characteristics of the steel sheet will not be impaired even with forced cooling to the bainite processing temperature at a cooling rate of 5°C/sec to 200°C/sec and with direct conveyance to a heating zone preset to the desired temperature. On the other hand, since the sufficient amount of retained austenite cannot be ensured in cases

where the steel sheet is held at below 200°C or held at above 500°C, the range for the holding temperature was determined to be 200°C to 500°C. If the temperature is held at 200°C to 500°C for less than 15 seconds, the bainite transformation does not proceed to a sufficient degree, making it impossible to obtain the final necessary amount of retained austenite, while if it is held in that range for more than 20 minutes, precipitation of iron carbides or pearlite transformation will result after bainite transformation, resulting in waste of the C which is indispensable for production of the retained austenite and making it impossible to obtain the necessary amount of retained austenite; the holding time range was therefore determined to be from 15 seconds to 20 minutes. The holding at 200°C to 500°C in order to promote bainite transformation may be at a constant temperature throughout, or the temperature may be deliberately varied within this temperature range without impairing the characteristics of the final steel sheet.

As preferred cooling conditions after annealing according to the invention, annealing for 10 seconds to 3 minutes at a temperature of from 0.1 x (Ac_3 - Ac_1) + Ac_1 °C to Ac_3 + 50°C is followed by cooling to a secondary cooling start temperature Tq in the range of 550~720°C at the primary cooling rate of 1~10°C/sec and then by cooling to a secondary cooling stop temperature Te in the range from the temperature Tem determined by the component and annealing temperature To to 500°C at the secondary cooling rate of 10~200°C/sec, after which the temperature Toa is held in a range of Te - 50°C to 500°C for 15 seconds to 20 minutes prior to cooling to room temperature. This is a method wherein the quenching end point temperature Te in a continuous annealing cycle as shown in Fig. 10, is represented as a function of the component and annealing temperature To, and cooling is carried out at above a given critical value, while the

range of the overaging temperature Toa is defined by the relationship with the quenching end point temperature Te.

Here, Tem is the martensite transformation start temperature for the retained austenite at the quenching start temperature Tq. That is, Tem is defined by Tem = T1 -T2, or the difference between the value excluding the effect of the C concentration in the austenite (T1) and the value indicating the effect of the C concentration (T2). Here, T1 is the temperature calculated from the solid solution element concentration excluding C, and T2 is the temperature calculated from the C concentration in the retained austenite at Ac_1 and Ac_3 determined by the components of the steel sheets and Tq determined by the annealing temperature To. Ceq^* represents the carbon equivalents in the retained austenite at the annealing temperature To.

T1 = is the difference between 561 - 33 x {Mn% + (Ni + Cr + Cu + Mo)/2} and T2, where T2 is expressed in terms of:

Ac_1 = 723 - 0.7 x Mn% - 16.9 x Ni% + 29.1 x Si% + 16.9 x Cr%,

Ac_3 = 910 - 203 x $(C\%)^{1/2}$ - 15.2 x Ni% + 44.7 x Si% + 104 x V% + 31.5 x Mo% - 30 x Mn% - 11 x Cr% - 20 x Cu% + 700 x P% + 400 x Al% + 400 x Ti%,

and the annealing temperature To, such that when

Ceq^* = $(Ac_3 - Ac_1)$ x C/(To - Ac_1) + (Mn + Si/4 + Ni/7 + Cr + Cu + 1.5 Mo)/6

is greater than 0.6, T2 = 474 x $(Ac_3 - Ac_1)$ x C/(To - Ac_1),

and when it is 0.6 or less, T2 = 474 x $(Ac_3 - Ac_1)$ x C/{3 x $(Ac_3 - Ac_1)$ x C + [(Mn + Si/4 + Ni/7 + Cr + Cu + 1.5 Mo)/2 - 0.85)] x (To - Ac_1).

In other words, when Te is less than Tem, more martensite is produced than necessary making it impossible to ensure a sufficient amount of retained austenite, while also lowering the value of σd - ds and

(σdyn - σst); this was therefore determined as the lower limit for Te. Also, if Te is higher than 500°C, pearlite or iron carbides are produced resulting in waste of the C which is indispensable for production of the retained austenite and making it impossible to obtain the necessary amount of retained austenite. If Toa is less than Te - 50°C, additional cooling equipment is necessary, and greater scattering will result in the material due to the difference between the temperature of the continuous annealing furnace and the temperature of the steel sheet; this temperature was therefore determined as the lower limit. Furthermore, if Toa is higher than 500°C, pearlite or iron carbides are produced resulting in waste of the C which is indispensable for production of the retained austenite and making it impossible to obtain the necessary amount of retained austenite. Also, if Toa is maintained for less than 15 seconds, the bainite transformation will not proceed to a sufficient degree, so that the amount and properties of the final retained austenite will not fulfill the object of the present invention.

By employing the steel sheet composition and production method described above, it is possible to produce press formable high-strength steel sheets with high flow stress during dynamic deformation, characterized in that the microstructure of the steel sheets in their final form is a composite microstructure of a mixture of ferrite and/or bainite, either of which is the dominant phase, and a third phase including retained austenite at a volume fraction between 3% and 50%, wherein the difference between the static tensile strength σs when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10%, and the dynamic tensile strength σd when deformed at a strain rate of $5 \times 10^{2} \sim 5 \times 10^{3}$ (1/s) after

the aforementioned pre-deformation, i.e. σd - σs, is at least 60 MPa, the difference between the average value σdyn (MPa) of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range of $5 \times 10^2 \sim 5 \times 10^3$ (1/s) and the average value σst (MPa) of the flow stress at an equivalent strain in the range of 3~10% when deformed in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s) satisfies the inequality: (σdyn - σst) ≥ -0.272 x TS + 300 as expressed in terms of the maximum stress TS (MPa) in the static tensile test as measured in a strain rate range of $5 \times 10^{-4} \sim 5 \times 10^{-3}$ (1/s), and the work hardening coefficient between 5% and 10% of a strain is at least 0.130.

The press formable high-strength steel sheets according to the invention may be made into any desired product by annealing, tempered rolling, electroplating or the like.

The microstructure was evaluated by the following methods.

Identification of the ferrite, bainite and remaining structure, observation of the location and measurement of the mean circle equivalent diameter and volume fraction were accomplished using a 1000 magnification optical micrograph with the thin steel sheets rolling direction cross-section etched with a nital reagent and the reagent disclosed in Japanese Unexamined Patent Publication No. 59-219473.

The mean circle equivalent diameter of the retained γ was determined from a 1000 magnification optical micrograph, with the rolling direction cross-section etched with the reagent disclosed in Japanese Patent Application No. 3-351209. The position was also observed from the same photograph.

The volume fraction of the retained γ ($V\gamma$: percentage unit) was calculated according to the following equation, upon Mo-Kα X-ray analysis.

$$V\gamma = (2/3)\{100/(0.7 \times \alpha(211)/\gamma(220) + 1)\} + (1/3)\{100/(0.78 \times \alpha(211)/\gamma(311) + 1)\}$$

where $\alpha(211)$, $\gamma(220)$, $\alpha(211)$ and $\gamma(311)$ represent pole intensities.

The C concentration of the retained γ ($C\gamma$: percentage unit) was calculated according to the following equation, upon determining the lattice constant (unit: Angstroms) from the reflection angle on the (200) plane, (220) plane and (311) plane of the austenite using Cu-Kα X-ray analysis.

$$C\gamma = (\text{lattice constant} - 3.572)/0.033$$

The properties were evaluated by the following methods.

A tensile test was conducted according to JIS5 (gauge length: 50 mm, parallel part width: 25 mm) with a strain rate of 0.001/s, and upon determining the tensile strength (TS), total elongation (T.El) and work hardening coefficient (n value for strain of 5~10%), TS x T.El was calculated.

The stretch flanging property was measured by expanding a 20 mm punched hole from the burrless side with a 30° cone punch, and determining the hollow extension ratio (d/do) between the hollow diameter at the moment at which the crack penetrated the sheet thickness and (d) the original hollow diameter (do, 20 mm).

The spot weldability was judged to be unsuitable if a spot welding test piece bonded at a current of 0.9 times the expulsion current using an electrode with a tip radius of 5 times the square root of the steel sheet thickness underwent peel fracture when ruptured with a chisel.

Examples

The present invention will now be explained by way of examples.

Example 1

The 15 steel sheets listed in Table 1 were heated to 1050~1250°C and subjected to hot rolling, cooling and coiling under the production conditions listed in Table 2, to produce hot-rolled steel sheets. As shown in Fig. 3, the steel sheets satisfying the component conditions and production conditions according to the invention have an M value of at least 140 and less than 70 as determined by the solid solution [C] in the retained austenite and the average Mn eq in the steel material, an initial retained austenite of at least 3% and no greater than 50%, a retained austenite after pre-deformation of at least 2.5%, and suitable stability as represented by a ratio of at least 0.3 between the volume fraction of retained austenite after 10% pre-deformation and the initial volume fraction. As is clear from Fig. 4, the steel sheets satisfying the component conditions, production conditions and microstructure according to the invention all exhibited excellent anti-collision safety and formability as represented by $\sigma d - \sigma s \geq 60$, $\sigma dyn - dst > -0.272 \times TS + 300$, work hardening coefficient between 5% and 10% of a strain ≥ 0.130 and $TS \times T.El \geq 20,000$, while also having suitable spot weldability.

Table 1 Chemical components of steels

Steel No.		1	2	3	4	5	6	7	8
Chemical components (wt%)	C	0.15	0.15	0.15	0.15	0.11	0.16	0.09	0.10
	Si	1.45	1.45	1.45	1.45	1.36	1.60	2.10	2.00
	Mn	0.99	0.79	0.69	0.79	1.54	0.90	1.20	1.10
	P	0.012	0.012	0.012	0.012	0.020	0.020	0.009	0.015
	S	0.002	0.005	0.002	0.002	0.003	0.003	0.001	0.002
	Al	0.02	0.02	0.02	0.02	0.20	0.01	0.02	0.02
	N	0.003	0.002	0.003	0.002	0.003	0.003	0.002	0.003
	Al+Si	1.47	1.47	1.47	1.47	1.56	1.61	2.12	2.02
	Ni		0.4						
	Cr			0.6					
	Cu				0.4				
	Mo					0.4			
	Nb						0.04		
	Ti							0.06	
	V								
	B								
	Ca		0.004						
	REM			0.010					
	*1	0.99	1.19	1.29	1.19	1.94	0.90	1.20	1.10
	Ceq	0.32	0.32	0.32	0.32	0.40	0.31	0.29	0.28
	Mneq	0.99	0.99	0.99	0.99	1.74	0.90	1.20	1.10
Transformation temperature (°C)	Ac1	755	750	768	757	746	760	771	769
	Ac3	868	868	871	866	879	875	932	904
	Ar3	809	809	809	809	750	819	831	833
Type		A	A	A	A	A	A	A	B

A: Present invention
B: Comparison example
*1: Mn + Ni + Cr + Cu + Mo

Table 1 Chemical components of steels (cont.)

Steel No.		9	10	11	12	13	14	15
Chemical components (wt%)	C	0.10	0.10	0.15	0.15	0.35	0.15	0.19
	Si	2.00	2.00	1.98	0.01	1.50	0.30	1.10
	Mn	1.10	1.10	1.76	1.00	1.90	1.48	1.50
	P	0.015	0.015	0.016	0.015	0.015	0.010	0.090
	S	0.002	0.002	0.001	0.002	0.003	0.003	0.003
	Al	0.02	0.02	0.02	1.70	0.03	0.05	0.04
	N	0.003	0.002	0.002	0.002	0.003	0.003	0.005
	Al+Si	2.02	2.02	2.00	1.71	1.53	0.35	1.14
	Ni							
	Cr							
	Cu							
	Mo							
	Nb							
	Ti							
	V			0.06				
	B				0.001			
	Ca							
	REM							
	*1	1.10	1.10	1.76	1.00	1.90	1.48	1.50
	Ceq	0.28	0.28	0.44	0.32	0.67	0.40	0.44
	Mneq	1.10	1.10	1.76	1.00	1.90	1.48	1.50
Trans-formation tempera-ture (°C)	Ac1	769	769	762	713	746	716	739
	Ac3	904	904	875	871	802	803	834
	Ar3	833	833	756	761	662	726	738
Type		A	A	A	A	A	A	A

A: Present invention
B: Comparison example
Underlined data indicate values outside of the range of the invention
*1: Mn + Ni + Cr + Cu + Mo

Table 2 Production conditions

Steel No.		1	2	3	4	5	6	7	8
Hot rolling conditions	Finishing temperature °C	905	910	800	790	860	840	795	960
	Initial steel sheet thickness (mm)	26	27	27	26	28	28	35	20
	Final pass rolling speed (mpm)	600	600	600	600	700	700	500	400
	Final steel sheet thickness (mm)	1.8	1.8	1.8	1.8	1.4	1.4	2.2	2.2
	Strain rate (1/sec)	150	150	150	160	190	190	100	90
	Calculation (log A)	13.65	13.60	14.77	14.91	13.50	14.46	14.87	13.15
	ΔT (°C)	100	80	120	125	90	110	120	120
	Condition of inequality (2)	o	o	o	o	o	o	o	x
Cooling conditions	Average cooling rate (°C/sec)	40	35	80	90	50	90	60	50
	Note	*1	*1						
Coiling conditions	Coiling temperature (°C)	405	410	475	450	440	420	425	505
	Condition of inequality (3)	o	o	o	o	o	o	o	x

Underlined data indicate values outside of the range of the invention.
*1: 15°C/sec for 750~700°C.

Table 2 Production conditions (cont.)

Steel No.		9	10	11	12	13	14	15
Hot rolling conditions	Finishing temperature °C	<u>730</u>	900	870	875	780	840	790
	Initial steel sheet thickness (mm)	26	25	26	28	30	32	55
	Final pass rolling speed (mpm)	500	500	700	800	800	700	1000
	Final steel sheet thickness (mm)	2.2	2.2	1.2	1.2	1.2	1.2	1.2
	Strain rate (1/sec)	100	100	200	230	240	210	300
	Calculation (log A)	15.77	13.77	13.07	14.12	12.09	13.78	14.09
	ΔT (°C)	130	100	85	110	60	90	110
	Condition of inequality (2)	o	o	o	o	o	o	o
Cooling conditions	Average cooling rate (°C/sec)	60	50	50	55	60	50	100
	Note							
Coiling conditions	Coiling temperature (°C)	<u>510</u>	<u>555</u>	460	425	395	415	445
	Condition of inequality (3)	<u>x</u>	<u>x</u>	o	o	o	o	o

Underlined data indicate values outside of the range of the invention.

Table 3 Microstructure of steels

Steel No.			1	2	3	4	5	6	7	8
Dominant phase	Name		ferrite	ferrite	ferrite	ferrite	ferrite	ferrite	ferrite	bainite
	Circle equivalent diameter (μm)		5.1	5.7	3.4	2.9	3.9	3.8	2.6	10.8
Ferrite	Volume fraction (%)		79	76	85	86	82	82	85	39
Retained austenite	Circle equivalent diameter (μm)		2.5	2.7	1.6	1.7	1.9	1.5	1.5	4.9
	Grain diameter ratio to dominant phase		0.49	0.47	0.47	0.59	0.49	0.39	0.58	0.45
	C concentration (%)		1.35	1.45	1.36	1.42	1.40	1.36	1.41	1.01
	Volume fraction	Without pre-deformation V(0)	9.2	7.9	10.0	9.1	10.8	12.4	10.3	<u>2.3</u>
		After 10% pre-deformation V(10)	6.0	5.7	7.1	5.8	8.0	8.5	6.6	<u>0.2</u>
		V(10)/V(0)	0.65	0.72	0.71	0.64	0.74	0.69	0.64	<u>0.09</u>
Remaining composition			B	B+M	B+P	B	B	B	B	P
M value	Calculated M value		68	25	63	38	21	66	35	<u>209</u>
	Conditions		o	o	o	o	o	o	o	<u>x</u>

Underlined data indicate values outside of the range of the invention.
Remaining composition: B=bainite, M=martensite, P=pearlite

Table 3 Microstructure of steels (cont.)

Steel No.			9	10	11	12	13	14	15
Dominant phase	Name		ferrite	ferrite	ferrite	ferrite	ferrite	ferrite	ferrite
	Circle equivalent diameter (μm)		converted	7.6	3.2	4.9	2.4	2.9	2.5
Ferrite	Volume fraction (%)		89	61	60	80	51	41	72
Retained austenite	Circle equivalent diameter (μm)		--	--	1.9	2.4	1.1	--	1.5
	Grain diameter ratio to dominant phase		--	--	0.59	0.49	0.46	--	0.60
	C concentration (%)		--	--	1.30	1.36	1.50	--	1.32
	Volume fraction	Without pre-deformation V(0)	0.0	0.0	10.8	8.5	6.1	0.0	13.1
		After 10% pre-deformation V(10)	0.0	0.0	7.0	5.4	3.8	0.0	10.1
		V(10)/V(0)	--	--	0.65	0.64	0.62	--	0.77
Remaining composition			P	P	B	B	B+P	B+P	B+P
M value	Calculated M value		--	--	64	63	-27	--	64
	Conditions		--	--	o	o	o	--	o

Underlined data indicate values outside of the range of the invention.
Remaining composition: B=bainite, M=martensite, P=pearlite

Table 4 Mechanical properties of steels

Steel No.		1	2	3	4	5	6	7	8
Static tensile test (strain rate= 0.001/sec)	TS (MPa)	623	631	638	645	670	649	641	657
	T.El (%)	38	37	39	36	38	42	41	30
	5-10% of n value	0.136	0.171	0.162	0.221	0.174	0.149	0.181	<u>0.118</u>
	TSxT.El (MPa)•(%)	23674	23347	24882	23220	25460	27258	26281	19710
Pre-deformation and BH treatment	Pre-deformation method	C	C	L	C	C	C	C	C
	Pre-deformation equivalent strain (%)	5%	5%	5%	3%	5%	7%	5%	5%
	BH treatment	yes	no	yes	yes	yes	yes	yes	yes
Static and dynamic tensile test (strain rate= 1000/sec) after pre-deformation/BH treat-ment	Static maximum strength σs (MPa)	643	651	658	665	690	669	661	667
	Static 3-10% average flow stress σst (MPa)	598	605	612	618	642	622	615	654
	Dynamic maximum strength σs (MPa)	776	781	786	792	814	795	788	711
	Dynamic 3-10% average flow stress σst (MPa)	763	771	778	785	810	789	781	710
	Expression σd-σs	133	130	128	127	124	126	127	<u>44</u>
	Expression *1	34	37	40	42	51	43	41	<u>-65</u>
Other properties	Welding	ok	ok	ok	ok	ok	ok	ok	ok
	d/do	1.56	1.37	1.47	1.27	1.42	1.47	1.53	1.53

Underlined data indicate values outside of the range of the invention.
*1: (σdyn-σst) - (-0.272 x TS + 300)
C = Uniaxial tension in C direction
L = Uniaxial tension in L direction

Table 4 Mechanical properties of steels (cont.)

Steel No.		9	10	11	12	13	14	15
Static tensile test (strain rate= 0.001/sec)	TS (MPa)	565	570	837	604	1001	643	639
	T.El (%)	22	31	31	40	21	24	39
	5-10% of n value	0.125	0.121	0.156	0.152	0.132	0.114	0.162
	TSxT.El (MPa)•(%)	12430	17670	25947	24160	21021	15432	24921
Pre-deformation and BH treatment	Pre-deformation method	C	C	C	E	C	E	C
	Pre-deformation equivalent strain (%)	5%	5%	5%	5%	5%	5%	5%
	BH treatment	yes	yes	yes	yes	yes	yes	yes
Static and dynamic tensile text (strain rate= 1000/sec) after pre-deformation/BH treatment	Static maximum strength σs (MPa)	615	601	857	624	938	653	659
	Static 3-10% average flow stress σst (MPa)	609	589	797	580	882	633	613
	Dynamic maximum strength σs (MPa)	671	660	936	761	1056	700	788
	Dynamic 3-10% average flow stress σst (MPa)	636	637	930	744	1055	698	779
	Expression σd-σs	56	59	79	137	118	47	129
	Expression *1	-119	-97	61	28	146	-61	40
Other properties	Welding	ok	ok	ok	ok	poor	ok	ok
	d/do	1.20	1.51	1.31	1.54	1.10	1.62	1.41

Underlined data indicate values outside of the range of the invention.
*1: (σdyn-σst) - (-0.272 x TS + 300)
C = Uniaxial tension in C direction
E = Equal biaxial tension

Example 2

The 25 steel sheets listed in Table 5 were subjected to a complete hot-rolling process at Ar3 or greater, and after cooling they were coiled and then cold-rolled following acid pickling. The Ac1 and Ac3 temperatures were then determined from each steel component, and after

heating, cooling and holding under the annealing conditions listed in Table 6, they were cooled to room temperature. As shown in Figs. 7 and 8, the steel sheets satisfying the production conditions and component conditions according to the invention have an M value of at least 140 and less than 70 as determined by the solid solution [C] in the retained austenite and the average Mn eq in the steel sheet, a work hardening coefficient between 5% and 10% of strain is at least 0.130, a retained austenite after pre-deformation of at least 2.5%, a ratio V(10)/V(0) of at least 0.3, a value of maximum stress x total elongation of at least 20,000, and exhibit excellent anti-collision safety and formability as represented by satisfying both $\sigma d - \sigma s \geq 60$ and $\sigma dyn - dst > -0.272 \times TS + 300$.

Table 5 Chemical components of steels

Steel No.		16	17	18	19	20	21	22	23
Chemical components (wt%)	C	0.05	0.12	0.20	0.26	0.12	0.12	0.12	0.12
	Si	1.20	1.20	1.20	1.20	2.00	1.80	1.20	1.20
	Mn	1.50	1.50	1.50	1.50	0.50	0.15	1.00	0.15
	P	0.010	0.012	0.008	0.007	0.008	0.007	0.013	0.012
	S	0.003	0.005	0.002	0.003	0.003	0.002	0.003	0.005
	Al	0.04	0.05	0.04	0.05	0.04	0.03	0.05	0.04
	N	0.003	0.002	0.003	0.002	0.003	0.003	0.002	0.003
	Al+Si	0.24	1.25	1.24	1.25	2.04	1.83	1.25	1.24
	Ni					0.8			1.5
	Cr						1.8		
	Cu							0.6	
	Mo								0.2
	Nb								
	Ti								
	V								
	B								
	*1	1.50	1.50	1.50	1.50	1.30	1.95	1.60	1.85
	Ceq	0.30	0.37	0.45	0.51	0.27	0.30	0.34	0.29
	Mneq	1.50	1.50	1.50	1.50	0.90	1.05	1.30	1.00
Transformation temperature (°C)	Ac1	742	742	742	742	762	804	747	731
	Ac3	876	851	830	818	904	898	854	875
	Ar3	786	764	738	718	845	825	782	810
Type		A	A	A	A	A	A	A	A

A: Present invention
B: Comparison example
Underlined data indicate values outside of the range of the invention
*1: Mn + Ni + Cr + Cu + Mo

Table 5 Chemical components of steels (cont.)

Steel No.		24	25	26	27	28	29	30	31
Chemical components (wt%)	C	0.12	0.10	0.14	0.25	0.15	0.10	0.10	0.10
	Si	1.20	0.50	0.01	1.50	1.00	1.20	1.20	1.20
	Mn	1.20	1.50	1.50	2.00	1.70	1.50	1.50	1.50
	P	0.010	0.013	0.012	0.012	0.100	0.008	0.008	0.008
	S	0.003	0.005	0.003	0.005	0.003	0.003	0.003	0.003
	Al	0.04	1.20	1.50	0.04	0.05	0.04	0.04	0.04
	N	0.003	0.002	0.002	0.002	0.003	0.003	0.003	0.003
	Al+Si	1.24	1.70	1.51	1.54	1.05	1.24	1.24	1.24
	Ni								
	Cr	2.0							
	Cu								
	Mo								
	Nb						0.01		0.02
	Ti							0.02	
	V								0.01
	B				0.002				
	*1	3.20	1.50	1.50	2.00	1.70	1.50	1.50	1.50
	Ceq	0.49	0.35	0.39	0.58	0.43	0.35	0.35	0.35
	Mneq	2.20	1.50	1.50	2.00	1.70	1.50	1.50	1.50
Transformation temperature (°C)	Ac1	779	722	707	745	734	742	742	742
	Ac3	838	872	850	818	834	857	865	858
	Ar3	699	747	718	685	729	770	770	770
Type		A	A	A	A	B	A	A	A

A: Present invention
B: Comparison example
Underlined data indicate values outside of the range of the invention
*1: Mn + Ni + Cr + Cu + Mo

Table 5 Chemical components of steels (cont.)

Steel No.		32	33	34	35	36	37	38	39	40
Chemical components (wt%)	C	0.02	0.35	0.12	0.12	0.10	0.12	0.10	0.12	0.12
	Si	1.20	1.00	0.20	3.50	1.50	1.20	1.20	1.50	1.20
	Mn	1.50	1.20	1.50	1.50	1.50	1.50	1.50	0.10	1.50
	P	0.010	0.008	0.010	0.010	0.250	0.010	0.010	0.010	0.010
	S	0.003	0.002	0.003	0.003	0.003	0.003	0.003	0.002	0.002
	Al	0.04	0.05	0.04	0.05	0.04	0.04	0.04	0.05	0.04
	N	0.003	0.003	0.002	0.003	0.003	0.003	0.003	0.003	0.003
	Al+Si	1.24	1.05	0.24	3.55	1.54	1.24	1.24	1.55	1.24
	Ni							1.5	0.2	
	Cr									
	Cu							1.0		
	Mo									
	Nb									0.20
	Ti									0.15
	V									
	B						0.012			
	*1	1.50	1.20	1.50	1.50	1.50	1.50	4.00	0.30	1.50
	Ceq	0.27	0.55	0.37	0.37	0.35	0.37	0.56	0.15	0.37
	Mneq	1.50	1.20	1.50	1.50	1.50	1.50	2.75	0.20	1.50
Transformation temperature (°C)	Ac1	742	739	713	809	751	742	717	762	742
	Ac3	892	801	806	954	887	851	814	903	911
	Ar3	796	710	731	840	780	764	655	893	764
Type		B	B	B	B	B	B	B	B	B

A: Present invention
B: Comparison example
Underlined data indicate values outside of the range of the invention
*1: Mn + Ni + Cr + Cu + Mo

Table 6 Production conditions

Steel No.		16	17	18	19	20	21	22	23	24	25	26	27	28
Cold rolling conditions	Rolling reduction (%)	80	80	80	80	80	80	80	80	80	80	80	80	80
	Sheet thickness (mm)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Annealing conditions	Annealing temperature (To °C)	800	800	800	800	800	850	800	800	790	780	780	780	800
	Annealing time (sec)	90	90	90	90	120	120	90	90	90	90	90	90	90
	Primary cooling rate (°C/sec)	5	5	5	5	8	8	5	5	5	5	5	5	8
	Quenching start temperature (Tq °C)	680	680	700	680	680	680	680	650	650	650	650	680	680
	Secondary cooling rate (°C/sec)	100	100	100	80	100	100	100	130	130	100	100	100	100
	Quenching end temperature (Te °C)	400	400	400	430	350	430	400	350	330	400	350	400	<u>300</u>
	Calculated (T1°C)	512	512	512	512	531	526	518	528	488	512	512	495	505
	Calculated (Ceq*)	0.41	0.53	0.60	0.64	0.64	0.64	0.56	0.41	1.22	0.53	0.53	0.92	0.55
	Calculated (T2 °C)	138	147	144	161	214	116	139	310	300	166	179	248	134
	Calculated (Tem °C)	374	364	368	351	317	410	379	218	188	345	332	247	371
	Holding temperature (Toa °C)	400	400	400	400	400	430	400	400	300	400	330	400	400
	Holding time (sec)	150	180	180	250	180	180	180	180	180	180	150	180	180

Underlined data indicate values outside of the range of the invention.

CA 02278841 1999-07-27

Table 6 Production conditions (cont.)

Steel No.		29	30	31	32	33	34	35	36	37	38	39	40
Cold rolling conditions	Rolling reduction (%)	68	68	68	80	80	80	80	80	80	70	70	70
	Sheet thickness (mm)	1.2	1.2	1.2	0.8	0.8	0.8	0.8	0.8	0.8	1.2	1.2	1.2
Annealing conditions	Annealing temperature (To °C)	780	780	780	800	760	780	850	800	800	780	800	800
	Annealing time (sec)	90	90	90	90	90	90	90	90	90	90	90	90
	Primary cooling rate (°C/sec)	8	5	5	5	5	5	5	5	5	5	5	5
	Quenching start temperature (Tq °C)	680	630	680	680	680	650	680	680	680	680	680	680
	Secondary cooling rate (°C/sec)	100	150	100	100	100	100	100	100	100	100	100	100
	Quenching end temperature (Te °C)	400	400	400	400	350	400	350	400	400	430	400	400
	Calculated (T1 °C)	512	512	512	512	521	512	512	512	512	470	554	512
	Calculated (Ceq*)	0.60	0.62	0.60	0.35	1.29	0.42	0.82	0.59	0.52	0.66	0.53	0.65
	Calculated (T2 °C)	143	153	144	120	495	186	200	143	147	73	285	165
	Calculated (Tem °C)	369	359	368	392	26	326	311	369	364	398	270	346
	Holding temperature (Toa °C)	400	400	400	400	350	400	400	400	370	430	400	400
	Holding time (sec)	180	180	180	180	180	180	150	180	180	180	180	180

CA 02278841 1999-07-27

Table 7 Microstructure of steels

Steel No.			16	17	18	19	20	21	22	23	24	25	26	27	28
Dominant phase	Name		ferrite	ferrite	ferrite	ferrite	ferrite	ferrite	ferrite	ferrite	ferrite	ferrite	ferrite	bainite	ferrite
	Circle equivalent diameter (μm)		7.1	6.5	5.4	5.6	8.3	7.2	5.2	5.2	5.2	6.9	5.8	3.7	5.1
Ferrite	Volume fraction (%)		84	66	49	43	81	54	68	81	56	72	68	40	56
Retained austenite	Circle equivalent diameter (μm)		2.8	1.9	1.1	1.2	2.4	3.1	2.6	2.9	2.5	2.3	3.1	1.2	1.8
	Grain diameter ratio to dominant phase		0.39	0.29	0.20	0.21	0.29	0.43	0.50	0.56	0.48	0.33	0.53	0.32	0.35
	C concentration (%)		1.54	1.48	1.35	1.60	1.52	1.67	1.79	1.42	1.32	1.65	1.52	1.49	1.18
	Volume fraction	Without pre-deformation V(0)	4	7	12	14	7	7	6	8	9	6	9	16	8
		After 10% pre-deformation V(10)	2.5	3.2	4.6	7.2	3.8	4.2	4.1	3.5	3.5	3.7	4.8	7.6	2.1
		V(10)/V(0)	0.63	0.46	0.38	0.51	0.54	0.60	0.68	0.44	0.39	0.62	0.53	0.48	<u>0.26</u>
Remaining composition			B	B	B	B	B	B	B	B	B	B	B	B	B
M value	Calculated M value		-31	-5	51	-56	-2	-71	-131	37	40	-78	-22	-26	<u>117</u>
	Conditions		o	o	o	o	o	o	o	o	o	o	o	o	X

Underlined data indicate values outside of the range of the invention.

CA 02278841 1999-07-27

Table 7 Microstructure of steels (cont.)

Steel No.			29	30	31	32	33	34	35	36	37	38	39	40
Dominant phase	Name		fer-rite	fer-rite	fer-rite	fer-rite	bai-nite	fer-rite	bai-nite	fer-rite	fer-rite	fer-rite	fer-rite	bai-nite
	Circle equivalent diameter (μm)		6.9	7.2	6.5	10.7	4.5	6.8	5.2	6.1	5.3	5.2	10.9	6.2
Ferrite	Volume fraction (%)		74	69	72	90	24	68	51	63	59	32	84	66
Retained austenite	Circle equivalent diameter (μm)		2.1	1.9	1.8	2.4	1.1	--	2.5	2.3	1.9	1.1	--	2.2
	Grain diameter ratio to dominant phase		0.30	0.26	0.28	0.22	0.24	--	0.48	0.38	0.36	0.21	--	0.35
	C concentration (%)		1.56	1.40	1.56	1.26	1.29	--	1.20	1.16	1.06	1.01	--	1.17
	Volume fraction	Without pre-deformation V(0)	5	7	5	1	25	0	10	7	11	9	0	8
		After 10% pre-deformation V(10)	2.7	3.1	2.7	0.0	6.5	0.0	2.7	1.9	2.6	1.9	0.0	2.2
		V(10)/V(0)	0.54	0.44	0.54	--	0.26	--	0.27	0.27	0.24	0.21	--	0.28
Remaining composition			B	B	B	B	B+P	B	B	B	B	B	B	B
M value	Calculated M value		-39	29	-39	89	88	--	114	134	174	154	--	127
	Conditions		o	o	o	x	x	x	x	x	x	x	x	x

Underlined data indicate values outside of the range of the invention.

CA 02278841 1999-07-27

Table 8 Mechanical properties of steels

Steel No.		16	17	18	19	20	21	22	23	24	25	26	27	28
Static tensile test (strain rate =0.001/sec)	TS (MPa)	566	630	782	911	659	661	623	718	719	588	601	1023	773
	T.El (%)	45	39	29	26	37	37	42	34	33	44	42	22	26
	5~10% of n value	0.243	0.238	0.238	0.256	0.247	0.268	0.277	0.241	0.232	0.251	0.243	0.227	0.211
	TSxT.El (MPa)•(%)	24570	24570	22678	23686	24383	24457	26166	24412	23727	25872	25242	22506	20098
Pre-deformation and BH treatment	Pre-deformation method	C	C	L	C	C	C	C	C	E	C	L	C	C
	Pre-deformation equivalent strain %	5	5	10	5	5	3	5	5	10	5	5	1	5
	BH treatment	yes	no	yes	yes	yes	yes	yes	yes	no	yes	no	yes	yes
Static and dynamic tensile test (strain rate= 1000/sec) after pre-deformation/BH treatment	Static maximum strength σs (MPa)	627	706	823	967	715	683	612	792	824	630	726	1119	884
	Static 3-10% average flow stress σst (MPa)	522	601	747	871	627	615	563	675	693	523	550	1112	772
	Dynamic maximum strength σd (MPa)	753	841	948	1063	844	831	748	895	913	776	848	1182	935
	Dynamic 3-10% average flow stress σdyn (MPa)	684	750	871	963	789	794	738	810	821	711	723	1150	860
	Expression σd-σs	126	135	125	96	129	148	136	103	89	146	122	63	<u>51</u>
	Expression *1	16	20	37	40	41	59	44	30	24	48	36	16	<u>-2</u>
Welding		ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok

Underlined data indicate values outside of the range of the invention. *1: (σdyn-σst) - (-0.272 x TS + 300)
C = Uniaxial tension in C direction, L = Uniaxial tension in L direction, E = Equal biaxial tension

CA 02278841 1999-07-27

Table 8 Mechanical properties of steels (cont.)

Steel No.		29	30	31	32	33	34	35	36	37	38	39	40
Static tensile test (strain rate =0.001/sec)	TS (MPa)	642	651	683	502	1095	570	865	849	716	916	515	756
	T.El (%)	38	35	36	31	17	25	27	23	26	22	27	27
	5-10% of n value	0.239	0.216	0.224	0.156	0.155	0.126	0.195	0.168	0.188	0.169	0.129	0.198
	TSxT.El (MPa)•(%)	24396	22785	24588	15562	18615	14250	23355	19527	18616	20152	13905	20412
Pre-deformation and BH treatment	Pre-deformation method	C	E	C	C	C	C	C	C	C	C	C	C
	Pre-deformation equivalent strain %	5	5	5	5	5	5	5	5	5	5	5	5
	BH treatment	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Static and dynamic tensile test (strain rate= 1000/s) after pre-deformation/BH treatment	Static maximum strength σs (MPa)	719	750	753	587	1040	693	934	926	827	1021	631	851
	Static 3-10% average flow stress σst (MPa)	601	622	623	512	1034	586	820	807	703	900	515	741
	Dynamic maximum strength σd (MPa)	838	852	862	642	1065	723	986	968	863	1042	659	890
	Dynamic 3-10% average flow stress σdyn (MPa)	754	770	772	598	1035	641	872	855	773	915	604	792
	Expression σd-σs	119	102	109	55	25	30	52	42	36	21	28	39
	Expression *1	28	25	35	-77	-1	-90	-13	-21	-35	-36	-71	-43
Welding		ok	ok	ok	ok	poor	ok	ok	ok	ok	poor	ok	ok

Underlined data indicate values outside of the range of the invention. *1: (σdyn-σst) - (-0.272 x TS + 300)
C = Uniaxial tension in C direction, E = Equal biaxial tension

CA 02278841 1999-07-27

Industrial Applicability

As explained above, the present invention makes it possible to provide in an economical and stable manner high-strength hot-rolled steel sheets and cold-rolled steel sheets for automobiles which provide previously unobtainable excellent anti-collision safety and formability, and thus offers a markedly wider range of objects and conditions for uses of high-strength steel sheets.

CLAIMS

1. A press formable high-strength steel sheet containing, in terms of weight percentage, C at from 0.03% to 0.3%, at least one of Si and Al at a total of from 0.5% to 3.0% as a primary component, characterized in that a microstructure of the steel sheet in its final form is a composite microstructure of a mixture of at least one of ferrite and bainite, either of which is a dominant phase, and a third phase including retained austenite at a volume fraction between 3% and 50%, wherein a difference between a static tensile strength σs when deformed in a strain rate range of 5×10^{-4} - 5×10^{-3} (1/sec) after pre-deformation at an equivalent strain of greater than 0% and at most equal to 10%, and a dynamic tensile strength σd when deformed at a strain rate of 5×10^{2} - 5×10^{3} (1/s) after said pre-deformation, namely $\sigma d - \sigma s$, is at least 60 MPa, and a work hardening coefficient between 5% and 10% of a strain is at least 0.130, said steel sheet optionally further containing, in terms of weight percentage, at least one from among Mn, Ni, Cr, Cu and Mo at a total of from 0.5% to 3.5%, with the remainder Fe as the primary component, and further optionally at least one from among Nb, Ti, V, P and B, with at least one from among Nb, Ti and V at a total of at most 0.3%, P at at most 0.3% and B at at most 0.01%, and further optionally Ca at from 0.0005% to 0.01% and REM at from 0.005% to 0.05%.

2. A press formable high-strength steel sheet containing, in terms of weight percentage, C at from 0.03% to 0.3%, at least one of Si and Al at a total of from 0.5% to 3.0% as a primary component, characterized in that a

microstructure of the steel sheet in its final form is a composite microstructure of a mixture of at least one of ferrite and bainite, either of which is a dominant phase, and a third phase including retained austenite at a volume fraction between 3% and 50%, wherein a difference between the static tensile strength σs when deformed in a strain rate range of $5 \times 10^{-4} - 5 \times 10^{-3}$ (1/s) after pre-deformation at an equivalent strain of greater than 0% and at most equal to 10%, and a dynamic tensile strength σd when deformed at a strain rate of $5 \times 10^{2} - 5 \times 10^{3}$ (1/s) after said pre-deformation, namely $\sigma d - \sigma s$, is at least 60 MPa, a difference between the average value σdyn (MPa) of a flow stress at an equivalent strain in the range of 3 - 10% when deformed in a strain rate range of $5 \times 10^{2} - 5 \times 10^{3}$ (1/s) and an average value σst (Mpa) of the flow stress at an equivalent strain in the range of 3 - 10% when deformed in a strain rate range of $5 \times 10^{-4} - 5 \times 10^{-3}$ (1/s) satisfies the inequality: $(\sigma dyn - \sigma st) \geq -0.272 \times TS + 300$ as expressed in terms of a maximum stress TS (MPa) in a static tensile test as measured in a strain rate range of $5 \times 10^{-4} - 5 \times 10^{-3}$ (1/s), and a work hardening coefficient between 5% and 10% of a strain is at least 0.130, said steel sheet optionally further containing, in terms of weight percentage, at least one from among Mn, Ni, Cr, Cu and Mo at a total of from 0.5% to 3.5%, with the remainder Fe as the primary component, and further optionally at least one from among Nb, Ti, V, P and B, with at least one from among Nb, Ti and V at a total of at most 0.3%, P at at most 0.3% and B at at most 0.01%, and further optionally Ca at from 0.0005% to 0.01% and REM at from 0.005% to 0.05%.

3. A press formable high-strength steel sheet containing, in terms of weight percentage, C at from 0.03% to 0.3%, at least one of Si and Al at a total of from 0.5% to 3.0% as a primary component, characterized in that a microstructure of the steel sheet in its final form is a composite microstructure of a mixture of at least one of ferrite and bainite, either of which is a dominant phase, and a third phase including retained austenite at a volume fraction between 3% and 50%, wherein a difference between a static tensile strength σs when deformed in a strain rate range of 5×10^{-4} - 5×10^{-3} (1/s) after pre-deformation at an equivalent strain of greater than 0% and at most equal to 10%, and a dynamic tensile strength σd when deformed at a strain rate of 5×10^{2} - 5×10^{3} (1/s) after said pre-deformation, namely σd - σs, is at least 60 MPa, a difference between an average value σdyn (MPa) of a flow stress at an equivalent strain in the range of 3 - 10% when deformed in a strain rate range of 5×10^{2} - 5×10^{3} (1/s) and an average value σst (MPa) of the flow stress at an equivalent strain in the range of 3 - 10% when deformed in a strain rate range of 5×10^{-4} - 5×10^{-3} (1/s) satisfies the inequality: $(\sigma dyn - \sigma st) \geq -0.272 \times TS + 300$ as expressed in terms of a maximum stress TS (MPa) in a static tensile test as measured in a strain rate range of 5×10^{-4} - 5×10^{-3} (1/s), a value (M) determined by a solid solution [C] in said retained austenite and an average Mn equivalents of the steel sheet {Mn eq = Mn + (Ni + Cr + Cu = Mo)/2}, defined by the equation M = 678 - 428 x [C] - 33 Mn eq is at least -140 and less than 70, the retained austenite volume fraction of the steel sheet

after pre-deformation at an equivalent strain of greater than 0% and at most equal to 10% is at least 2.5%, a ratio between an initial volume fraction of the retained austenite V(0) and a volume fraction of the retained austenite after pre-deformation at an equivalent strain of 10% V(10) is at least 0.3, and a work hardening coefficient between 5% and 10% of a strain is at least 0.130, said steel sheet optionally further containing, in terms of weight percentage, at least one from among Mn, Ni, Cr, Cu and Mo at a total of from 0.5% to 3.5%, with the remainder Fe as the primary component, and further optionally at least one from among Nb, Ti, V, P and B, with at least one from among Nb, Ti and V at a total of at most 0.3%, P at at most 0.3% and B at at most 0.01%, and further optionally Ca at from 0.0005% to 0.01% and REM at from 0.005% to 0.05%.

4. The steel sheet according to any one of claims 1 to 3, wherein an average grain diameter of said retained austenite is at most 5 μm; a ratio of the average grain diameter of said retained austenite and an average grain diameter of one of ferrite and bainite in the dominant phase is at most 0.6, and an average grain diameter of the dominant phase is at most 10 μm.

5. The steel sheet according to claim 4, wherein the average grain diameter of the dominant phase is at most 6 μm.

6. The steel sheet according to any one of claims 1 to 5, wherein a volume fraction of the ferrite is at least 40%.

7. The steel sheet according to any one of claims 1 to 6, wherein a value of tensile strength x total elongation is at least 20,000.

8. A method for producing a press formable high-strength hot-rolled steel sheet with high flow stress during dynamic deformation where a microstructure of the hot-rolled steel sheet is a composite microstructure of a mixture of at least one of ferrite and bainite, either of which is a dominant phase, and a third phase including retained austenite of a volume fraction between 3% and 50%, wherein a difference between a static tensile strength σs when deformed in a strain rate range of 5×10^{-4} - 5×10^{-3} (1/s) after pre-deformation at an equivalent strain of greater than 0% and at most equal to 10%, and a dynamic tensile strength σd when deformed at a strain rate of 5×10^{2} - 5×10^{3} (1/s) after said pre-deformation, namely $\sigma d - \sigma s$, is at least 60 MPa, a difference between an average value σdyn (MPa) of a flow stress at an equivalent strain in the range of 3 - 10% when deformed in a strain rate range of 5×10^{2} - 5×10^{3} (1/s) and an average value σst (MPa) of the flow stress at an equivalent strain in the range of 3 - 10% when deformed in a strain rate range of 5×10^{-4} - 5×10^{-3} (1/s) satisfies the inequality: $(\sigma dyn - \sigma st) \geq -0.272 \times TS + 300$ as expressed in terms of a maximum stress TS (MPa) in a static tensile test as measured in a strain rate range of 5×10^{-4} - 5×10^{-3} (1/sec), and a work hardening coefficient between 5% and 10% of a strain is at least 0.130, which is characterized in that a continuous cast

slab containing, in terms of weight percentage, C at from 0.03% to 0.3%, at least one of both Si and Al at a total of from 0.5% to 3.0%, is fed directly from casting to a hot rolling step, or is hot rolled after reheating, said hot rolling being completed at a finishing temperature of Ar_3 - 50°C to Ar_3 + 120°C, and after cooling at an average cooling rate of 5°C/sec in a cooling process following said hot rolling, the sheet is coiled up at a temperature of at most 500°C, the cast slab optionally containing, in terms of weight percentage, at least one from among Mn, Ni, Cr, Cu and Mo at a total of from 0.5% to 3.5% and at least one from among Nb, Ti, V, P, B, Ca and REM, with at least one from among Nb, Ti and V at a total of at most 0.3%, P at at most 0.3%, B at at most 0.01%, Ca at from 0.0005% to 0.01% and REM at from 0.005 to 0.05%, with the remainder Fe as the primary component.

9. The method according to claim 8, in which the continuous cast slab contains, in terms of weight percentage, at least one from among Mn, Ni, Cr, Cu and Mo at a total of from 0.5% to 3.5%.

10. The method according to any one of claims 8 and 9, in which the continuous cast slab contains, in terms of weight percentage, at least one from among Nb, Ti, V, P, B, Ca and REM, with at least one from among Nb, Ti and V at a total of at most 0.3%, P at at most 0.3%, B at at most 0.01%, Ca at from 0.0005% to 0.01% and REM at from 0.005 to 0.05%, with the remainder Fe as the primary component.

11. The method according to any one of claims 8 to 10, wherein at the finishing temperature for said hot-rolling in a range of Ar_3 - 50°C to Ar_3 + 120°C, the hot rolling is carried out so that the metallurgy parameter A satisfies inequalities (1) and (2) below, the subsequent average cooling rate in the run-out table is at least 5°C/sec, and the coiling is accomplished so that the relationship between said metallurgy parameter A and the coiling temperature (CT) satisfies inequality (3) below:

$$9 \leq \log A \leq 18 \quad \ldots\ldots(1)$$

$$\Delta T \leq 21 \times \log A - 178 \quad \ldots\ldots(2)$$

$$6 \times \log A + 312 \leq CT \leq 6 \times \log A + 392 \quad \ldots\ldots(3)$$

12. A method for producing a press formable high-strength cold-rolled steel sheet with high flow stress during dynamic deformation where the microstructure of the cold-rolled steel sheet is a composite microstructure of a mixture of ferrite and/or bainite, either of which is the dominant phase, and a third phase including retained austenite of the volume fraction between 3% and 50%, wherein the difference between the static tensile strength σs when deformed in a strain rate range of 5×10^{-4} - 5×10^{-3} (1/s) after pre-deformation at an equivalent strain of greater than 0% and less than or equal to 10%, and the dynamic tensile strength σd when deformed at a strain rate of 5×10^{2} - 5×10^{3} (1/s) after said pre-deformation, namely $\sigma d - \sigma s$, is at least 60 MPa, the difference between the average value σdyn (MPa) of the flow stress at an equivalent strain in the range of 3 - 10% when deformed in a strain rate range of 5×10^{2} - 5×10^{3} (1/sec) and the average value σst (MPa) of the flow

stress at an equivalent strain in the range of 3 - 10% when deformed in a strain rate range of 5×10^{-4} - 5×10^{-3} (1/s) satisfies the inequality: $(\sigma dyn - \sigma st) \geq -0.272 \times TS + 300$ as expressed in terms of the maximum stress TS (MPa) in the static tensile test as measured in a strain rate range of 5×10^{-4} - 5×10^{-3} (1/sec), and the work hardening coefficient between 5% and 10% of a strain is at least 0.130, which is characterized in that a continuous cast slab containing, in terms of weight percentage, C at from 0.03% to 0.3%, either or both Si and Al at a total of from 0.5% to 3.0%, is fed directly from casting to a hot rolling step, or is hot rolled after reheating, the coiled hot-rolled steel sheet after hot rolling is subjected to acid pickling and then cold-rolled, and during annealing in a continuous annealing step for preparation of the final product, annealing for 10 seconds to 3 minutes at a temperature of from $0.1 \times (Ac_3 - Ac_1) + Ac_1$°C to $Ac_3 + 50$°C is followed by cooling to a primary cooling stop temperature in the range of 550 - 720°C at a primary cooling rate of 1 - 10°C/sec and then by cooling to a secondary cooling stop temperature in the range of 200 - 450°C at a secondary cooling rate of 10 - 200/sec after which the temperature is held in a range of 200 - 500°C for 15 seconds to 20 minutes prior to cooling to room temperature, the cast slab optionally containing at least one from among Mn, Ni, Cr, Cu and Mo at a total of from 0.5% to 3.5% and at least one from among Nb, Ti, V, P, B, Ca and REM, with at least one from among Nb, Ti and V at a total of at most 0.3%, P at at most 0.3%, B at at most 0.01%, Ca at from 0.0005% to 0.01% and REM at from 0.005 to 0.05%, with the remainder Fe as the primary component.

13. The method according to claim 12, in which the continuous cast slab contains at least one from among Mn, Ni, Cr, Cu and Mo at a total of from 0.5% to 3.5%.

14. The method according to any one of claims 12 and 13, in which the continuous cast slab contains at least one from among Nb, Ti, V, P, B, Ca and REM, with at least one from among Nb, Ti and V at a total of at most 0.3%, P at at most 0.3%, B at at most 0.01%, Ca at from 0.0005% to 0.01% and REM at from 0.005 to 0.05%, with the remainder Fe as the primary component.

15. The method according to any one of claims 12 to 14, where the microstructure of the cold-rolled steel sheet is a composite microstructure of a mixture of ferrite and/or bainite, either of which is the dominant phase, and a third phase including retained austenite of the volume fraction between 3% and 50%, wherein the difference between the static tensile strength σs when deformed in a strain rate range of $5 \times 10^{-4} - 5 \times 10^{-3}$ (1/s) after pre-deformation at an equivalent strain of greater than 0% and at most 10%, and the dynamic tensile strength σd when deformed at a strain rate of $5 \times 10^{2} - 5 \times 10^{3}$ (1/sec) after the aforementioned pre-deformation, namely $\sigma d - \sigma s$, is at least 60 MPa, the difference between the average value σdyn (MPa) of the flow stress at an equivalent strain in the range of 3 - 10% when deformed in a strain rate range $5 \times 10^{2} - 5 \times 10^{3}$ (1/s) and the average value σst (MPa) of the flow stress at an equivalent strain in the range of 3 - 10% when deformed in a strain rate range of $5 \times 10^{-4} - 5 \times 10^{-3}$ (1/s) satisfies the inequality:

(σdyn - σst) $\geq$ -0.272 x TS + 300 as expressed in terms of the maximum stress TS (MPa) in the static tensile test as measured in a strain rate range of 5 x 10^{-4} - 5 x 10^{-3} (1/s), and the work hardening coefficient between 5% and 10% of a strain is at least 0.130, which is characterized in that during annealing in said continuous annealing step for preparation of the final product, annealing for 10 seconds to 3 minutes at a temperature of from 0.1 x (Ac_3 - Ac_1) + Ac_1°C to Ac_3 + 50°C is followed by cooling to a secondary cooling start temperature Tq in the range of 550 - 720°C at the primary cooling rate of 1 - 10°C/sec and then by cooling to a secondary cooling stop temperature Te in the range from the temperature Tem determined by the component and annealing temperature To to 500°C at the secondary cooling rate of 10 - 200°C/sec, after which the temperature Toa is held in a range of Te - 50°C to 500°C for 15 seconds to 20 minutes prior to cooling to room temperature.

Fig.1

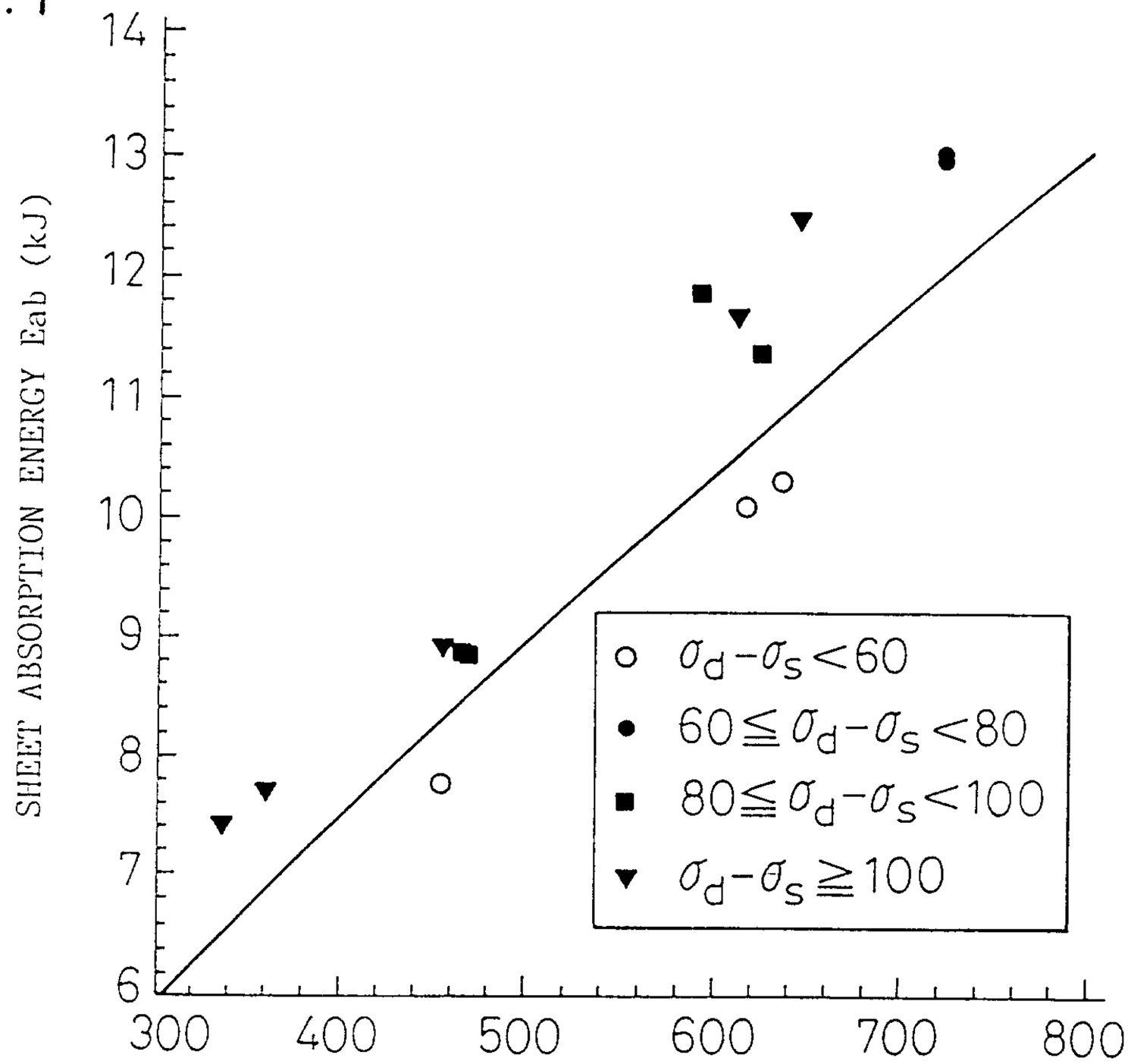

SHEET ABSORPTION ENERGY Eab (kJ)
14
13
12
11
10
9
8
7
6
300
400
500
600
700
800
SHEET TENSILE STRENGTH (MPa)
$\sigma_d-\sigma_s<60$
$60\leqq\sigma_d-\sigma_s<80$
$80\leqq\sigma_d-\sigma_s<100$
$\sigma_d-\sigma_s\geqq100$

Fig.2

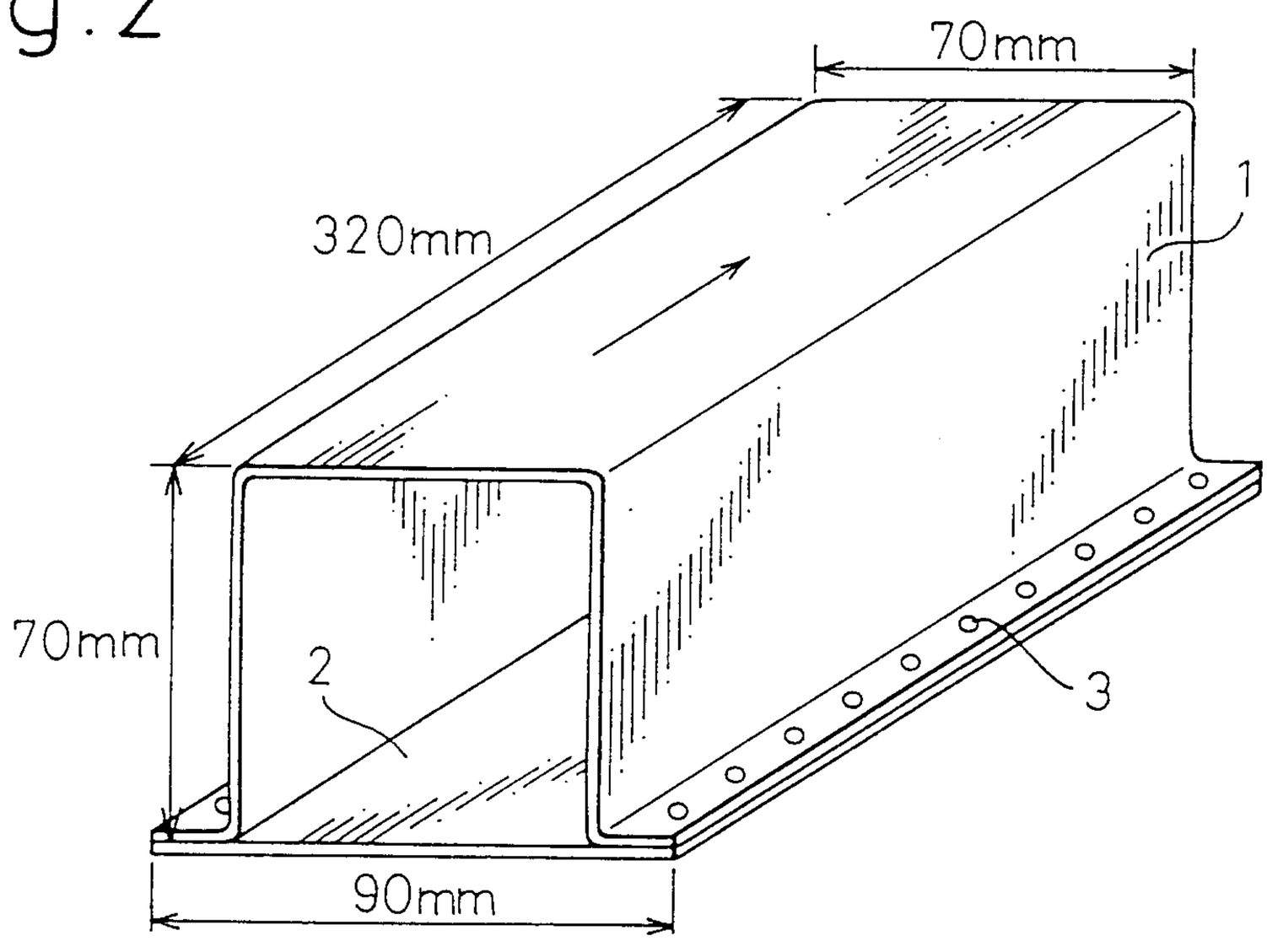

70mm
320mm
1
70mm
2
3
90mm

Fig.3

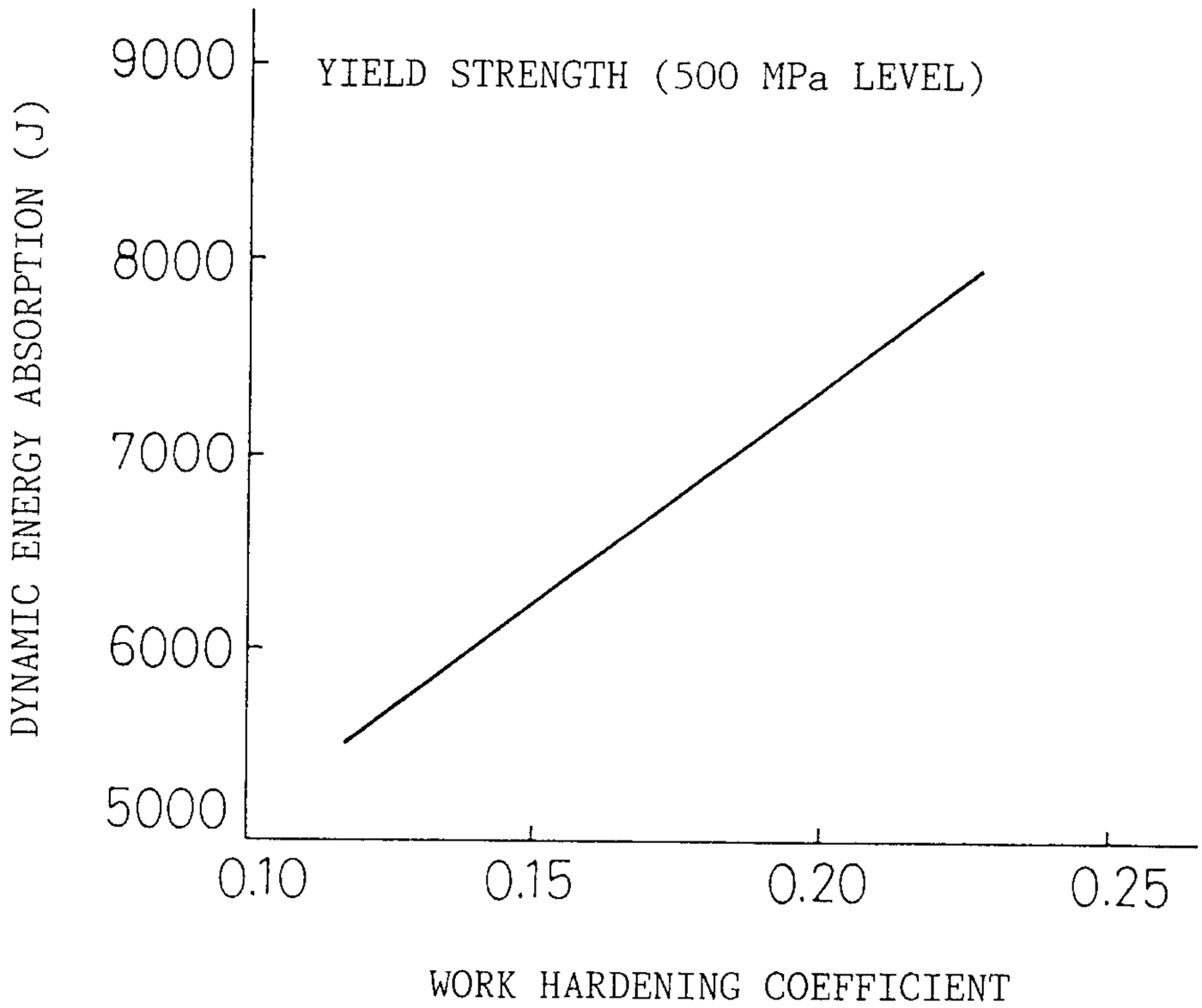

YIELD STRENGTH (500 MPa LEVEL)
DYNAMIC ENERGY ABSORPTION (J)
9000
8000
7000
6000
5000
0.10
0.15
0.20
0.25
WORK HARDENING COEFFICIENT

Fig.4 a

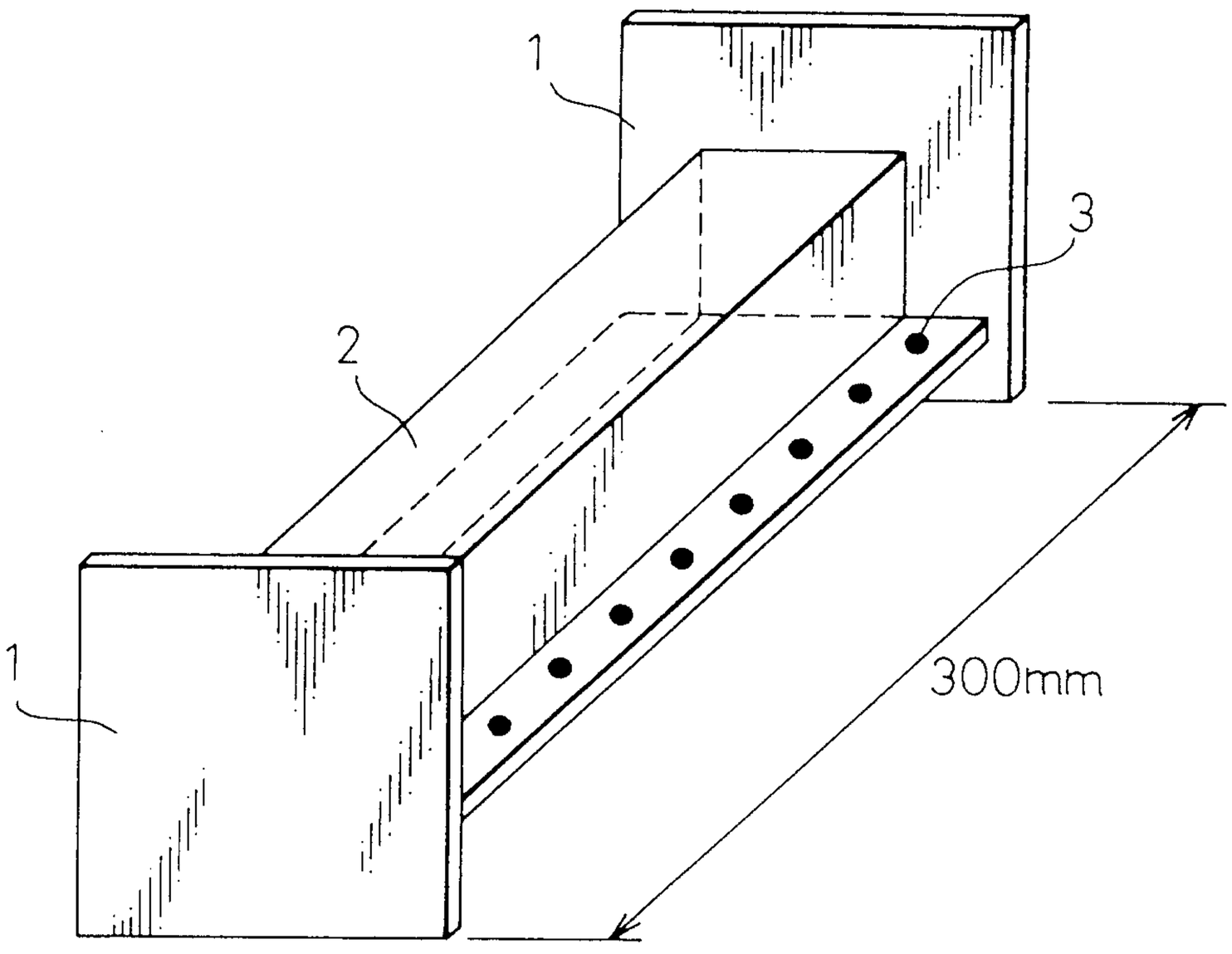

1
2
3
1
300mm

Fig.4 b

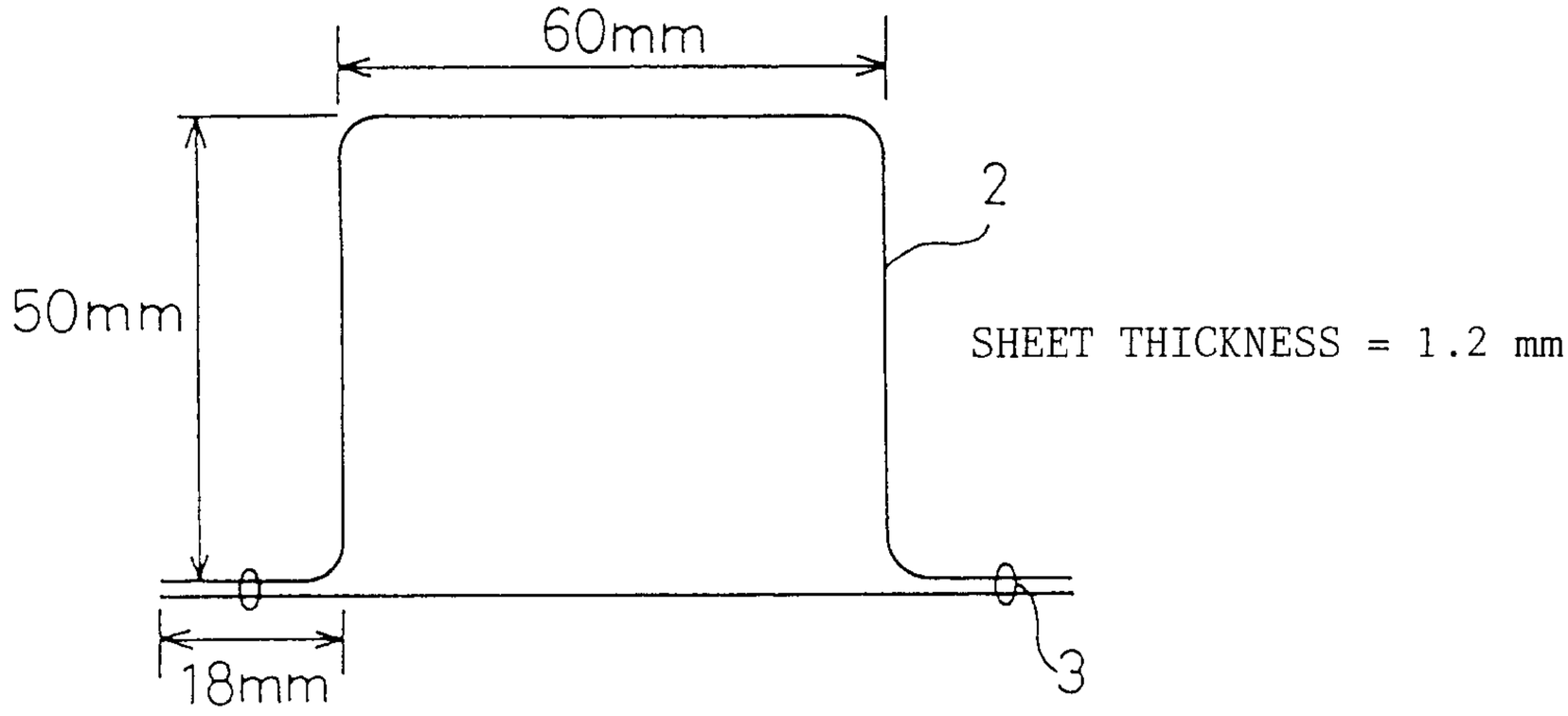


Fig.4 c

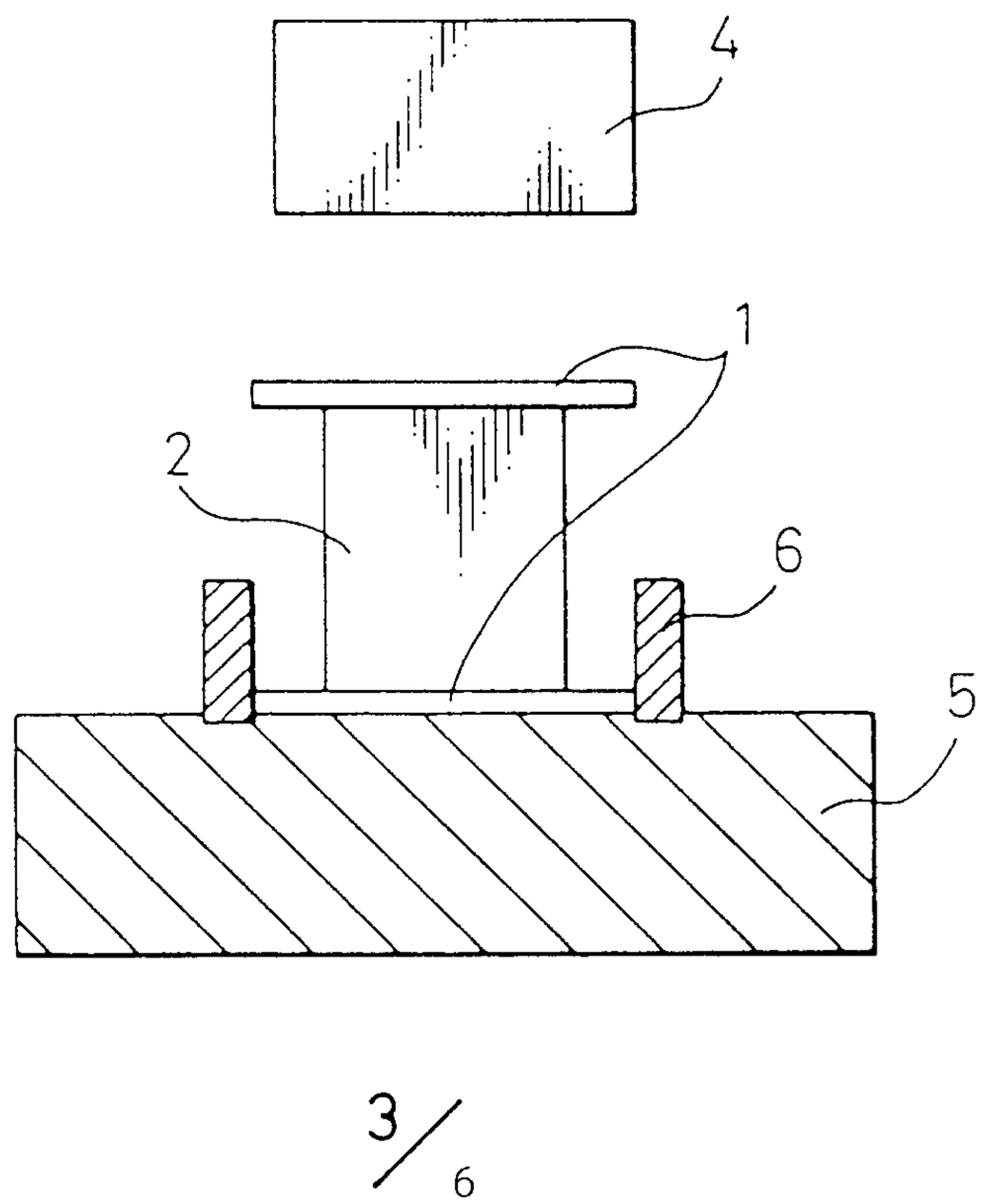


Fig.5

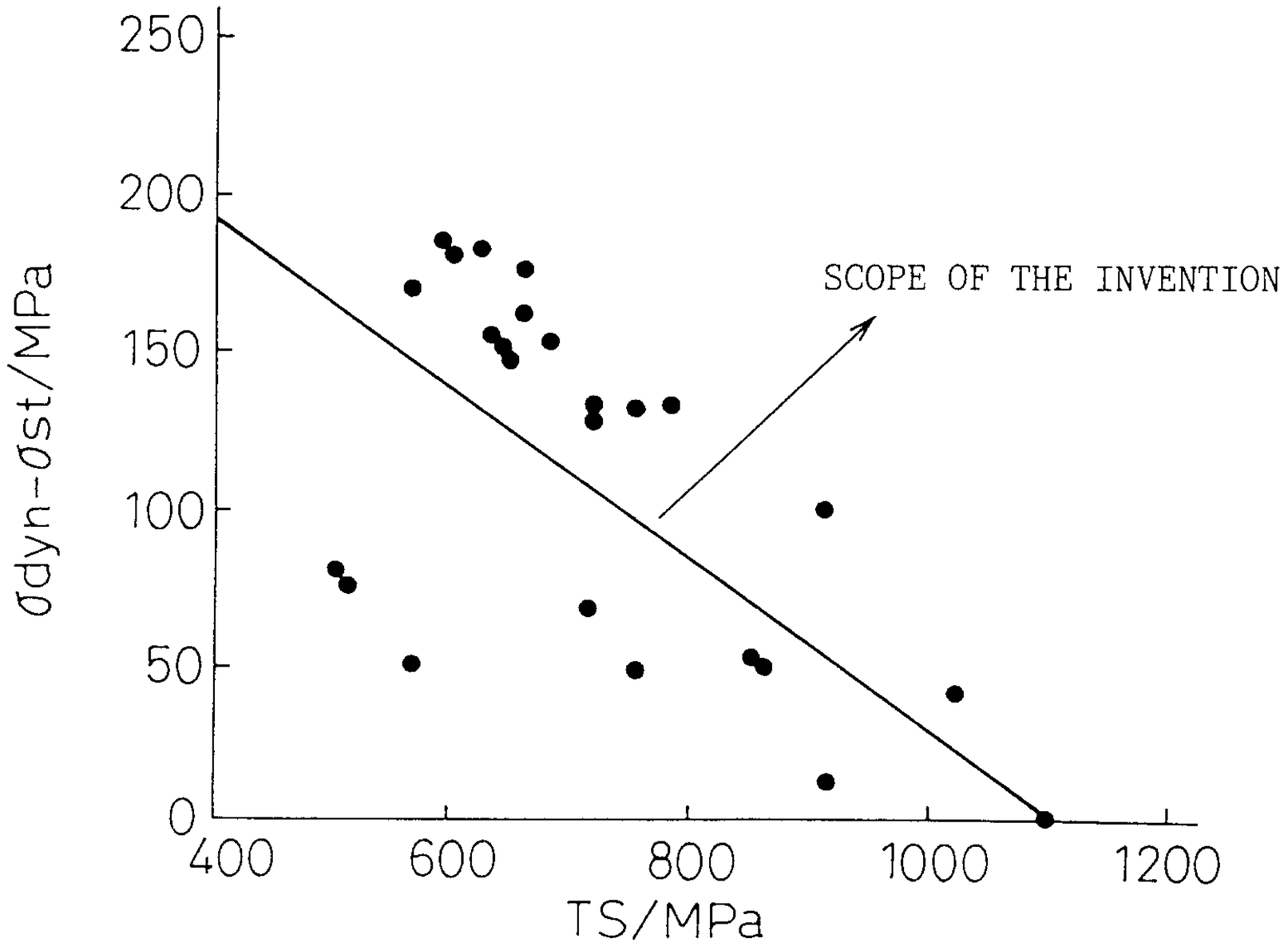

250
200
150
100
50
0
400
600
800
1000
1200
σdyn-σst/MPa
TS/MPa
SCOPE OF THE INVENTION

Fig.6

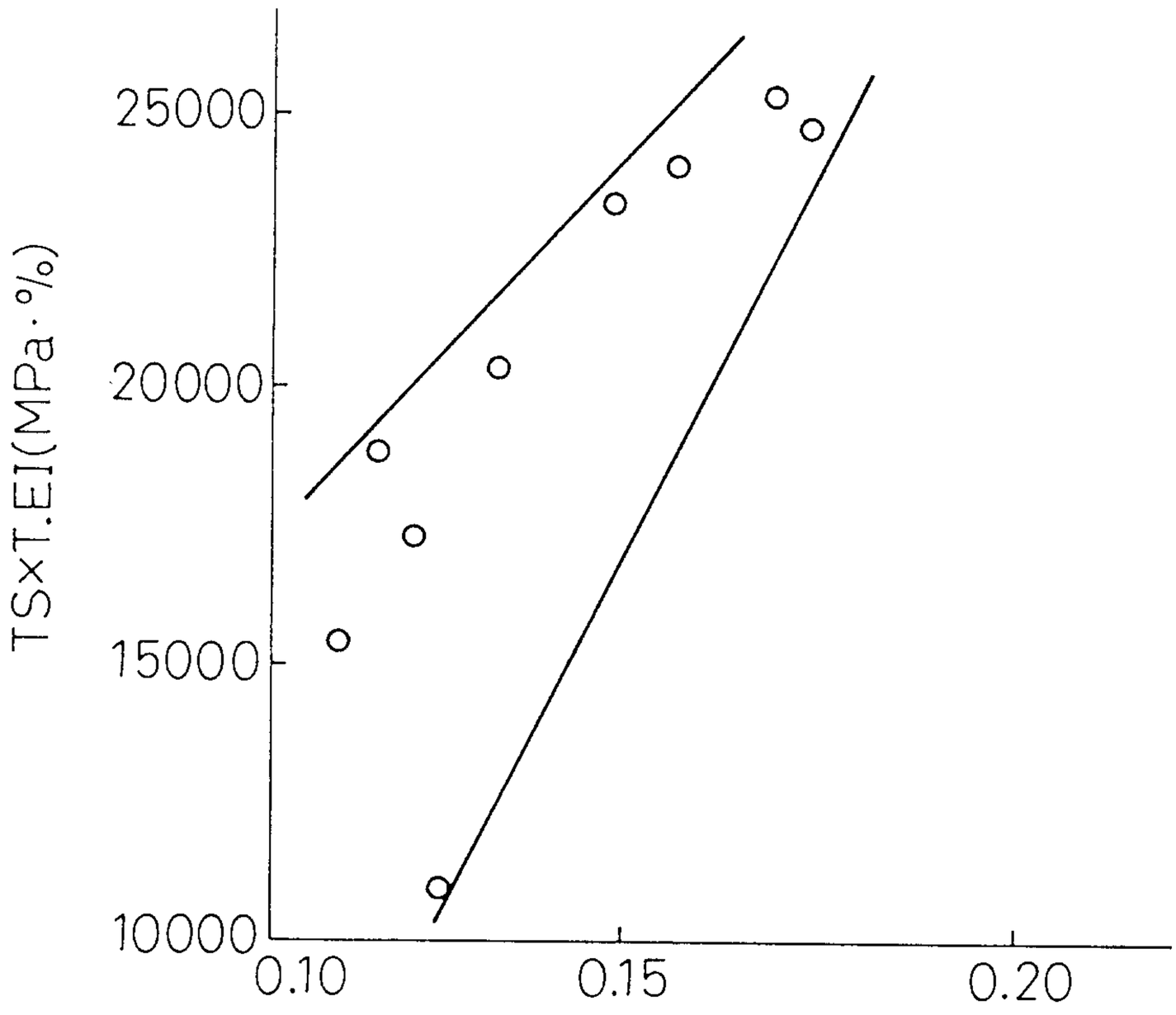

25000
20000
15000
10000
0.10
0.15
0.20
TS×T.EI(MPa·%)
WORK HARDENING COEFFICIENT

Fig.7

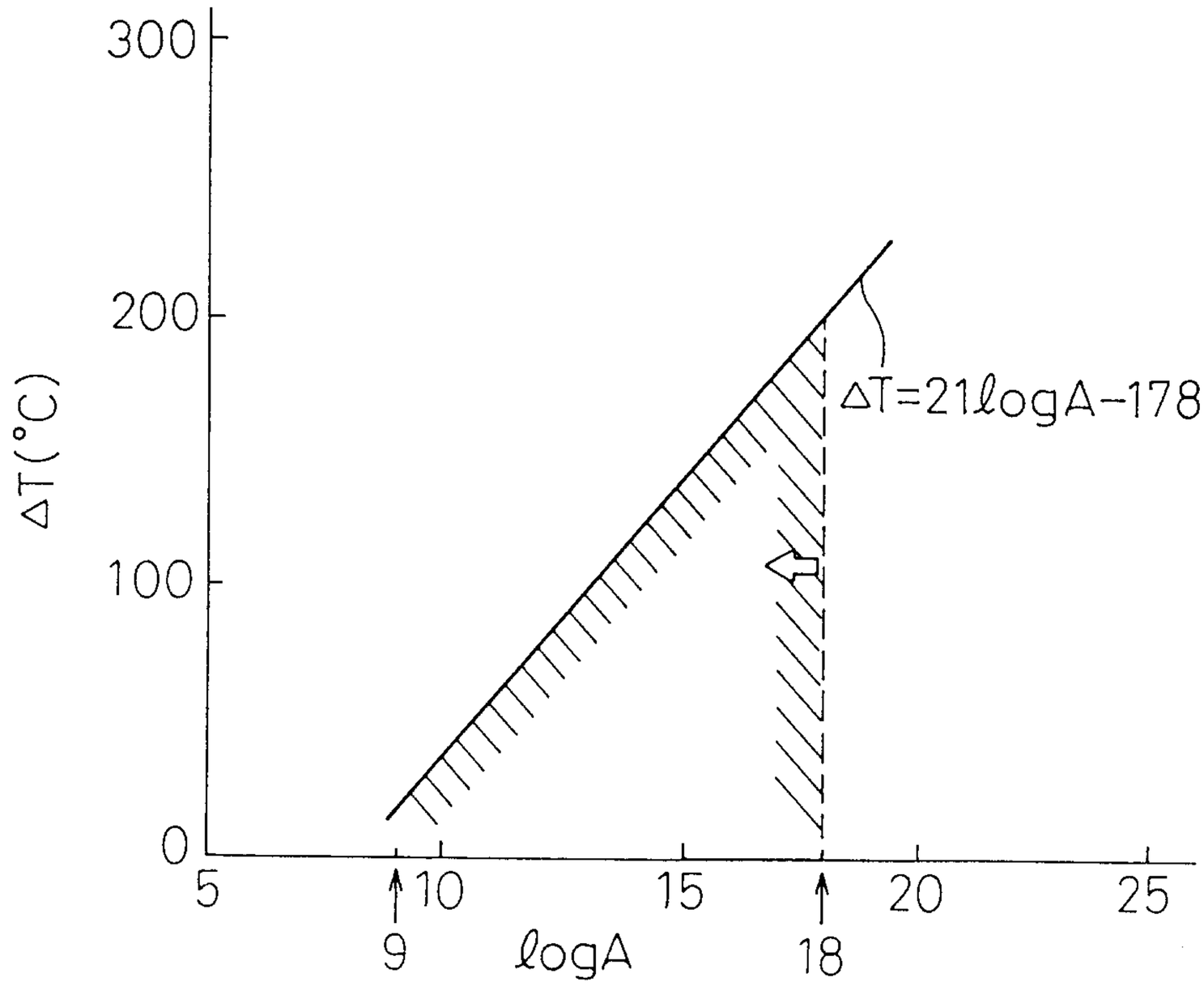

300
200
100
0
ΔT(°C)
ΔT=21ℓogA−178
5
10
15
20
25
9
18
ℓogA

Fig.8

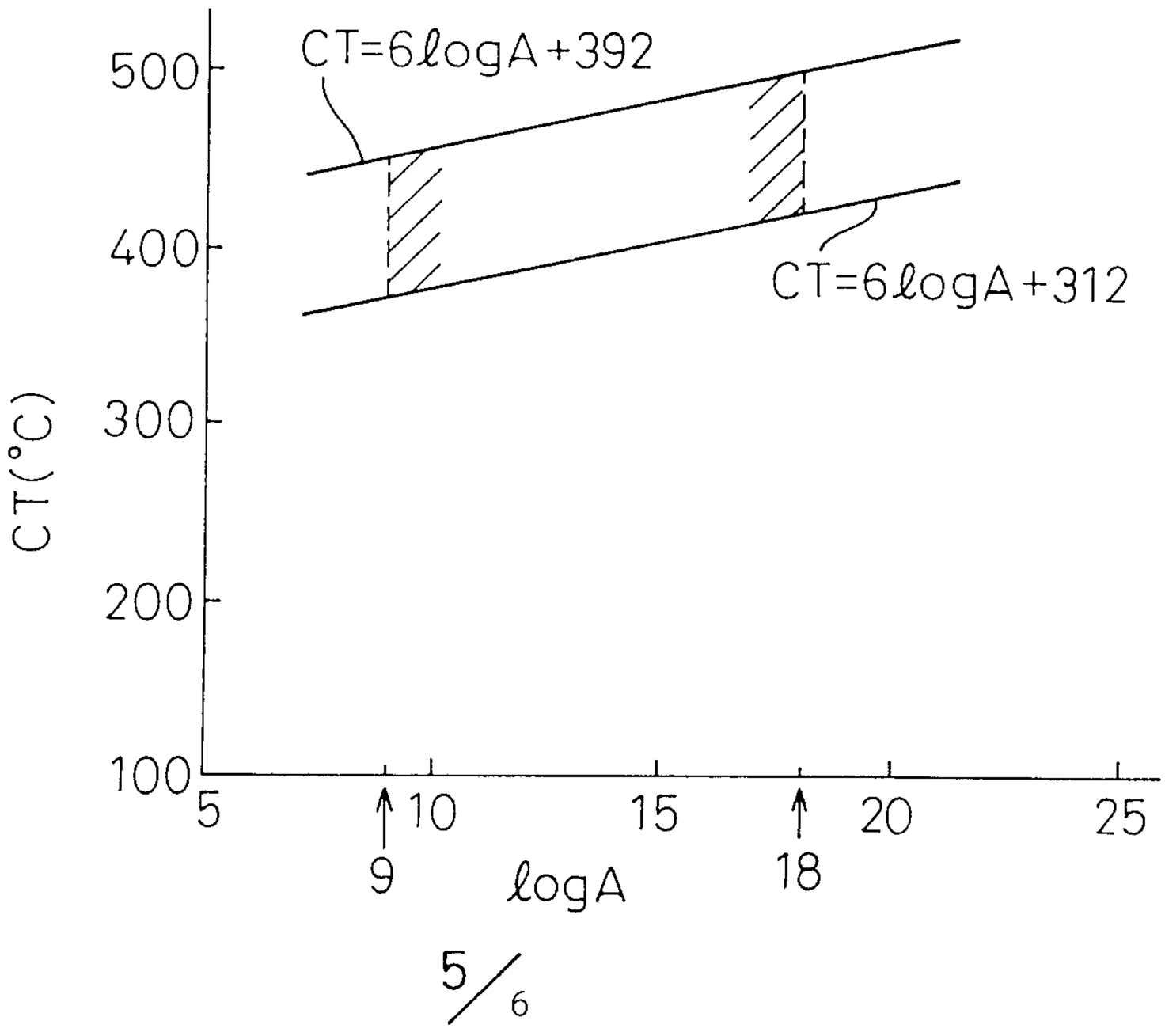

500
400
300
200
100
CT(°C)
CT=6ℓogA+392
CT=6ℓogA+312
5
10
15
20
25
9
18
ℓogA

Fig.9

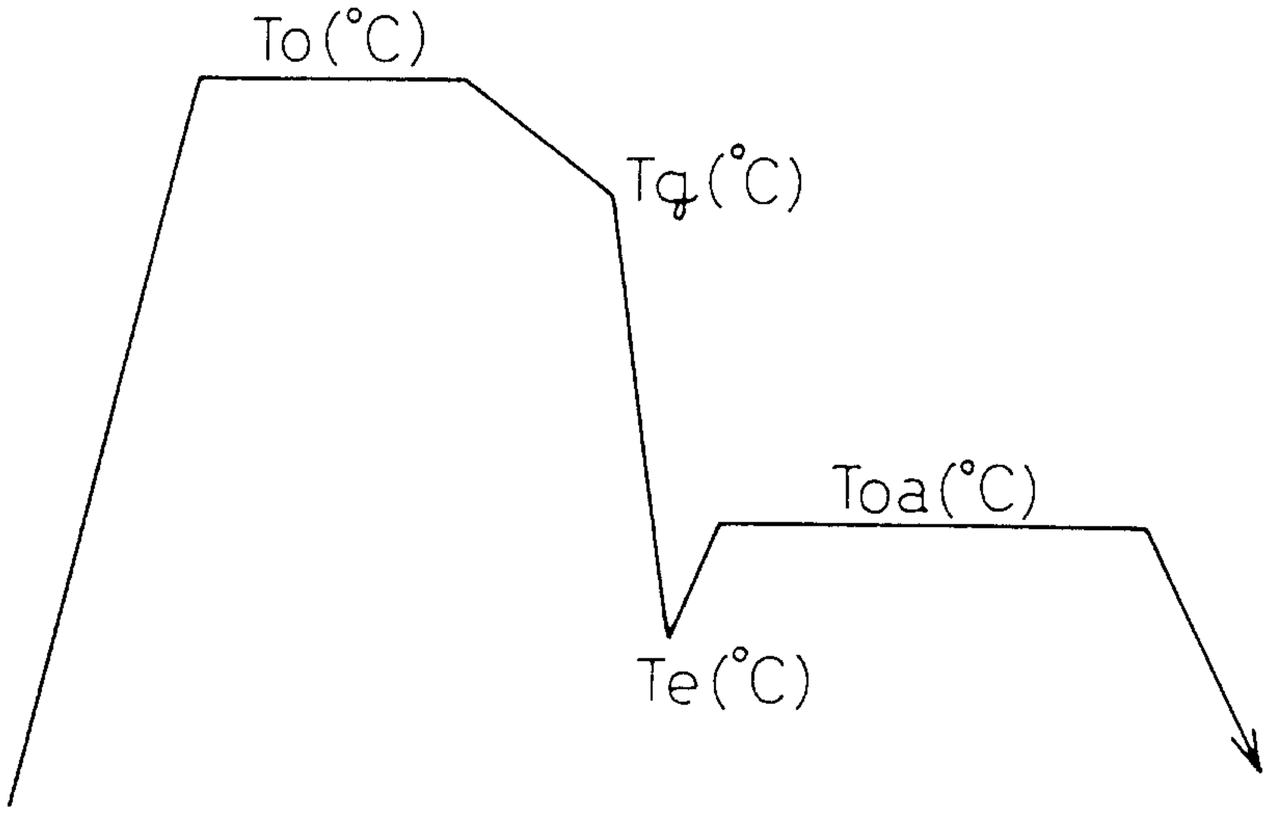
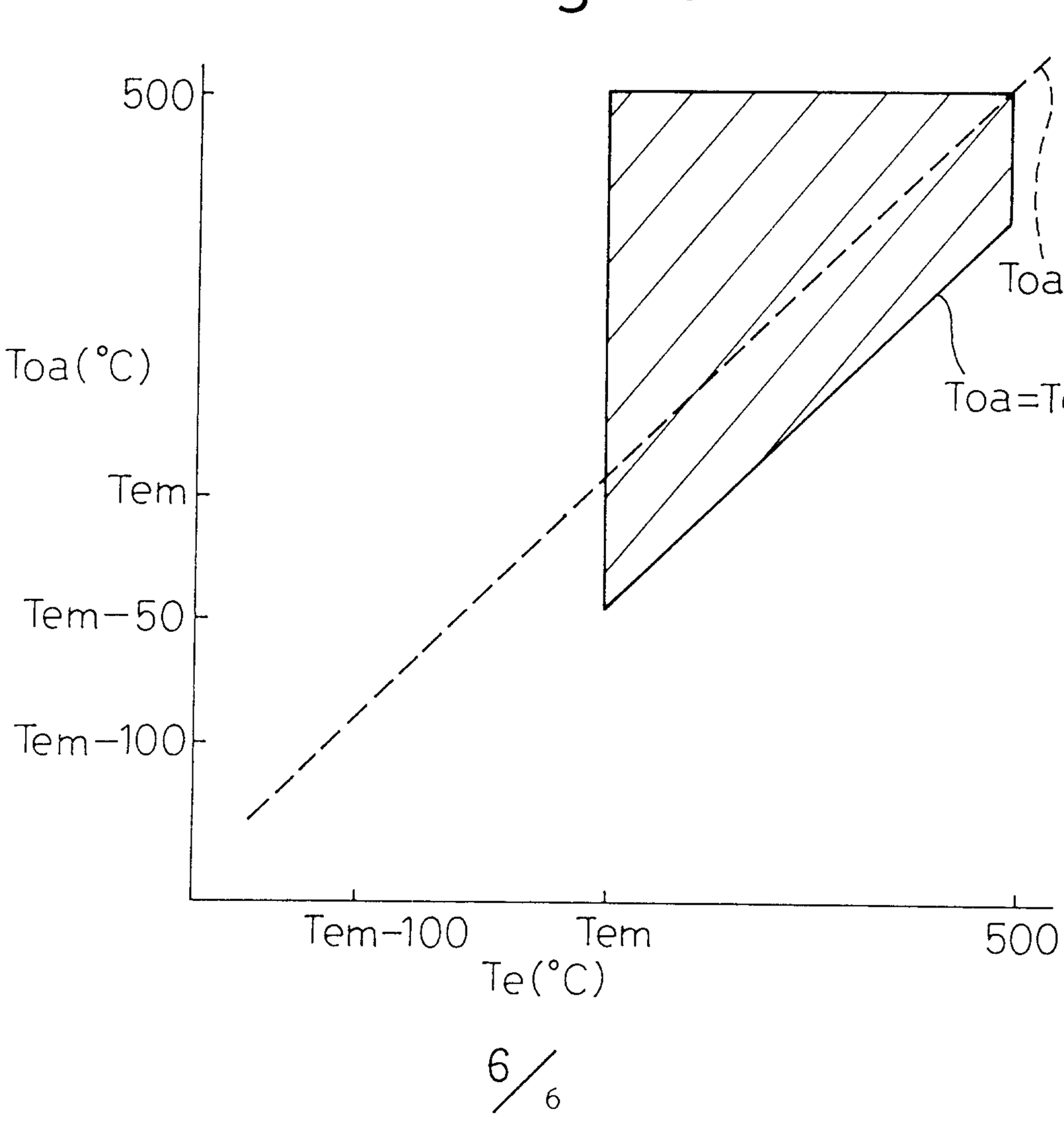
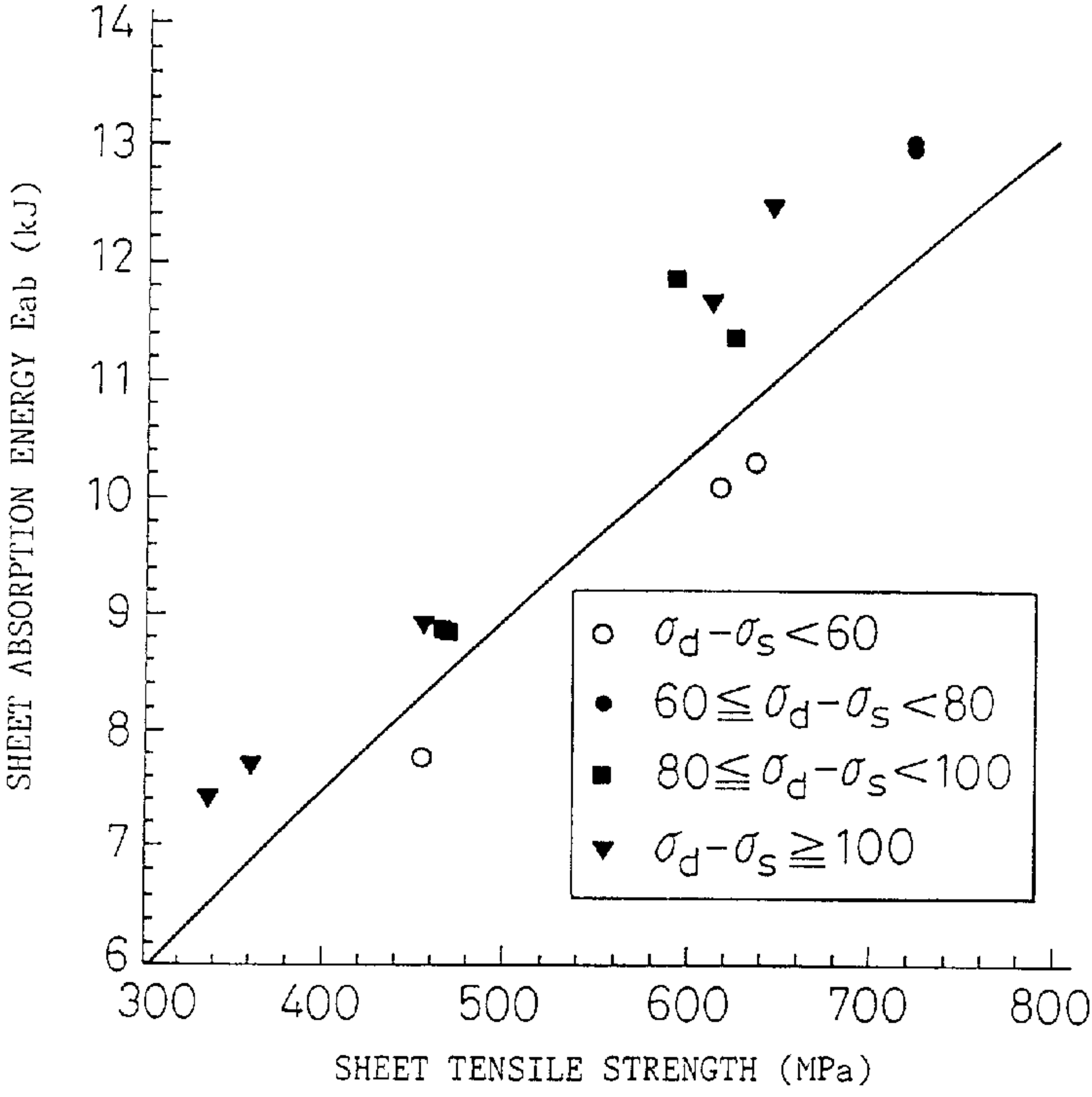

To(°C)
Tq(°C)
Toa(°C)
Te(°C)

Fig.10


500
Toa(°C)
Tem
Tem−50
Tem−100
Toa=Te
Toa=Te−50
Tem−100
Tem
500
Te(°C)


SHEET ABSORPTION ENERGY Eab (kJ)
14
13
12
11
10
9
8
7
6
300
400
500
600
700
800
SHEET TENSILE STRENGTH (MPa)
$\sigma_d-\sigma_s<60$
$60\leqq\sigma_d-\sigma_s<80$
$80\leqq\sigma_d-\sigma_s<100$
$\sigma_d-\sigma_s\geqq100$