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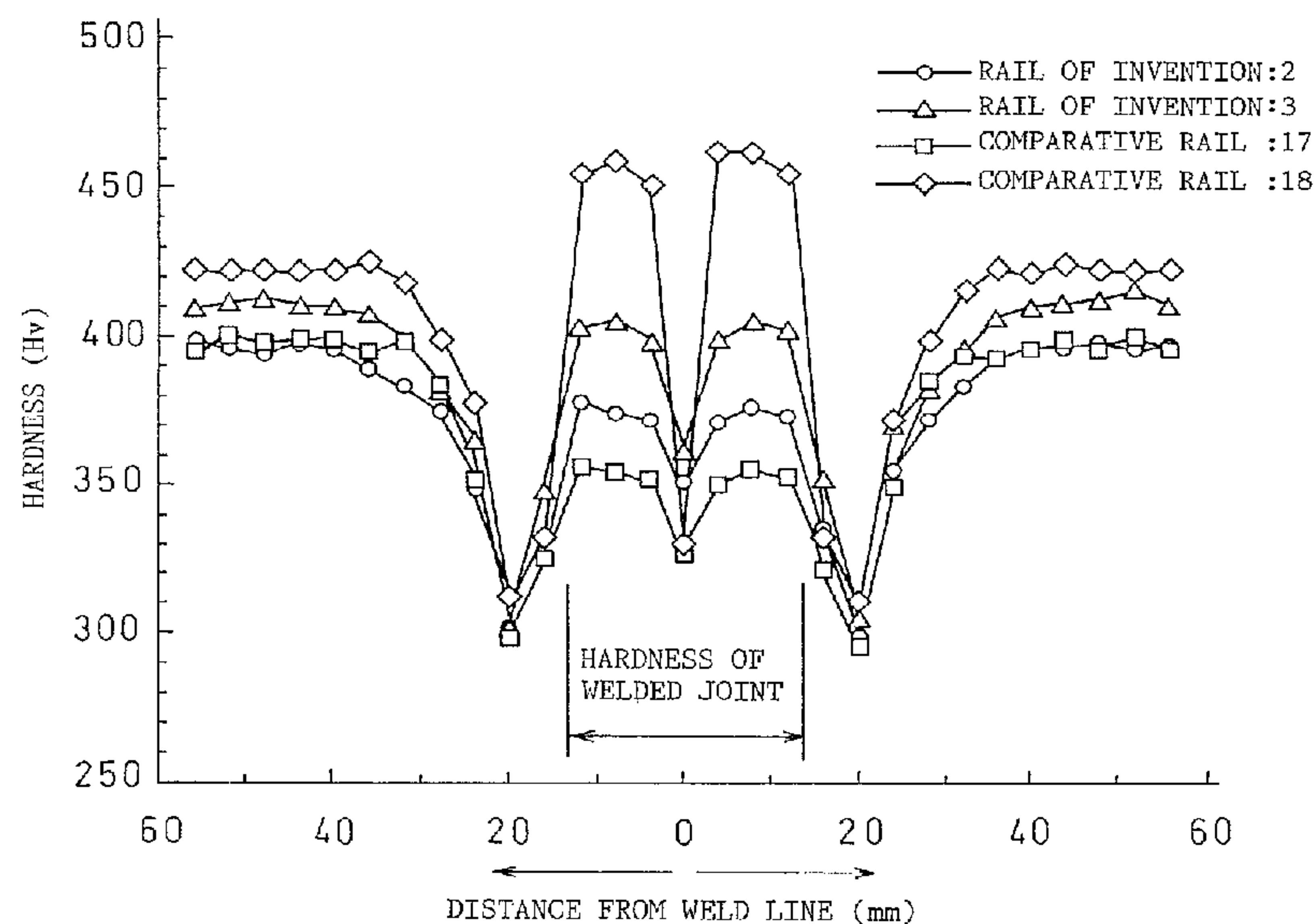
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(54) Titre : RAILS D'ACIER FAIBLEMENT ALLIÉS, A STRUCTURE PERLITIQUE, TRAITÉS A CHAUD, TEMOIGNANT D'UNE REMARQUABLE RESISTANCE A L'USURE ET DOTES D'EXCELLENTE CARACTERISTIQUES DE SOUDAGE ET PROCEDE DE FABRICATION

(54) Title: LOW-ALLOY HEAT-TREATED PEARLITIC STEEL RAIL EXCELLENT IN WEAR RESISTANCE AND WELDABILITY AND PROCESS FOR PRODUCING THE SAME



(57) **Abrégé/Abstract:**

The present invention relates to a pearlitic steel rail having the significantly improved wear resistance and weldability (welding construction, properties of the welded joints) that rails for heavy load are required to have, and a process for producing the same. The present invention particularly relates to a pearlitic steel rail excellent in wear resistance and weldability, comprising, in terms of weight, more than 0.85 to 1.20% of C, 0.10 to 1.00% of Si, 0.20 to 1.50% of Mn, more than 0.50 to 1.00% of Cr, or comprising more than 0.85 to 1.20% of C, 0.40 to 1.00% of Si, 0.20 to less than 0.40% of Mn, 0.35 to 0.50% of Cr, the content sum Si/4 + Mn/2 + Cr being 0.80 to 0.95% or being 0.8 to 1.8% in terms of weight, further comprising, in terms of weight, one or at least two elements selected from the group consisting of Mo, V, Nb and B and the balance Fe and unavoidable impurities and having a pearlite structure to the depth of at least 20 mm from the head portion corner and the head top surface as a starting point, the pearlite structure having a Vickers hardness of at least 320, the difference in Vickers hardness between the base steel and the welded joint of the steel rail being made up to 30 to prevent a wear dent caused by the local wear of the rail top surface in the welded joint without impairing the weldability.

ABSTRACT

The present invention relates to a pearlitic steel rail having the significantly improved wear resistance and weldability (welding construction, properties of the welded joints) that rails for heavy load are required to have, and a process for producing the same. The present invention particularly relates to a pearlitic steel rail excellent in wear resistance and weldability, comprising, in terms of weight, more than 0.85 to 1.20% of C, 0.10 to 1.00% of Si, 0.20 to 1.50% of Mn, more than 0.50 to 1.00% of Cr, or comprising more than 0.85 to 1.20% of C, 0.40 to 1.00% of Si, 0.20 to less than 0.40% of Mn, 0.35 to 0.50% of Cr, the content sum $Si/4 + Mn/2 + Cr$ being 0.80 to 0.95% or being 0.8 to 1.8% in terms of weight, further comprising, in terms of weight, one or at least two elements selected from the group consisting of Mo, V, Nb and B and the balance Fe and unavoidable impurities, and having a pearlite structure to the depth of at least 20 mm from the head portion corner and the head top surface as a starting point, the pearlite structure having a Vickers hardness of at least 320, the difference in Vickers hardness between the base steel and the welded joint of the steel rail being made up to 30 to prevent a wear dent caused by the local wear of the rail top surface in the welded joint without impairing the weldability.

DESCRIPTION

LOW-ALLOY HEAT-TREATED PEARLITIC STEEL RAIL EXCELLENT
IN WEAR RESISTANCE AND WELDABILITY AND PROCESS FOR
5 PRODUCING THE SAME

Field of the Invention

The present invention relates to a pearlitic steel rail having the significantly improved wear resistance and weldability (welding construction, properties of the welded joints) that rails for heavy haul railways are required to have, and a process for producing the same. The present invention particularly relates to a rail in which a difference in hardness between the welded joint of the rail and the base rail can be controlled in a given range so that a wear dent caused by the local wear of the rail top surface in the welded joint can be prevented, without impairing the weldability of the rail, and a process for producing the rail.

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Background of the Invention

Train speeds and a train loading are to be increased as means for making railroad transportation highly efficient. Such efficient railroad transportation signifies that the conditions of using the rail will become severe, and a further improvement in rail materials is required. Specifically, rails laid overseas in curved sections in rails for heavy haul railways have shown a drastic increase in wear, and the wear has produced concern about the wear life of the rails. However, as a result of the recent progress in highly strengthening heat treatment techniques, high strength (high hardness) rails, as described below, in which an eutectoid carbon steel is used and which have a fine pearlite structure have been developed. Consequently, the life of rails in the curved sections in rails for heavy haul railways has been greatly improved.

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(1) A heat treated rail for an ultraheavy loading having a sorbite structure or fine pearlite structure in the head portion (Japanese Examined Patent Publication (Kokoku)) No. 54-25490); and

5 (2) A process for producing a high strength rail which has a strength of at least 130 kgf/mm², including the step of subjecting a rail head portion which has been finish rolled or reheated to accelerated cooling from austenite region temperatures to temperatures from 850 to
10 500°C at a rate of 1 to 4°C/sec (Japanese Examined Patent Publication (Kokoku)) No. 63-23244).

The features of these rails, that the rails are high strength rails, result from their eutectoid carbon steel, and the rails are intended to have a wear resistance by
15 reducing the lamellar spacing in the pearlite structure.

On the other hand, rail joints have been welded for the purpose of preventing failure and reducing the cost of maintenance and control. Consequently, actual rails have been used as long rails. However, it is known that, in a
20 welded joint which has been reheated to the austenite region, the cooling rate of the welded joint subsequent to welding is slow compared with that of the heat treated head portion during production of the rail, and that, as a result, the hardness of the joint after welding is lowered
25 to form a softened portion. The softened portion tends to suffer local wear when in contact with train wheels, resulting in a wear dent on the rail top surface. Consequently, serious problems have been caused by the production of noise and the generation of vibration due to
30 the passage of trains, and the problems include deterioration of the railroads.

The following method has been used as the countermeasure:
the welded joint of a rail is subjected to accelerated
35 cooling heat treatment immediately after welding or after reheating so that the hardness is improved to about the same degree as the rail base steel. However, there arises

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a new problem, due to the method, in that the welding operation time becomes long and the operation efficiency is decreased. Accordingly, the welded joint, of a rail is prevented from forming a softened portion in an as-welded state as described below. As a result, it has become possible to improve not only the wear life but also the weldability (welding construction).

(3) A process for producing a low alloy heat treated rail having an improved wear resistance and an improved weldability (welding construction, properties of welded joint) by adding alloying elements such as Cr, Nb, etc. (Japanese Examined Patent Publication (Kokoku)) No. 59-19173)

However, in order to carry out still more highly efficient railroad transportation, on rails for heavy haul railways, in recent years, heavy loading freight has increased. Consequently, even when the rails developed as described above are used, ensuring the wear resistance and perfect prevention of the wear dent of the head top surface of the rails caused by local wear in the welded joints cannot be achieved due to an increase in the contact pressure of the wheels. As a result, a decrease in life, production of noise and generation of vibration in the welded joints and deterioration of railroads have become serious problems again.

From such a background, development of a wear-resistant rail as wear-resistant as the current high strength rail which is prepared from an eutectoid carbon steel, capable of preventing local wear in the as-welded joints, and excellent in weldability have come to be required.

In order to improve the wear resistance of the conventional rail steel having a pearlite structure with a carbon content corresponding to a eutectoid carbon steel, a method of improving the hardness by reducing the lamellar spacings in the pearlite structure has been employed.

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However, the current rail steel having the pearlite structure with a carbon content corresponding to the eutectoid carbon steel shows an upper limit Vickers hardness of 420. When the heat treatment cooling rate or the addition amounts of alloying elements are increased for the purpose of improving the hardness, a bainite or martensite structure is formed in the pearlite structure to cause a problem that the wear resistance and toughness of the rail are lowered.

Furthermore, a method of using a material having a metal structure showing a higher wear resistance than the pearlite structure as a rail steel may be recognized as another method for overcoming the problem. However, a material which costs less and which is more excellent in wear resistance than the fine pearlite structure in the rolling wear conditions such as those of rails and wheels has not been found at present.

The pearlite structure having a carbon component corresponding to a eutectoid carbon steel, of the conventional rail steel, has a lamellar structure of a ferrite phase having a low hardness and a harder cementite phase. As a result of analyzing the wear mechanism of the pearlite structure, the present inventors have confirmed that the wear resistance is ensured in the following manner: a soft ferrite phase is squeezed out at first by wheels passing the rails; and then a hard cementite phase alone is laminated directly under rolling surfaces.

The present inventors then have experimentally discovered that the wear resistance can be greatly improved by increasing the ratio of a harder cementite in the pearlite, which improves the hardness of the pearlite to effect the wear resistance and which increases the carbon content to ensure the wear resistance so that the cementite phase density directly under a rolling surface is increased.

Fig. 1 shows an experimental comparison of the relationship between a carbon content and a wear amount.

The wear amount decreases as the carbon content increases when the hardness of the steel materials is the same. It has thus been confirmed that the use of a high carbon steel (hyper-eutectoid steel) greatly improves the wear resistance compared with that of conventional eutectoid steels (carbon content of 0.7 to 0.8%).

Paying attention to the influence of the carbon content on the pearlite transformation characteristics, the present inventors have invented a heat treatment method for stably forming a pearlite structure in high carbon steel materials. Fig. 2 shows the relationship between the carbon content and the pearlite transformation characteristics with reference to a continuous cooling transformation diagram (CCT diagram). It has been confirmed that when the carbon content is increased, the pearlite transformation nose shifts to a shorter time side compared with conventional eutectoid steels (carbon content of 0.7 to 0.8%) so that pearlite transformation easily takes place in a high cooling rate range.

That is, the heat treatment method to be noted of the rail steel having a high carbon content (hyper-eutectoid steel) is as follows: the present inventors have discovered that even when the accelerated cooling rate of the heat treatment is increased further compared with conventional eutectoid steels, abnormal structures such as martensite are not formed, and that the pearlite structure is stably formed so that the rail steel may attain a high strength.

Furthermore, it has been discovered that formation of proeutectoid cementite detrimental to the ductility and toughness, a disadvantage in a high carbon steel (hyper-eutectoid steel), may be prevented by the accelerated cooling of the heat treatment for highly strengthening the steel, and that the wear resistance may be improved without impairing the ductility and toughness by producing a high carbon content steel.

Summary of the Invention

In addition to the former invention, the present inventors have investigated a method for preventing a wear dent caused by the local wear of the head top surface of a welded joint without impairing the weldability (welding construction). In order to prevent the local wear of the rail welded joint, the difference in hardness between the welded joint having been reheated to the austenite region and the base steel must be made as small as possible.

First, the present inventors have experimentally investigated the influence of addition elements on the hardness of the welded joint of a high carbon steel (hyper-eutectoid steel). Consequently, the present inventors have confirmed that the addition amount of Cr and that of Si influence the hardness of the welded joint of the high carbon steel (hyper eutectoid steel) though Si is not so effective as Cr, and discovered that controlling the addition amounts can prevent a decrease in the hardness of the welded joint.

The present inventors, therefore, have used high carbon steels (hyper-eutectoid steels) in which the addition amount of Cr, an element most effective in preventing a decrease in the hardness of the welded joint, is varied, and experimentally analyzed the relationship between the addition amount of Cr and the hardness of the as-welded (without heat treatment) rail welded joint. As a result, the hardness of the welded joint has been improved when the addition amount of Cr exceeds 0.50%, and a hardness comparable to that of the base rail has been ensured.

Furthermore, since the carbon content of the hyper-eutectoid steel is high, Mn, Cr, etc. are segregated in addition to C in the column portion of the rail, and a martensite structure detrimental to the toughness of the rail tends to form in the segregation portion. The present inventors, therefore, have examined a method for restricting the addition amounts of Mn and Cr to given

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ranges to diminish the segregation, and preventing a decrease in the hardness of the welded joint.

Consequently, they have discovered that in high carbon steels (hyper-eutectoid steels), controlling the addition amount of Si which substantially does not segregate, in the rail column portion, results in prevention of a decrease in the hardness of the welded joint, in the same manner as Cr.

Accordingly, the present inventors have experimentally analyzed the relationship between the addition amount of Si and the hardness of an as-welded joint of the rail (without heat treatment) for the purpose of preventing segregation using high carbon steels (hyper-eutectoid steels) in which the addition amount of Si has been varied while the addition amounts of Mn and Cr have been restricted to given ranges. As a result, when the addition amount of Si exceeds 0.40%, the hardness of the welded joint has been improved even with the addition amounts of Mn and Cr being in small ranges, and a hardness which is comparable to the base rail has been ensured.

From the experimental results, the present inventors have found the following method effective as a method for making the difference in hardness between the welded joint having been reheated to the austenite region and the base steel as small as possible: in variety of rail base steels produced under heat treatment conditions within the claims mentioned above, the addition amounts of the alloying elements Cr, Mn and Si principally influence the hardness, and control of the addition amount of Mn in addition to the control of the addition amounts of Cr and Si which are effective in ensuring the hardness of the welded joints is effective in controlling the difference in hardness between the base steels and the respective welded joints. The present inventors, therefore, have investigated the relationship between the difference in hardness between the rail base steel and the welded joint and the addition amounts of Si, Cr and Mn. The contribution of Cr to the

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hardness is defined as 1, and the results are arranged to derive the contribution of the three elements thereto. Consequently, when the addition amounts of Si, Mn and Cr are the same, the contribution of the elements are confirmed to be as follows: Si: 1/4, Mn: 1/2. That is, in order to allow the difference in hardness between the welded joint and the base rail to fall into a given range so that a collapse caused by the local wear of the head top surface of the welded joint is prevented without impairing the weldability (welding construction), it has been found that the total sum Cr (wt.%), Si (wt.%)/4 and Mn (wt.%)/2 must be in a certain range.

An object of the present invention is to provide a rail having significantly improved wear resistance and weldability (welding construction, properties of the welded joints), which rails for heavy haul railways are required to have, by the above investigation.

The present invention achieves the object mentioned above, and the subject matter of the present invention is a pearlitic steel rail excellent in wear resistance and weldability obtained as described below:

the head portion of a hot rolled steel rail having a high temperature thermal energy or steel rail heated to high temperature for the purpose of heat treatment which steel rail comprises, in terms of weight, more than 0.85 to 1.20% of C, 0.10 to 1.00% of Si, 0.20 to 1.50% of Mn, more than 0.50 to 1.00% of Cr, or more than 0.85 to 1.20% of C, 0.40 to 1.00% of Si, 0.20 to less than 0.40% of Mn, 0.35 to 0.50% of Cr, the content sum Si/4 + Mn/2 + Cr being 0.8 to 1.8% in terms of weight, and further comprises, in terms of weight, one or at least two elements selected from the group consisting of 0.01 to 0.20% of Mo, 0.02 to 0.30% of V, 0.002 to 0.050% of Nb, 0.10 to 2.00% of Co and 0.0005 to 0.005% of B, and the balance Fe and unavoidable impurities,

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is subjected to accelerated cooling and controlled cooling by any of the following methods: (1) the head portion is subjected to accelerated cooling from an austenite region temperature at a cooling rate of 1 to 10°C/sec, and the accelerated cooling is stopped at the time when the steel rail temperature reaches from 700 to 500°C; (2) the head portion is subjected to accelerated cooling from an austenite region temperature at a cooling rate of more than 10 to 30°C/sec, and the accelerated cooling is stopped at the time when the pearlite transformation of the steel rail proceeds in an amount of 70% of the entire transformation; and (3) the head portion is subjected to accelerated cooling from an austenite region temperature to a temperature from 750 to 600°C at a cooling rate of more than 10 to 30°C/sec, and is consecutively subjected to controlled cooling at a cooling rate of 1 to less than 10°C/sec in a temperature region from 750 to 600°C to 550 to 450°C;

the steel rail having a pearlite structure to the depth of at least 20 mm from the head portion corner and the head top surface as a starting point, the pearlite structure having a Vickers hardness of at least 320, and the difference in Vickers hardness between the base steel and the welded joint of the steel rail being up to 30, and a process for producing the same.

Brief Description of the Drawings

Fig. 1 is a graph showing the relationship between a carbon content and a wear amount.

Fig. 2 is a graph showing the relationship between a carbon content and pearlite transformation characteristics.

Fig. 3 is a view showing the names of the cross-sectional surface positions of a rail head portion, and the reference numerals 1 and 2 designate a head top portion and a head portion corner, respectively.

Fig. 4 is a schematic view of a Nishihara wear

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tester, and the reference numerals 3, 4 and 5 designate a rail test piece, a counterpart material and a cooling nozzle, respectively.

5 Fig. 5 is a graph showing the relationship between a hardness and a wear amount in Example 1.

Fig. 6 is a graph showing the hardness distribution of a head portion in a welded joint in Example 1.

Fig. 7 is a graph showing the relationship between a hardness and a wear amount in Example 2.

10 Fig. 8 is a graph showing the hardness distribution of a head portion in a welded joint in Example 2.

Fig. 9 is a graph showing the relationship between a hardness and a wear amount in Example 3.

15 Fig. 10 is a graph showing the hardness distribution of a head portion in a welded joint in Example 3.

Fig. 11 is a graph showing another relationship between a hardness and a wear amount in Example 3.

20 Fig. 12 is a graph showing another hardness distribution of a head portion in a welded joint in Example 2.

Best Mode for Carrying Out the Invention

When compared with conventional rail steels, the rail steel of the present invention has a high carbon content, shows a decreased wear amount at the same hardness, and has a greatly improved wear resistance. Moreover, a pearlite structure excellent in the wear resistance can be stably formed without forming martensite, bainite and proeutectoid cementite detrimental to the ductility, toughness and wear resistance of the rail by making the chemical composition fall into an appropriate range and selecting appropriate heat treatment conditions.

35 Furthermore, a decrease in the hardness on the weld line caused by decarburization is improved, and abnormal structures such as martensite are not formed in the welded joint (portion reheated to the austenite region). The difference in Vickers hardness between the welded joint

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and the base steel is up to 30, and as a result partial wear such as a local wear dent caused by the wear of the head top surface of the welded joint in an as-welded state (without heat treatment) can be prevented.

5 According to the present invention, rails excellent in wear resistance and weldability (welding construction, properties of welded joints) may be provided to rails for heavy load.

 The present invention will be explained in detail.

10 Reasons for restricting the range of the chemical composition, that of the pearlite structure and the hardness will be explained in detail.

(1) On Chemical Composition

15 First, reasons for restricting the chemical composition of the rail in the present invention as described above will be explained.

 C is an element which is effective in promoting pearlite transformation and ensuring wear resistance. C
20 is added to the conventional rail steel in an amount of 0.60 to 0.85%. However, when the C amount is up to 0.85%, the cementite phase density in the pearlite structure for improving the wear resistance cannot be ensured, and moreover intergranular ferrite which is to become the
25 starting point of a fatigue failure within the rail head portion tends to form. Furthermore, when the C amount exceeds 1.20%, much proeutectoid cementite is formed in the rail head portion after heat treatment to lower the ductility and toughness considerably. The C amount is,
30 therefore, restricted to more than 0.85 but less than 1.20%.

 Si is an element which improves the hardness (strength) of a rail base steel and the welded joint reheated to the austenite region, by solid-solution
35 hardening the ferrite phase in a pearlite structure. Si is also an element which is concentrated at boundaries between ferrite and cementite in the pearlite structure,

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and the Si concentrated zone inhibits spheroidization of cementite in a heat-affected zone reheated to temperatures up to the austenite region temperature during welding. As a result, Si suppresses a decrease in the hardness of the heat-affected zone, that is, Si increases the temper softening resistance of the steel. When the Si amount is less than 0.10%, such effects cannot be expected. Moreover, when the Si amount exceeds 1.00%, many surface defects are formed during hot rolling. Moreover the rail is embrittled, and the weldability is lowered. The Si amount is, therefore, restricted to 0.10 to 1.00%. In addition, in the chemical composition system of a rail in which the amounts of Mn and Cr are restricted to certain values to decrease segregation in the rail column portion, it is necessary that the Si amount be restricted to at least 0.40% to ensure the hardness of the rail base steel and the welded joints.

Mn is an element which contributes to the high hardness (strength) of the rail steel by lowering the pearlite transformation temperature and increasing the hardenability, and moreover which inhibits the formation of proeutectoid cementite. When the Mn amount is less than 0.20%, the effect is not significant, and proeutectoid cementite tends to form in the rail head portion after heat treatment. Furthermore, when the Mn amount exceeds 1.50%, a martensite structure detrimental to the toughness of the rail tends to form. Accordingly, the Mn amount is restricted to 0.20 to 1.50%. In addition, in order to diminish the segregation of the rail column portion and inhibit the formation of a martensite structure detrimental to the toughness of the rail, the Mn amount must be from 0.20 to less than 0.40%.

Cr is an element which raises the equilibrium transformation point of pearlite and as a result makes the pearlite structure fine. Cr thus makes the rail base steel have a high hardness (strength), improves the hardness of the welded joint reheated to the austenite

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temperature region, and makes a difference in hardness between the rail base steel and the welded joint small. Moreover, Cr is an element which forms Cr carbides, and thus strengthens the cementite in the pearlite structure. As a result, Cr not only improves the wear resistance but also inhibits the softening of cementite in the heat affected zone having been reheated to temperatures up to the austenite region temperature during welding. Although the rail base steel may be highly strengthened when the Cr amount is less than 0.50%, the hardness of the welded joint cannot be ensured satisfactorily, and a difference in hardness between the rail base steel and the welded joint becomes significant. As a result, a wear dent is formed in the welded joint due to local wear.

Furthermore, when Cr is added in an amount exceeding 1.00%, namely in an excessive amount, a bainite structure and a martensite structure are formed to lower the wear resistance and toughness of the rail. Accordingly, the addition amount of Cr is restricted to 0.50 to 1.00%. In addition, in order to diminish segregation of the rail column portion and inhibit formation of a martensite structure detrimental to the toughness of the rail, the addition amount of Cr can be restricted to 0.20 to less than 0.40% by adding Si in a large amount.

Furthermore, for the purpose of improving the strength, ductility and toughness of the rail which is to be produced with the chemical composition as mentioned above, one or at least two elements selected from the following elements are optionally added:

Mo: 0.01 to 0.20%, V: 0.02 to 0.30%, Nb: 0.002 to 0.050%, Co: 0.10 to 2.00% and B: 0.0005 to 0.005%.

Next, the reasons for defining the chemical composition as mentioned above will be explained.

Mo is similar to Cr in that it raises the equilibrium transformation point of pearlite and as a result makes the pearlite structure fine to contribute to highly strengthening the rail steel and improve the wear

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resistance. When the addition amount is less than 0.01%, the effect is not significant. When Mo is added in an amount exceeding 0.20%, namely in an excessive amount, Mo lowers the transformation rate of pearlite, and as a result tends to form a martensite structure detrimental to the toughness. Accordingly, the addition amount of Mo is restricted to 0.01 to 0.20%.

V is a constituent effective in increasing the strength by precipitation hardening with V carbonitrides formed in the course of cooling during hot rolling, making austenite grains fine by the action of inhibiting the grain growth during heat treatment by heating the steel to high temperatures, and consequently improving the strength, ductility and toughness required of the rail. However, the effect cannot be sufficiently expected when the addition amount is less than 0.02%. Further effect cannot be expected when V is added in an amount exceeding 0.30%. The addition amount of V is, therefore, restricted to 0.02 to 0.30%.

Nb is similar to V in that it is an element effective in making austenite grains fine by forming Nb carbonitrides. Nb exerts an influence on inhibiting austenite grain growth at higher temperatures close to 1,200°C than V, and improves the ductility and toughness of the rail. The effect cannot be expected when the addition amount is less than 0.002%. Moreover, even when Nb is added in an amount exceeding 0.050%, namely in an excessive amount, a further effect cannot be expected. Accordingly, the addition amount of Nb is restricted to 0.002 to 0.050%.

Co is an element which improves the strength by increasing the transformation energy of pearlite to make the pearlite structure fine. However, the effect cannot be expected when the addition amount is less than 0.10%. When Co is added in an amount exceeding 2.00%, namely in an excessive amount, the effect is saturated. Accordingly, the addition amount of Co is restricted to

0.10 to 2.00%.

B is an element which has an effect on inhibiting the formation of proeutectoid cementite from former austenite grain boundaries, and which is effective in stably forming a pearlite structure. However, when the addition amount is less than 0.0005%, the effect is weak. When B is added in an amount exceeding 0.0050%, coarse boron carbides are formed to deteriorate the ductility and toughness of the rail. Accordingly, the addition amount is restricted to 0.0005 to 0.0050%.

Furthermore, reasons for restricting the total content sum $\text{Si}/4 + \text{Mn}/2 + \text{Cr}$ to 0.8 to 1.8% in terms of % by weight will be explained. When the total sum $\text{Si}/4 + \text{Mn}/2 + \text{Cr}$ is less than 0.8% in terms of % by weight, the welded joint hardness of the rail greatly lowers, compared with the base steel, subsequent to welding such as resistance flash butt welding, and the difference in hardness between the welded joint and the base steel increases, resulting in that the difference in Vickers hardness of up to 30, a condition under which local wear of the rail at the head top surface of the welded joint can be prevented, cannot be satisfied. Moreover, when the total sum $\text{Si}/4 + \text{Mn}/2 + \text{Cr}$ in terms of % by weight exceeds 1.8%, the welded joint hardness of the rail significantly increases compared with the base steel, and the difference in Vickers hardness of up to 30, a condition under which local wear of the rail at the head top surface of the welded joint can be prevented, cannot be satisfied. In addition to the unsatisfactoriness, abnormal structures such as martensite are formed in the welded joint, and the toughness and fatigue strength of the rail welded joint greatly lowers. Accordingly, the total content sum $\text{Si}/4 + \text{Mn}/2 + \text{Cr}$ is restricted to 0.8 to 1.8%. In addition, in order to prevent segregation in the rail column portion, in a constituent system in which the addition amounts of Mn and Cr are reduced and Si is added in a large amount to prevent the segregation of the rail column portion,

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abnormal structures such as martensite are not formed in the welded joint even when Mn, Cr and Si are added to the upper limits, and the difference in Vickers hardness between the welded joint and the base steel does not exceed 30. Accordingly, the total content sum $Si/4 + Mn/2 + Cr$ is restricted to up to 0.95.

The rail steel having such a chemical composition as described above is prepared in a conventional melting furnace such as a converter or electric furnace. The resultant molten steel is subjected to ingot making and blooming, or continuous casting, and the resultant steel product is then hot rolled to give a rail. The hot rolled rail at high temperature having thermal energy or a rail heated to high temperature for the purpose of heat treatment is subjected to accelerated cooling in the head portion to improve the hardness of the pearlite structure of the rail head portion.

(2) Hardness of Pearlite structure and Its Range

First, reasons for restricting the Vickers hardness of the pearlite structure to at least 320 will be explained. When the Vickers hardness is less than 320, the following problems arise: ensuring the wear resistance, which rails for heavy haul railways are required to have, in the present constituent system becomes difficult; moreover, a metal flow is formed as due to a heavy contact between the rail and wheels in the rail gauge corner (G.C.) in a sharply curved section, and consequently surface defects such as a head check or flaking is formed. Accordingly, the Vickers hardness of the pearlite structure is restricted to at least 320.

Furthermore, reasons for restricting the range of the pearlite structure having a Vickers hardness of at least 320 to the depth of 20 mm from the head portion corner and the head top surface as a starting point will be explained. When the depth is less than 20 mm, the depth is small as a wear-resistant region which the rail head portion is required to have, and an effect of sufficiently

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improving the rail life cannot be obtained as the wear of the rail proceeds. Moreover, when the range of the pearlite structure mentioned above is to the depth of at least 30 mm from the head portion corner and the head top surface as a starting point, the effect of improving the rail life is further improved. Accordingly, the range is desirable.

Fig. 3 shows the names of the cross-sectional surface positions of the rail head portion in the present invention excellent in wear resistance and weldability. In the rail head portion, the reference numerals 1 and 2 designate a head top portion and head portion corners, respectively. One of the head portion corners 2 is a gauge corner (G.C.) to be mainly contacted with wheels.

Next, reasons for restricting the difference in Vickers hardness to up to 30 between the rail base steel and the welded joint will be explained. When the difference in Vickers hardness between the welded joint and the base steel exceeds 30, partial wear such as a wear dent is formed on the head top surface of the rail welded joint. As a result, a noise is produced and vibrations are generated when a train passes, and the deterioration of the railroad track markedly proceeds. Accordingly, the difference in Vickers hardness between the welded joint and the base steel is restricted to up to 30. In addition, the difference in hardness is restricted to a difference of the head portion hardness distribution between the rail welded joint reheated to the austenite region and the base steel. The difference in hardness does not signify a difference of the hardness between the heat-affected zone formed around the welded joint or a hardness-lowered region formed by decarburization on the welded line, and the base steel. Moreover, the difference in hardness is principally an absolute value of a decrease in the hardness of the welded joint from that of the base steel. The hardness of the welded joint sometimes becomes high to some degree compared with the base steel,

depending on the constituent system and welding conditions. However, since the high hardness to such a degree does not much influence the properties of the welded joint in the present invention, the difference in hardness is made when the hardness of the welded joint is low compared with that of the base steel, or when the hardness of the welded joint is high compared therewith.

(3) On production conditions

Reasons for restricting each of the cooling conditions, as mentioned above during the rail production, in claims 4 to 6 will be explained in detail.

In claim 4, the steel rail is subjected to accelerated cooling from an austenite region temperature at a cooling rate of 1 to 10°C/sec, and the cooling is stopped when the steel rail temperature reaches from 700 to 500°C. Reasons for restricting the cooling conditions will be explained. In addition, the cooling conditions are heat treatment production conditions in which air or a mixture containing air mainly and mist is used as a cooling medium.

First, in the step of subjecting the steel rail to accelerated cooling from an austenite region temperature to 700 to 500°C at a cooling rate of 1 to 10°C/sec, reasons for restricting the accelerated cooling stop temperature and the accelerated cooling rate as mentioned above will be explained.

When the accelerated cooling is stopped at a temperature exceeding 700°C, pearlite transformation starts immediately after the accelerated cooling, and a large amount of a pearlite structure having a low hardness is formed. As a result, the Vickers hardness of the rail head portion becomes less than 320, and a necessary wear resistance cannot be ensured. Accordingly, the accelerated cooling stop temperature is restricted to up to 700°C. Moreover, when accelerated cooling is conducted to a temperature less than 500°C, sufficient recuperation cannot be expected from the interior of the rail after

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accelerated cooling, and a martensite structure detrimental to the toughness and wear resistance of the rail is formed in the segregation portion. Accordingly, the accelerated cooling stop temperature is restricted to be at least 500°C.

Reasons for restricting the accelerated cooling rate to from 1 to 10°C/sec will be explained.

When the accelerated cooling rate becomes less than 1°C/sec, pearlite transformation starts in a high temperature region in the course of the accelerated cooling, and a pearlite structure having a low hardness is formed in a large amount. Consequently, the rail head portion has a Vickers hardness of less than 320, and a necessary wear resistance cannot be ensured. Moreover, proeutectoid cementite detrimental to the toughness and ductility of the rail is formed in a large amount. Accordingly, the accelerated cooling rate is restricted to at least 1°C/sec. Furthermore, when air or a medium containing air, mainly, mist, etc. which media have the least cost and have stabilized properties in the heat treatment production, is used as a cooling medium, a cooling rate exceeding 10°C/sec cannot be ensured stably. Accordingly, the accelerated cooling rate is restricted to from 1 to 10°C/sec.

In addition, the accelerated cooling rate is defined as an average cooling rate from the start of cooling to the completion thereof. A temporary temperature rise may sometimes be caused by the heat generation of pearlite transformation or natural recuperation from the interior of the rail in the course of the accelerated cooling. However, when the average cooling rate from start to completion of the accelerated cooling is within the range as mentioned above, no significant influence is exerted on the properties of the pearlitic steel rail of the present invention. The accelerated cooling conditions for the rail of the invention, therefore, include a decrease in the cooling rate resulting from temporary temperature rise

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in the course of cooling.

5 A given cooling rate of 1 to 10°C/sec may be obtained with air or a cooling medium containing air, mainly mist and the like, or a combination of air and the cooling medium.

10 Accordingly, in order to produce a rail having a pearlite structure with a Vickers hardness of at least 320 and excellent in wear resistance and weldability, the head portion of a steel rail is subjected to accelerated cooling from an austenite region temperature at a cooling rate of 1 to 10°C/sec with air, or a cooling medium containing air mainly, mist, etc., and the accelerated cooling is stopped at the time when the steel rail temperature reaches from 700 to 500°C so that in the rail head, formation of a pearlite structure having a low hardness is prevented and abnormal structures such as a proeutectoid cementite structure and a martensite structure detrimental to the ductility, toughness and wear resistance are not formed. As a result, a pearlite structure having a high hardness can be stably formed.

20 Although a pearlite structure is desirable as the metal structure of the rail, a trace amount of proeutectoid cementite is sometimes formed therein depending on the constituent system, the accelerated cooling rate and the segregation state of the steel material. However, even when a trace amount of proeutectoid cementite is formed therein, no significant influence is exerted on the ductility, toughness, wear resistance and strength by the proeutectoid cementite.

25 The structure of the pearlitic steel rail of the invention may, therefore, include a proeutectoid cementite structure to a low degree.

30 Reasons for determining the following cooling conditions in claim 5 will be explained: the head portion of a steel rail is subjected to accelerated cooling from an austenite temperature region at a cooling rate of more than 10 to 30°C/sec; and the accelerated cooling is

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stopped at the time when the pearlite transformation of the steel rail proceeds in an amount of 70% of the entire transformation. In addition, the present cooling conditions are heat treatment production conditions in which a cooling medium mainly containing water such as mist or water spray, is used.

As shown in Fig. 2 mentioned above, when the accelerated cooling rate is up to $10^{\circ}\text{C}/\text{sec}$, a cooling curve invariably passes the pearlite nose, and the pearlite transformation is completed during continuous cooling in most cases. However, when the accelerated cooling rate exceeds $10^{\circ}\text{C}/\text{sec}$, the cooling curve is found to pass the pearlite transformation nose only when steels containing at least a certain amount of C are used. Furthermore, when the accelerated cooling rate exceeds $10^{\circ}\text{C}/\text{sec}$, continuation of cooling to temperatures as low as up to 300°C results in the formation of a large amount of a martensite structure in the pearlite structure. Consequently, adverse effects are exerted on the wear resistance and toughness of the rail.

However, when the steel rail is cooled in such a high cooling rate range, the supercooling degree becomes significant during pearlite transformation. When the pearlite transformation proceeds in a certain amount in the course of cooling, heat generation of pearlite transformation and natural recuperation from the interior of the rail head portion are caused by stopping the accelerated cooling in a certain temperature region in the course of transformation, and a state similar to isothermal transformation temporarily results. Consequently, pearlite transformation can be completed in the entire rail head portion.

Detailed experiments have been conducted, and it has been confirmed that in order to complete the pearlite transformation in the rail head portion by utilizing the heat of pearlite transformation and the natural recuperation from the interior of the rail head portion

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after the accelerated cooling, the minimum necessary amount of pearlite transformation is at least 70% of the entire transformation.

5 The concept of the above-mentioned production process is shown on a continuous cooling transformation diagram (CCT diagram) by taking a steel containing 1.0% of C in Fig. 2 as an example. In the example, the steel is subjected to accelerated cooling (more than 10 to 30°C/sec) from the austenite region, and the accelerated cooling is stopped when the amount of pearlite transformation becomes at least 75% of the entire transformation. The cooling rate becomes up to 10°C/sec after stopping the accelerated cooling due to the heat generation of pearlite transformation and the natural recuperation of the rail itself. The pearlite transformation can thus be stably accomplished.

15 First, reasons for restricting the accelerated cooling rate to more than 10 to 30°C/sec will be explained.

20 When the steel rail is cooled with a cooling medium other than air mainly containing water such as mist and spray water at an accelerated cooling rate of up to 10°C/sec, the cooling stability becomes very poor in such a low cooling rate region due to the very high cooling ability, and the cooling control becomes very difficult. Moreover, the hardness varies in the unstabilized cooling portion, and stably adjusting the Vickers hardness of the rail head portion to at least 320 becomes difficult. Accordingly, the accelerated cooling rate is restricted to more than 10°C/sec. Furthermore, as shown in the continuous cooling transformation diagram (CCT diagram) in Fig. 2, when the accelerated cooling rate exceeds 30°C/sec, the cooling curve does not cross the pearlite transformation nose sufficiently during the accelerated cooling, and a martensite structure detrimental to the toughness and wear resistance of the rail is formed. Moreover, even when the cooling curve crosses the pearlite

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transformation nose to some degree during the accelerated cooling, a pearlite transformation corresponding to at least 70% of the entire transformation cannot be expected and, as a result, the pearlite transformation is not completed in the whole rail head portion. A martensite structure detrimental to the toughness and wear resistance of the rail is subsequently formed. Accordingly, the accelerated cooling rate is restricted to more than 10 to 30°C/sec.

In addition, the accelerated cooling rate is defined as an average cooling rate from the start of cooling to the completion thereof. A temporary temperature rise may sometimes be caused by the heat generation of pearlite transformation or natural recuperation from the interior of the rail in the course of the accelerated cooling. However, when the average cooling rate from start to completion of the accelerated cooling is within the range as mentioned above, no significant influence is exerted on the properties of the pearlitic steel rail of the present invention. The accelerated cooling conditions for the rail of the invention include a decrease in the cooling rate resulting from the temporary temperature rise in the course of cooling.

Furthermore, methods for obtaining a predetermined cooling rate in the range of more than 10 to 30°C/sec are as follows: injection cooling with a mixture of water and air or a combination of these; the rail head portion or the entire rail is immersed in oil, hot water, a mixture of polymer and water or a salt bath.

Next, reasons for stopping the accelerated cooling at the time when 70% of the entire pearlite transformation proceeds will be explained.

If up to 70% of the entire pearlite transformation proceeds when the accelerated cooling is finished, the amount of heat generation caused by pearlite transformation subsequent to stopping cooling is small, and as a result the pearlite transformation cannot be

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completed in the entire rail head portion. Consequently, a large amount of martensite is formed within the rail head portion. Moreover, when micro-segregation portions exist within the rail head portion, the portions are
5 further cooled without the transformation, resulting in the formation of island-like portions here and there each having a martensite structure. The toughness and wear resistance of the rail are thus lowered considerably. The progress of the pearlite transformation at the time when
10 the accelerated cooling is stopped is, therefore, restricted to at least 70%.

The progress of the pearlite transformation can be estimated from the temperature change of the rail head portion during the accelerated cooling. When the pearlite
15 transformation starts, a distinct heat generation region resulting from the transformation is observed. According to detailed experiments, the state of the rail immediately before finishing the temperature rise in the heat generation region corresponds to the temperature at which
20 70% of the entire pearlite transformation is completed. In addition, as a simple method for controlling the transformation amount, controlling the amount mainly by a cooling time during accelerated cooling is most desirable.

Accordingly, in order to produce a rail having a
25 pearlite structure with a Vickers hardness of at least 320 and excellent in wear resistance and weldability, the rail head portion is subjected to accelerated cooling at a cooling rate of more than 10 and up to 30°C/sec with a cooling medium other than air mainly containing water such
30 as mist and spray water, and the accelerated cooling is stopped at the time when the pearlite transformation of the steel rail proceeds in an amount of 70% of the entire transformation. As a result, a pearlite structure having a high hardness can be stably formed.

35 In addition, although the metal structure of the rail is desirably a pearlite structure, a trace amount of proeutectoid cementite may sometimes be formed therein

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depending on the constituent system, the cooling rate and the segregation state of the steel material. However, even when a trace amount of proeutectoid cementite is formed in the pearlite structure, the cementite exerts no significant effect on the ductility, toughness and wear resistance of the rail. Accordingly, the pearlitic steel rail of the present invention may contain a proeutectoid cementite structure, to some extent, in the structure.

Reasons for restricting the cooling conditions in claim 6 as follows will be explained: the head portion of a steel rail is subjected to accelerated cooling from an austenite region temperature to a temperature from 750 to 600°C at a cooling rate of more than 10 to 30°C/sec, and consecutively to controlled cooling at a cooling rate of 1 to less than 10°C/sec in a temperature region from 750 to 600°C to 550 to 450°C. In addition, the cooling conditions are heat treatment production conditions in cases where water such as mist and spray water is mainly used in the initial cooling, and a cooling medium containing air, or air mainly and mist is used in the subsequent cooling.

As shown in Fig. 2, the cooling curve invariably passes the pearlite nose when the accelerated cooling rate is up to 10°C/sec, and most of the pearlite transformation is finished during continuous cooling. When the accelerated cooling rate exceeds 10°C/sec, the cooling curve is found to pass the pearlite transformation nose only for steels containing carbon at least in a certain amount. Furthermore, when the accelerated cooling rate exceeds 10°C/sec, continuation of the cooling to a low temperature region of up to 300°C results in the formation of a large amount of a martensite structure in the pearlite structure. The resultant martensite structure exerts adverse effects on the wear resistance and toughness of the rail.

However, in cooling at an accelerated cooling rate exceeding 10°C/sec, the pearlite transformation can be

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completed in the entire rail head portion by stopping the accelerated cooling in a temperature region where a pearlite structure having a high hardness is stably formed, and subjecting to cooling so that heat generation of the pearlite transformation can be subsequently controlled and natural recuperation can occur from within the rail head portion.

A steel containing 1.0% of C shown in Fig. 2 is taken as an example, and the concept of the above production process is shown on the continuous cooling transformation diagram (CCT diagram). In the example, the steel is subjected to accelerated cooling from the austenite region at a rate of more than 10 to 30°C/sec, and the pearlite transformation can be stably completed by further controlling the subsequent heat generation of pearlite transformation and natural recuperation from within the rail head portion (1-10°C/sec).

First, in the method for subjecting the steel to accelerated cooling from the austenite region temperature to 750 to 600°C at a cooling rate of more than 10 to not more than 30°C/sec, reasons for restricting the accelerated cooling stop temperature and the accelerated cooling rate as mentioned above will be explained.

When the accelerated cooling is stopped at temperatures exceeding 750°C, proeutectoid cementite is formed in the high temperature region in the course of the subsequent controlled cooling, and the ductility and toughness of the rail is considerably lowered. Accordingly, the accelerated cooling stop temperature is restricted to up to 750°C. When the accelerated cooling is conducted to temperatures less than 600°C, the pearlite transformation is not completed during the subsequent controlled cooling. As a result, abnormal structures such as bainite and martensite, which are detrimental to the toughness and wear resistance of the rail, tend to be formed. Accordingly, the accelerated cooling stop temperature is restricted to at least 600°C.

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Reasons for restricting the accelerated cooling rate to from more than 10 to 30°C/sec will be explained.

When the steel rail is cooled with a cooling medium other than air mainly containing water such as mist and spray water, at an accelerated cooling rate of up to 10°C/sec, the cooling stability becomes very poor in such a low cooling rate region due to the very high cooling ability, and the cooling control becomes very difficult. Moreover, the hardness varies in the unstabilized cooling portion, and stably adjusting the Vickers hardness of the rail head portion to at least 320 becomes difficult. Accordingly, the accelerated cooling rate is restricted to more than 10°C/sec. Moreover, when the accelerated cooling rate exceeds 30°C/sec, the pearlite transformation is not completed during controlled cooling subsequent to the accelerated cooling, and abnormal structures such as bainite and martensite detrimental to the toughness and wear resistance of the rail tend to be formed. Accordingly, the accelerated cooling rate is restricted to from more than 10 to 30°C/sec.

In addition, the accelerated cooling rate is defined as an average cooling rate from the start of cooling to the completion thereof. A temporary temperature rise may sometimes be caused by the heat generation of pearlite transformation or natural recuperation from the interior of the rail in the course of the accelerated cooling. However, when the average cooling rate from start to completion of the accelerated cooling is within the range as mentioned above, no significant influence is exerted on the properties of the pearlitic steel rail of the present invention. The accelerated cooling conditions for the rail of the invention, therefore, include a decrease in the cooling rate resulting from the temporary temperature rise in the course of cooling.

Furthermore, methods for obtaining a predetermined cooling rate in the range of more than 10 to 30°C/sec are as follows: injection cooling with a mixture of water and

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air or a combination of these; the rail head portion or the entire rail is immersed in oil, hot water, a mixture of polymer and water or salt bath.

Next, in the method of controlled cooling at a cooling rate of 1 to 10°C/sec from temperatures of 750 to 600°C to temperatures of 550 to 450°C, reasons for restricting the controlled cooling stop temperature and the controlled cooling rate as mentioned above will be explained.

When the controlled cooling is stopped at temperatures exceeding 550°C, a large amount of a pearlite structure having a low hardness is formed immediately after the controlled cooling. Consequently, the rail head portion has a Vickers hardness of less than 320, and the wear resistance of the head portion cannot be ensured. Accordingly, the controlled cooling stop temperature is restricted to up to 550°C. Moreover, when the controlled cooling is conducted at temperatures of less than 450°C, sufficient natural recuperation from the interior of the rail cannot be expected after the accelerated cooling, and a martensite structure detrimental to the toughness of the rail is formed in the segregation portion, etc. Accordingly, the controlled cooling stop temperature is restricted to at least 450°C.

Reasons for restricting the controlled cooling rate to from 1 to 10°C/sec will be explained. When the controlled cooling rate becomes less than 1°C/sec, a large amount of a pearlite structure having a low hardness is formed in a high temperature region in the course of controlled cooling. As a result, the Vickers hardness of the rail head portion becomes less than 320, and a necessary wear resistance of the head portion cannot be ensured. Accordingly, the controlled cooling rate is restricted to at least 1°C/sec. Moreover, when the controlled cooling is conducted at a cooling rate of at least 10°C/sec, the pearlite transformation is not completed in the course of cooling, and abnormal

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structures such as bainite and martensite detrimental to the toughness and wear resistance of the rail are formed in the course of controlled cooling and subsequent cooling. Accordingly, the controlled cooling rate is
5 restricted to from 1 to less than 10°C/sec.

In addition, the controlled cooling rate is defined as an average cooling rate from the start of cooling to the completion thereof. A temporary temperature rise may sometimes be caused by the heat generation of pearlite
10 transformation or natural recuperation from the interior of the rail in the course of the controlled cooling. However, when the average cooling rate from start to completion of the controlled cooling is within the range as mentioned above, no significant influence is exerted on
15 the properties of the pearlitic steel rail of the present invention. The controlled cooling conditions for the rail of the invention, therefore, include a decrease in the cooling rate resulting from the temporary temperature rise in the course of cooling.

20 A predetermined cooling rate in the range of 1 to 10°C/sec may be obtained with a cooling medium of air or one containing mainly air and mist, etc. or a combination of these media.

Accordingly, in order to produce a rail having a
25 pearlite structure with a Vickers hardness of at least 320 and excellent in wear resistance and weldability, the rail head portion is subjected to accelerated cooling at a cooling rate of more than 10 to 30°C/sec, and subsequently subjected to controlled cooling at a cooling rate of 1 to
30 less than 10°C/sec from temperatures of 750 to 600°C to temperatures of 550 to 450°C, using a cooling medium other than air mainly containing water such as mist and spray water. The pearlite structure can thus be stably formed in the rail head portion.

35 Although the metal structure of the rail is desirably a pearlite structure, a trace amount of proeutectoid cementite is sometimes formed in the pearlite structure in

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the rail head portion and the column portion, depending on the constituent system, the cooling rate and the segregation state of the steel material. However, even when a trace amount of proeutectoid cementite is formed in the pearlite structure, no significant influence is exerted on the ductility, toughness, wear resistance and strength of the rail. The structure of the pearlitic steel rail may, therefore, contain a proeutectoid cementite structure to some degree.

Examples

Next, the present invention will be explained with reference to examples.

Example 1

The present example is one within the scope of claims 1 to 3.

Tables 1 and 2 show the chemical compositions, the base steel hardness and microstructures, and the wear amounts after repeating 700,000 times in the Nisihara type wear tester shown in Fig. 4 under forced conditions, of the rail steels of the present invention and comparative rail steels.

Table 1

Rail	Reference numeral	Chemical composition (wt.%)					
		C	Si	Mn	Cr	Mo, V, Nb, Co, B	Si/4+Mn/2+Cr
R.S.I.*	1	0.86	0.11	1.48	0.51	Co: 0.15	1.28
R.S.I.*	2	0.91	0.45	0.41	0.55	-	0.87
R.S.I.*	3	0.91	0.32	0.37	0.98	-	1.25
R.S.I.*	4	0.95	0.81	0.22	0.52	V: 0.06	0.83
R.S.I.*	5	0.96	0.84	0.21	0.94	V: 0.05	1.26
R.S.I.*	6	1.01	0.61	1.05	0.82	Mo: 0.02	1.50
R.S.I.*	7	1.05	0.28	0.42	0.75	B: 0.0019	1.03
R.S.I.*	8	1.11	0.98	0.52	0.51	Nb: 0.02	1.02
R.S.I.*	9	1.19	0.25	0.34	0.74	-	0.97

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Table 1 (Continued)

Rail	Reference numeral	Hardness of head portion in base rail (Hv)	Micro-structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (ΔH_v)
R.S.I.*	1	386	Pearlite	0.99	405	19
R.S.I.*	2	395	Pearlite	0.91	374	21
R.S.I.*	3	410	Pearlite	0.85	406	4
R.S.I.*	4	402	Pearlite	0.81	378	24
R.S.I.*	5	412	Pearlite	0.74	411	1
R.S.I.*	6	431	Pearlite	0.49	440	9
R.S.I.*	7	385	Pearlite	0.74	402	17
R.S.I.*	8	410	Pearlite	0.43	408	2
R.S.I.*	9	401	Pearlite	0.42	411	10

Table 2 (Continued from Table 1)

Rail	Reference numeral	Chemical composition (wt.%)					
		C	Si	Mn	Cr	Mo, V, Nb, Co, B	Si/4+Mn/2+Cr
C.R.S.*	10	<u>0.76</u>	0.55	1.08	0.28	-	0.96
C.R.S.*	11	<u>0.81</u>	0.62	1.31	-	V: 0.06	0.81
C.R.S.*	12	<u>0.77</u>	0.85	0.81	0.58	V: 0.04	1.20
C.R.S.*	13	<u>0.81</u>	0.81	1.24	-	-	0.82
C.R.S.*	14	1.01	<u>1.25</u>	0.61	0.65	-	1.26
C.R.S.*	15	0.90	0.74	0.42	<u>1.30</u>	-	1.70
C.R.S.*	16	<u>1.36</u>	0.41	0.50	0.74	-	1.09
C.R.S.*	17	0.90	0.61	0.56	<u>0.21</u>	-	<u>0.64</u>
C.R.S.*	18	0.90	0.90	<u>1.52</u>	<u>1.05</u>	-	<u>2.03</u>

5 Table 2 (Continued)

Rail	Reference numeral	Hardness of head portion in base rail (Hv)	Micro-structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (ΔH_v)
C.R.S.*	10	381	Pearlite	1.22	-	-
C.R.S.*	11	389	Pearlite	1.15	-	-
C.R.S.*	12	401	Pearlite	1.06	-	-
C.R.S.*	13	394	Pearlite	1.12	-	-
C.R.S.*	14	surface defects produced during rolling				
C.R.S.*	15	506	Pearlite+ <u>bainite</u>	-	-	-
C.R.S.*	16	452	Pearlite+ <u>proeutectoid</u> <u>cementite</u>	-	-	-
C.R.S.*	17	396	Pearlite	0.91	352	<u>44</u>
C.R.S.*	18	421	Pearlite	0.75	461 martensite formed	<u>40</u>

Note: R.S.I. = Rail Steel of Invention, C.R.S. = Comparative Rail Steel
The balance of the chemical composition is unavoidable impurities and Fe.

#: Ref. N. = Reference Numeral

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Further, Tables 1 and 2 clearly show a difference in hardness between the flash butt welded joint and the base steel of any of the rail steels of the present invention and the comparative rail steels. In addition, the
5 hardness of the base steel and that of the flash butt welded joint of any of the rail steels shown in Tables 1 and 2 are average values of a head portion, and are neither the maximum values nor the minimum values.

Furthermore, Fig. 5 shows the relationship between a
10 hardness and a wear amount of the rail steels of the present invention and the comparative rail steels (eutectoid carbon steels: reference numerals of 10 to 13) listed in Tables 1 and 2 to compare the wear test results. Fig. 6 shows instances of the hardness distributions of
15 the head portions of the welded joints of the rail steels of the present invention (reference numerals: 2, 3) and the comparative rail steels (reference numerals: 17, 18) shown in the examples in Tables 1 and 2. In addition, the rails used in the examples are as described below.

20 * Rails of the present invention (9 pieces) with reference numerals of 1 to 9:

the steel rails being heat treated rails each having a chemical composition as mentioned above and a pearlite structure to the depth of at least 20 mm from the
25 rail head portion surface as a starting point, the pearlite structure having a Vickers hardness of at least 320, and the head portion having been subjected to accelerated cooling.

* Comparative rails (9 pieces):

30 comparative rails (4 pieces) with reference numerals of 10 to 13: prepared from eutectoid carbon steels having chemical compositions outside the scope of the claims of the present invention, and

comparative rails (5 pieces) with reference
35 numerals of 14 to 18: prepared from hyper-eutectoid carbon steels having chemical compositions outside the scope of the claims of the present invention

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The wear test conditions are as follows:

tester: the Nisihara type wear tester,
 shape of a test piece: a disc-like test piece
 (outside diameter: 30 mm, thickness: 8 mm),
 5 test load: 686 N,
 slip ratio: 20%,
 counter material: pearlitic steel (Vickers
 hardness of 390),
 atmosphere: in air,
 10 cooling: forced cooling with compressed air
 (flow rate: 100 Nl/min), and
 number of repeats: 700,000.

Flash butt welding conditions are as follows:

welder: K-355 (manufactured in Soviet Union),
 15 capacity: 150 KVA,
 secondary current: 20,000 A (max.),
 clamping force: 125 ton (max.), and
 upsetting amount: 10 mm.

Example 2

20 The present example is one within the scope of claims
 2 to 3.

Tables 3 and 4 show the chemical compositions, the
 base steel hardness and microstructures, and the wear
 amounts after repeating 700,000 times in the Nisihara type
 25 wear tester shown in Fig. 4 in Example 1 under forced
 cooling conditions, of the rail steels of the present
 invention and comparative rail steels.

Table 3

Rail	Reference numeral	Chemical composition (wt.%)					
		C	Si	Mn	Cr	Mo, V, Nb, Co, B	Si/4+Mn/2+Cr
R.S.I.*	19	0.85	0.81	0.38	0.47		0.86
R.S.I.*	20	0.90	0.45	0.39	0.49	V: 0.04	0.80
R.S.I.*	21	0.90	0.98	0.39	0.48	V: 0.04	0.92
R.S.I.*	22	0.95	0.98	0.21	0.48	-	0.83
R.S.I.*	23	0.95	0.98	0.39	0.37	-	0.81
R.S.I.*	24	1.00	0.85	0.35	0.41	Mo: 0.01	0.80
R.S.I.*	25	1.04	0.78	0.39	0.43	Co: 0.21	0.82
R.S.I.*	26	1.10	0.65	0.35	0.48	B: 0.0014	0.82
R.S.I.*	27	1.20	0.95	0.22	0.49	Nb: 0.03	0.84

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Table 3 (Continued)

Rail	Reference numeral	Hardness of head portion in base rail (Hv)	Micro-structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (Δ Hv)
R.S.I.*	19	384	Pearlite	0.99	369	15
R.S.I.*	20	391	Pearlite	0.95	370	21
R.S.I.*	21	392	Pearlite	0.94	383	9
R.S.I.*	22	384	Pearlite	0.93	375	9
R.S.I.*	23	380	Pearlite	0.95	370	10
R.S.I.*	24	395	Pearlite	0.75	380	15
R.S.I.*	25	386	Pearlite	0.72	382	4
R.S.I.*	26	395	Pearlite	0.53	385	10
R.S.I.*	27	401	Pearlite	0.38	395	6

Table 4 (Continued from Table 3)

Rail	Reference numeral	Chemical composition (wt.%)					
		C	Si	Mn	Cr	Mo, V, Nb, Co, B	Si/4+Mn/2+Cr
C.R.S.*	28	0.77	0.50	1.00	0.25	-	0.88
C.R.S.*	29	0.82	0.55	1.35	-	V: 0.05	0.81
C.R.S.*	30	0.79	0.85	0.83	0.54	-	1.16
C.R.S.*	31	0.80	0.80	1.22	-	V: 0.04	0.81
C.R.S.*	32	1.01	1.36	0.39	0.49	-	1.03
C.R.S.*	33	1.02	0.51	0.84	0.86	-	1.41
C.R.S.*	34	1.33	0.85	0.35	0.44	-	0.83
C.R.S.*	35	0.90	0.39	0.38	0.35	-	0.64
C.R.S.*	36	0.90	0.95	0.12	0.48	-	0.78

5 Table 4 (Continued)

Rail	Reference numeral	Hardness of head portion in base rail (Hv)	Micro-structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (Δ Hv)
C.R.S.*	28	379	Pearlite	1.22	-	-
C.R.S.*	29	388	Pearlite	1.15	-	-
C.R.S.*	30	403	Pearlite	1.06	-	-
C.R.S.*	31	395	Pearlite	1.12	-	-
C.R.S.*	32	surface defects produced during rolling				
C.R.S.*	33	422	Pearlite	0.58	martensite formed in a trace amount (3%) in segregation in column portion	
C.R.S.*	34	452	Pearlite+proeutectoid cementite	-	-	-
C.R.S.*	35	401	Pearlite	0.91	356	45
C.R.S.*	36	398	Pearlite	0.75	364	34

Note: *: R.S.I. = Rail Steel of Invention, * C.R.S. = Comparative Rail Steel

The balance of the chemical composition is unavoidable impurities and Fe.

#: Ref. N. = Reference Numeral

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Further, Tables 3 and 4 clearly show a difference in hardness between the flash butt welded joint and the base steel of any of the rail steels of the present invention and the comparative rail steels. In addition, the
5 hardness of the base steel and that of the flash butt welded joint of any of the rail steels shown in Tables 3 and 4 are average values of a head portion, and are neither the maximum values nor the minimum values.

Furthermore, Fig. 7 shows the relationship between a
10 hardness and a wear amount of the rail steels of the present invention and the comparative rail steels (eutectoid carbon steels: reference numerals of 28 to 31) listed in Tables 3 and 4 to compare the wear test results. Fig. 8 shows instances of the hardness distributions of
15 the head portions of the welded joints of the rail steel of the present invention (reference numeral: 21) and the comparative rail steel (reference numeral: 35) shown in the examples in Tables 3 and 4.

In addition, the rails used in the examples are as
20 described below.

* Rails of the present invention (9 pieces) with reference numerals of 19 to 27:

the steel rails being heat treated rails each having a chemical composition as mentioned above and a
25 pearlite structure to the depth of at least 20 mm from the rail head portion surface as a starting point, the pearlite structure having a Vickers hardness of at least 320, and the head portion having been subjected to accelerated cooling.

30 * Comparative rails (9 pieces)

comparative rails (4 pieces) with reference numerals of 28 to 31: prepared from eutectoid carbon steels having chemical compositions outside the scope of the claims of the present invention, and

35 comparative rails (5 pieces) with reference numerals of 32 to 36: prepared from hyper-eutectoid carbon steels having chemical compositions outside the scope of

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the claims of the present invention.

The wear test conditions and flash butt welding conditions are the same as in Example 1.

Example 3

5 The present example is one within the scope of claims 4 to 6.

10 Tables 5 to 10 and Tables 11 to 16 show the chemical compositions, the heat treatment conditions (heat treatment temperature ranges, cooling rates and pearlite formation ratios), the base steel hardness and microstructures, and the wear amounts after repeating 700,000 times in the Nisihara type wear tester shown in Fig. 4 in Example 1 under forced cooling conditions, of the rail steels of the present invention and comparative rail steels. Further, Tables 5 to 8, and Tables 11 to 14 clearly show the hardness in the flash butt welded joints of the rail steels of the present invention and comparative rail steels and the differences in hardness between the flash butt welded joints and the base steels.

20 Table 5

Rail	R.F. N.#	Chemical composition (wt.%)						Acceler- rated cooling range in head portion (°C)	Cooling rate (°C /sec)
		C	Si	Mn	Cr	Mo,V,Nb, Co,B	Si/4+ Mn/2+Cr		
R.S.I.*	37	0.86	0.12	1.48	0.52	Co: 0.16	1.29	745-589	2
R.S.I.*	38	0.86	0.12	1.48	0.52	Co: 0.16	1.29	721 (start)	11
R.S.I.*	39	0.86	0.12	1.48	0.52	Co: 0.16	1.29	781-625	11
R.S.I.*	40	0.90	0.44	0.43	0.52	-	0.85	752-544	4
R.S.I.*	41	0.90	0.44	0.43	0.52	-	0.85	781 (start)	13
R.S.I.*	42	0.90	0.44	0.43	0.52	-	0.85	756-600	13
R.S.I.*	43	0.92	0.34	0.35	0.98	-	1.24	731-578	3
R.S.I.*	44	0.92	0.34	0.35	0.98	-	1.24	721 (start)	12
R.S.I.*	45	0.92	0.34	0.35	0.98	-	1.24	761-631	12

Table 5 (Continued)

Rail	Ref. N.#	Other heat treatment conditions	Hard- ness of head portion in base rail (Hv)	Micro- structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (Δ Hv)
R.S.I.*	37	-	386	Pearlite	0.99	401	15
R.S.I.*	38	Pearlite formation ratio 70%	406	Pearlite	0.91	399	7
R.S.I.*	39	Controlled cooling range 625-471°C Cooling rate 3°C/sec	400	Pearlite	0.94	405	5
R.S.I.*	40	-	394	Pearlite	0.92	384	10
R.S.I.*	41	Pearlite formation ratio 84%	403	Pearlite	0.89	382	21
R.S.I.*	42	Controlled cooling range 600-501°C Cooling rate 4°C/sec	408	Pearlite	0.82	380	28
R.S.I.*	43	-	401	Pearlite	0.89	410	9
R.S.I.*	44	Pearlite formation ratio 74%	408	Pearlite	0.81	408	0
R.S.I.*	45	Controlled cooling range 631-540°C Cooling rate 2°C/sec	409	Pearlite	0.80	411	2

Table 6

(Continued from Table 5)

Rail	Ref. N. #	Chemical composition (wt.%)						Acceler- rated cooling range in head portion (°C)	Cooling rate (°C /sec)
		C	Si	Mn	Cr	Mo, V, Nb, Co, B	Si/4+ Mn/2+Cr		
R.S.I.*	46	0.96	0.80	0.25	0.53	V: 0.05	0.86	752-555	4
R.S.I.*	47	0.96	0.80	0.25	0.53	V: 0.05	0.86	764 (start)	17
R.S.I.*	48	0.96	0.80	0.25	0.53	V: 0.05	0.86	785-641	18
R.S.I.*	49	0.96	0.76	0.21	0.95	V: 0.04	1.25	720-592	3
R.S.I.*	50	0.96	0.76	0.21	0.95	V: 0.04	1.25	728 (start)	15
R.S.I.*	51	0.96	0.76	0.21	0.95	V: 0.04	1.25	761-622	14
R.S.I.*	52	1.01	0.62	1.04	0.80	Mo: 0.01	1.48	704-504	1
R.S.I.*	53	1.01	0.62	1.04	0.80	Mo: 0.01	1.48	815 (start)	16
R.S.I.*	54	1.01	0.62	1.04	0.80	Mo: 0.01	1.48	780-642	17

Table 6 (Continued)

Rail	Ref. N.#	Other heat treatment conditions	Hard- ness of head portion in base rail (Hv)	Micro- structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (Δ Hv)
R.S.I.*	46	-	397	Pearlite	0.82	381	16
R.S.I.*	47	Pearlite formation ratio 92%	404	Pearlite	0.78	381	23
R.S.I.*	48	Controlled cooling range 641-451°C Cooling rate 3°C/sec	409	Pearlite	0.77	380	29
R.S.I.*	49	-	408	Pearlite	0.76	414	6
R.S.I.*	50	Pearlite formation ratio 79%	412	Pearlite	0.75	410	2
R.S.I.*	51	Controlled cooling range 622-490°C Cooling rate 2°C/sec	416	Pearlite	0.70	412	4
R.S.I.*	52	-	410	Pearlite	0.65	432	22
R.S.I.*	53	Pearlite formation ratio 72%	421	Pearlite	0.61	430	9
R.S.I.*	54	Controlled cooling range 642-548°C Cooling rate 1°C/sec	432	Pearlite	0.51	429	3

Table 7

(Continued from Table 6)

Rail	Ref. N.#	Chemical composition (wt.%)						Acceler- ated cooling range in head portion (°C)	Cooling rate (°C /sec)
		C	Si	Mn	Cr	Mo,V,Nb, Co,B	Si/4+ Mn/2+Cr		
R.S.I.*	55	1.04	0.22	0.40	0.71	B:0.0014	0.97	789-562	3
R.S.I.*	56	1.04	0.22	0.40	0.71	B:0.0014	0.97	776 (start)	19
R.S.I.*	57	1.04	0.22	0.40	0.71	B:0.0014	0.97	815-691	18
R.S.I.*	58	1.10	0.97	0.52	0.51	Nb:0.03	1.01	851-625	6
R.S.I.*	59	1.10	0.97	0.52	0.51	Nb:0.03	1.01	842 (start)	20
R.S.I.*	60	1.10	0.97	0.52	0.51	Nb:0.03	1.01	790-625	23
R.S.I.*	61	1.18	0.21	0.35	0.78	-	1.01	880-700	9
R.S.I.*	62	1.18	0.21	0.35	0.78	-	1.01	821 (start)	29
R.S.I.*	63	1.18	0.21	0.35	0.78	-	1.01	840-750	28

Table 7 (Continued)

Rail	Ref. N.#	Other heat treatment conditions	Hard- ness of head portion in base rail (Hv)	Micro- structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (Δ Hv)
R.S.I.*	55	-	400	Pearlite	0.59	392	8
R.S.I.*	56	Pearlite formation ratio 94%	409	Pearlite	0.54	395	14
R.S.I.*	57	Controlled cooling range 691-532°C Cooling rate 5°C/sec	418	Pearlite	0.51	394	24
R.S.I.*	58	-	401	Pearlite	0.56	402	1
R.S.I.*	59	Pearlite formation ratio 84%	405	Pearlite	0.54	400	5
R.S.I.*	60	Controlled cooling range 625-531°C Cooling rate 4°C/sec	418	Pearlite	0.40	404	14
R.S.I.*	61	-	383	Pearlite	0.56	405	22
R.S.I.*	62	Pearlite formation ratio 71%	401	Pearlite	0.39	406	5
R.S.I.*	63	Controlled cooling range 750-549°C Cooling rate 10°C/sec	410	Pearlite	0.32	406	4

Note: *: R.S.I. = Rail Steel of Invention, * C.R.S. = Comparative Rail Steel

The balance of the chemical composition is unavoidable impurities and Fe.

#: Ref. N. = Reference Numeral

Table 8 (Continued from Table 7)

Rail	Ref. N.#	Chemical composition (wt.%)						Acceler- ated cooling range in head portion (°C)	Cooling rate (°C /sec)
		C	Si	Mn	Cr	Mo, V, Nb, Co, B	Si/4+ Mn/2+Cr		
C.R.S.*	64	<u>0.75</u>	0.55	1.04	<u>0.28</u>	-	0.94	-	-
C.R.S.*	65	<u>0.82</u>	0.52	1.33	-	V: 0.04	0.80	-	-
C.R.S.*	66	<u>0.78</u>	0.84	0.80	0.54	V: 0.04	1.15	-	-
C.R.S.*	67	<u>0.82</u>	0.80	1.20	-	-	0.80	-	-
C.R.S.*	68	1.01	<u>1.24</u>	0.66	0.62	-	1.26	-	-
C.R.S.*	69	0.90	0.71	0.43	<u>1.32</u>	-	1.71	752-555	4
C.R.S.*	70	<u>1.43</u>	0.40	0.50	0.77	-	1.12	845 (start)	12
C.R.S.*	71	0.91	0.61	0.50	<u>0.24</u>	-	<u>0.64</u>	780-574	5
C.R.S.*	72	0.91	0.61	<u>1.60</u>	<u>1.10</u>	-	2.05	765-625	14

Table 8 (Continued)

Rail	Ref. N.#	Other heat treatment conditions	Hard- ness of head portion in base rail (Hv)	Micro- structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (ΔHv)
C.R.S.*	64	-	384	Pearlite	1.21	-	-
C.R.S.*	65	-	387	Pearlite	1.16	-	-
C.R.S.*	66	-	397	Pearlite	1.08	-	-
C.R.S.*	67	-	390	Pearlite	1.14	-	-
C.R.S.*	68	-	surface defects formed during rolling				
C.R.S.*	69	-	364	Pearlite + <u>bainite</u>	-	-	-
C.R.S.*	70	Pearlite formation ratio 72%	478	Pearlite + <u>proeutectoid</u> <u>cementite</u>	-	-	-
C.R.S.*	71	-	398	Pearlite	0.89	352	<u>46</u>
C.R.S.*	72	Controlled cooling range 625-536°C Cooling rate 1°C/sec	421	Pearlite	0.74	478 martens- ite formed	<u>57</u>

Table 9

(Continued from Table 8)

Rail	Ref. N.#	Chemical composition (wt.%)						Acceler- ated cooling range in head portion (°C)	Cooling rate (°C /sec)
		C	Si	Mn	Cr	Mo, V, Nb, Co, B	Si/4+ Mn/2+Cr		
C.R.S.*	73	0.91	0.40	0.44	0.61	-	0.93	751-506	8-11 un- control- lable
C.R.S.*	74	0.91	0.40	0.44	0.61	-	0.93	781 (start)	8-13 un- control- lable
C.R.S.*	75	0.91	0.40	0.44	0.61	-	0.93	778-621	35
C.R.S.*	76	0.95	0.91	0.22	0.84	V: 0.05	1.18	751- ~~425~~	3
C.R.S.*	77	0.95	0.91	0.22	0.84	V: 0.05	1.18	752 (start)	34
C.R.S.*	78	0.95	0.91	0.22	0.84	V: 0.05	1.18	791-684	7-15 un- control- lable
C.R.S.*	79	1.00	0.54	1.00	0.74	Mo: 0.02	1.38	864- ~~724~~	5
C.R.S.*	80	1.00	0.54	1.00	0.74	Mo: 0.02	1.38	724 (start)	18
C.R.S.*	81	1.00	0.54	1.00	0.74	Mo: 0.02	1.38	780-631	15

Table 9 (Continued)

Rail	Ref. N.#	Other heat treatment conditions	Hard- ness of head portion in base rail (Hv)	Micro- structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (Δ Hv)
C.R.S.*	73	-	454	Pearlite + <u>martensite</u>	-	-	-
C.R.S.*	74	Pearlite formation ratio 75%	<u>308</u> hard- ness in un- stably cooled portion	Pearlite	-	-	-
C.R.S.*	75	Controlled cooling range 621-522°C Cooling rate 8°C/sec	542	Pearlite + <u>martensite</u>	-	-	-
C.R.S.*	76	-	471	Pearlite + <u>martensite</u>	-	-	-
C.R.S.*	77	Pearlite formation ratio 75%	564	Pearlite + <u>martensite</u>	-	-	-
C.R.S.*	78	Controlled cooling range 684-506°C Cooling rate 8°C/sec	<u>314</u> hard- ness in un- stably cooled portion	Pearlite	-	-	-
C.R.S.*	79	-	<u>302</u>	Pearlite	-	-	-
C.R.S.*	80	Pearlite formation ratio <u>42%</u>	474	Pearlite + <u>martensite</u>	-	-	-
C.R.S.*	81	Controlled cooling range 631-481°C Cooling rate <u>12°C/sec</u>	461	Pearlite + <u>martensite</u>	-	-	-

Table 10

(Continued from Table 9)

Rail	Ref. N.#	Chemical composition (wt.%)						Acceler- ated cooling range in head portion (°C)	Cooling rate (°C /sec)
		C	Si	Mn	Cr	Mo,V,Nb, Co,B	Si/4+ Mn/2+Cr		
C.R.S.*	82	1.18	0.31	0.38	0.86	-	1.13	864-506	0.5
C.R.S.*	83	1.18	0.31	0.38	0.86	-	1.13	824 (start)	29
C.R.S.*	84	1.18	0.31	0.38	0.86	-	1.13	820-724	27

Table 10 (Continued)

Rail	Ref. N.#	Other heat treatment conditions	Hard- ness of head portion in base rail (Hv)	Micro- structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (ΔHv)
C.R.S.*	82	-	441	Pearlite + <u>proeutectoid cementite</u>	-	-	-
C.R.S.*	83	Pearlite formation ratio 55%	541	Pearlite + <u>martensite</u>	-	-	-
C.R.S.*	84	Controlled cooling range 724-514°C Cooling rate 0.5°C/sec	442	Pearlite + <u>proeutectoid cementite</u>	-	-	-

5

Note: *: R.S.I. = Rail Steel of Invention, * C.R.S. = Comparative Rail Steel

The balance of the chemical composition is unavoidable impurities and Fe.

#: Ref. N. = Reference Numeral

10

Table 11

Rail	Ref. N. #	Chemical composition (wt.%)						Acceler- ated cooling range in head portion (°C)	Cooling rate (°C /sec)
		C	Si	Mn	Cr	Mo, V, Nb, Co, B	Si/4+ Mn/2+Cr		
R.S.I.*	85	0.86	0.82	0.37	0.48		0.87	792-562	3
R.S.I.*	86	0.86	0.82	0.37	0.48		0.87	761 (start)	12
R.S.I.*	87	0.86	0.82	0.37	0.48		0.87	776-622	12
R.S.I.*	88	0.92	0.48	0.37	0.49	V: 0.06	0.80	781-521	5
R.S.I.*	89	0.92	0.48	0.37	0.49	V: 0.06	0.80	794 (start)	14
R.S.I.*	90	0.92	0.48	0.37	0.49	V: 0.06	0.80	754-602	13
R.S.I.*	91	0.92	0.99	0.36	0.47	V: 0.04	0.90	762-532	5
R.S.I.*	92	0.92	0.99	0.36	0.47	V: 0.04	0.90	761 (start)	15
R.S.I.*	93	0.92	0.99	0.36	0.47	V: 0.04	0.90	721-640	14

Table 11 (Continued)

Rail	Ref. N.#	Other heat treatment conditions	Hard- ness of head portion in base rail (Hv)	Micro- structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (Δ Hv)
R.S.I.*	85	-	382	Pearlite	0.99	372	10
R.S.I.*	86	Pearlite formation ratio 71%	389	Pearlite	0.96	374	15
R.S.I.*	87	Controlled cooling range 622-481°C Cooling rate 3°C/sec	394	Pearlite	0.95	375	19
R.S.I.*	88	-	391	Pearlite	0.94	371	20
R.S.I.*	89	Pearlite formation ratio 86%	400	Pearlite	0.91	372	28
R.S.I.*	90	Controlled cooling range 602-504°C Cooling rate 4°C/sec	401	Pearlite	0.90	372	29
R.S.I.*	91	-	394	Pearlite	0.93	380	14
R.S.I.*	92	Pearlite formation ratio 72%	405	Pearlite	0.87	382	23
R.S.I.*	93	Controlled cooling range 640-547°C Cooling rate 2°C/sec	404	Pearlite	0.88	384	20

Table 12

(Continued from Table 11)

Rail	Ref. N.#	Chemical composition (wt.%)						Acceler- ated cooling range in head portion (°C)	Cooling rate (°C /sec)
		C	Si	Mn	Cr	Mo,V,Nb, Co,B	Si/4+ Mn/2+Cr		
R.S.I.*	94	0.96	0.90	0.21	0.49	-	0.82	748-549	
R.S.I.*	95	0.95	0.98	0.21	0.48	-	0.83	781 (start)	17
R.S.I.*	96	0.95	0.98	0.21	0.48	-	0.83	785-661	19
R.S.I.*	97	0.96	0.91	0.39	0.39	-	0.81	741-562	5
R.S.I.*	98	0.96	0.91	0.39	0.39	-	0.81	796 (start)	16
R.S.I.*	99	0.96	0.91	0.39	0.39	-	0.81	771-611	17
R.S.I.*	100	1.01	0.84	0.36	0.42	Mo: 0.02	0.81	741-502	2
R.S.I.*	101	1.01	0.84	0.36	0.42	Mo: 0.02	0.81	832 (start)	17
R.S.I.*	102	1.01	0.84	0.36	0.42	Mo: 0.02	0.81	774-621	17

Table 12 (Continued)

Rail	Ref. N.#	Other heat treatment conditions	Hard- ness of head portion in base rail (Hv)	Micro- structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (Δ Hv)
R.S.I.*	94	-	398	Pearlite	0.81	375	24
R.S.I.*	95	Pearlite formation ratio 90%	403	Pearlite	0.75	376	27
R.S.I.*	96	Controlled cooling range 661-454°C Cooling rate 3°C/sec	400	Pearlite	0.76	377	23
R.S.I.*	97	-	394	Pearlite	0.78	374	20
R.S.I.*	98	Pearlite formation ratio 94%	402	Pearlite	0.75	374	28
R.S.I.*	99	Controlled cooling range 611-514°C Cooling rate 2°C/sec	405	Pearlite	0.73	376	29
R.S.I.*	100	-	384	Pearlite	0.78	382	2
R.S.I.*	101	Pearlite formation ratio 89%	406	Pearlite	0.69	384	22
R.S.I.*	102	Controlled cooling range 621-524°C Cooling rate 1°C/sec	396	Pearlite	0.71	384	12

Table 13

(Continued from Table 12)

Rail	Ref. N.#	Chemical composition (wt.%)						Acceler- ated cooling range in head portion (°C)	Cooling rate (°C /sec)
		C	Si	Mn	Cr	Mo,V,Nb, Co,B	Si/4+ Mn/2+Cr		
R.S.I.*	103	1.05	0.77	0.39	0.44	Co: 0.14	0.83	769-560	4
R.S.I.*	104	1.05	0.77	0.39	0.44	Co: 0.14	0.83	801 (start)	18
R.S.I.*	105	1.05	0.77	0.39	0.44	Co: 0.14	0.83	835-662	19
R.S.I.*	106	1.09	0.68	0.36	0.49	B:0.0022	0.84	834-602	6
R.S.I.*	107	1.09	0.68	0.36	0.49	B:0.0022	0.84	832 (start)	21
R.S.I.*	108	1.09	0.68	0.36	0.49	B:0.0022	0.84	821-642	22
R.S.I.*	109	1.19	0.94	0.21	0.49	Nb: 0.03	0.83	842-695	10
R.S.I.*	110	1.19	0.94	0.21	0.49	Nb: 0.03	0.83	844 (start)	28
R.S.I.*	111	1.19	0.94	0.21	0.49	Nb: 0.03	0.83	860-741	29

Table 13 (Continued)

Rail	Ref. N.#	Other heat treatment conditions	Hard- ness of head portion in base rail (Hv)	Micro- structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (Δ Hv)
R.S.I.*	103	-	384	Pearlite	0.70	385	1
R.S.I.*	104	Pearlite formation ratio 94%	404	Pearlite	0.58	386	18
R.S.I.*	105	Controlled cooling range 662-540°C Cooling rate 4°C/sec	412	Pearlite	0.52	388	24
R.S.I.*	106	-	406	Pearlite	0.52	391	15
R.S.I.*	107	Pearlite formation ratio 89%	410	Pearlite	0.49	394	16
R.S.I.*	108	Controlled cooling range 624-544°C Cooling rate 5°C/sec	420	Pearlite	0.41	394	26
R.S.I.*	109	-	381	Pearlite	0.57	396	15
R.S.I.*	110	Pearlite formation ratio 74%	411	Pearlite	0.32	397	14
R.S.I.*	111	Controlled cooling range 741-501°C Cooling rate 10°C/sec	418	Pearlite	0.21	398	20

Note: *: R.S.I. = Rail Steel of Invention, * C.R.S. = Comparative Rail Steel

The balance of the chemical composition is unavoidable impurities and Fe.

#: Ref. N. = Reference Numeral

Table 14

(Continued from Table 13)

Rail	Ref. N.#	Chemical composition (wt.%)						Acceler- ated cooling range in head portion (°C)	Cooling rate (°C /sec)
		C	Si	Mn	Cr	Mo, V, Nb, Co, B	Si/4+ Mn/2+Cr		
C.R.S.*	112	<u>0.78</u>	0.54	0.98	0.30	-	0.93	-	-
C.R.S.*	113	<u>0.81</u>	0.56	1.39	-	V: 0.04	0.84	-	-
C.R.S.*	114	<u>0.80</u>	0.81	0.89	0.51	-	1.16	-	-
C.R.S.*	115	<u>0.81</u>	0.79	1.30	-	V: 0.06	0.85	-	-
C.R.S.*	116	1.00	<u>1.44</u>	0.23	0.44	-	0.92	-	-
C.R.S.*	117	1.02	0.42	<u>0.88</u>	<u>0.65</u>	-	1.20	745-544	6
C.R.S.*	118	<u>1.28</u>	0.88	0.38	0.40	-	0.81	764-561	2
C.R.S.*	119	0.91	0.91	0.38	<u>0.29</u>	-	<u>0.71</u>	801 (start)	12
C.R.S.*	120	0.91	<u>0.38</u>	0.38	0.48	-	<u>0.77</u>	741-640	13

Table 14 (Continued)

Rail	Ref. N.#	Other heat treatment conditions	Hard- ness of head portion in base rail (Hv)	Micro- structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (ΔHv)
C.R.S.*	112	-	394	Pearlite	1.10	-	-
C.R.S.*	113	-	382	Pearlite	1.17	-	-
C.R.S.*	114	-	402	Pearlite	1.05	-	-
C.R.S.*	115	-	386	Pearlite	1.16	-	-
C.R.S.*	116	-	surface defects produced during rolling				
C.R.S.*	117	-	404	Pearlite	0.72	trace amount (4%) of martensite formed in segregation in column portion	
C.R.S.*	118	-	441	Pearlite + <u>proeutectoid</u> <u>cementite</u>	-	-	-
C.R.S.*	119	Pearlite formation ratio 74%	396	Pearlite	0.92	360	<u>36</u>
C.R.S.*	120	Controlled cooling range 640-544°C Cooling rate 3°C/sec	408	Pearlite	0.82	364	<u>44</u>

Table 15

(Continued from Table 14)

Rail	Ref. N.#	Chemical composition (wt.%)						Acceler- ated cooling range in head portion (°C)	Cooling rate (°C /sec)
		C	Si	Mn	Cr	Mo,V,Nb, Co,B	Si/4+ Mn/2+Cr		
C.R.S.*	121	0.91	0.80	0.34	0.49	V: 0.04	0.86	774-504	8- ~~14~~ un- control- lable
C.R.S.*	122	0.91	0.80	0.34	0.49	V: 0.04	0.86	741 (start)	~~6~~ -13 un- control- lable
C.R.S.*	123	0.91	0.80	0.34	0.49	V: 0.04	0.86	764-642	~~36~~
C.R.S.*	124	0.95	0.96	0.24	0.45	-	0.81	764- ~~398~~	5
C.R.S.*	125	0.95	0.96	0.24	0.45	-	0.81	761 (start)	~~32~~
C.R.S.*	126	0.95	0.96	0.24	0.45	-	0.81	761-621	14- ~~8~~ un- control- lable
C.R.S.*	127	0.99	0.98	0.39	0.38	-	0.82	824- ~~712~~	6
C.R.S.*	128	0.99	0.98	0.39	0.38	-	0.82	764 (start)	16
C.R.S.*	129	0.99	0.98	0.39	0.38	-	0.82	774-603	15

Table 15 (Continued)

Rail	Ref. N.#	Other heat treatment conditions	Hard- ness of head portion in base rail (Hv)	Micro- structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (Δ Hv)
C.R.S.*	121	-	462	Pearlite + <u>martensite</u>	-	-	-
C.R.S.*	122	Pearlite formation ratio 72%	289 hard- ness in un- stably cooled portion	Pearlite	-	-	-
C.R.S.*	123	Controlled cooling range 642-464°C Cooling rate 7°C/sec	574	Pearlite + <u>martensite</u>	-	-	-
C.R.S.*	124	-	486	Pearlite + <u>martensite</u>	-	-	-
C.R.S.*	125	Pearlite formation ratio 79%	446	Pearlite + <u>martensite</u>	-	-	-
C.R.S.*	126	Controlled cooling range 621-641°C Cooling rate 6°C/sec	301 hard- ness in un- stably cooled portion	Pearlite	-	-	-
C.R.S.*	127	-	312	Pearlite	-	-	-
C.R.S.*	128	Pearlite formation ratio 37%	513	Pearlite + <u>martensite</u>	-	-	-
C.R.S.*	129	Controlled cooling range 603-472°C Cooling rate 14°C/sec	498	Pearlite + <u>martensite</u>	-	-	-

Table 16 (Continued from Table 15)

Rail	Ref. N.#	Chemical composition (wt.%)						Acceler- ated cooling range in head portion (°C)	Cooling rate (°C /sec)
		C	Si	Mn	Cr	Mo, V, Nb, Co, B	Si/4+ Mn/2+Cr		
C.R.S.*	130	1.18	0.90	0.36	0.40	-	0.81	841-541	0.3
C.R.S.*	131	1.18	0.90	0.36	0.40	-	0.81	836 (start)	29
C.R.S.*	132	1.18	0.90	0.36	0.40	-	0.81	841-741	28

Table 16 (Continued)

Rail	Ref. N.#	Other heat treatment conditions	Hard- ness of head portion in base rail (Hv)	Micro- structure of head portion	Wear amount (g/700,000 times)	Hardness of head portion in welded joint (Hv)	Difference in hardness between base rail and welded joint (ΔHv)
C.R.S.*	130	-	456	Pearlite + <u>proeutectoid</u> <u>cementite</u>	-	-	-
C.R.S.*	131	Pearlite formation ratio 66%	472	Pearlite + <u>martensite</u>	-	-	-
C.R.S.*	132	Controlled cooling range 741-522°C Cooling rate 0.4°C/sec	466	Pearlite + <u>proeutectoid</u> <u>cementite</u>	-	-	-

Note: *: R.S.I. = Rail Steel of Invention, * C.R.S. = Comparative Rail Steel

The balance of the chemical composition is unavoidable impurities and Fe.

#: Ref. N. = Reference Numeral

In addition, the hardness of the base steel and that of the flash butt welded joint of any of the rail steels shown in Tables 5 to 8 and Tables 11 to 14 are average values of the head portions, and are neither the maximum values nor the minimum ones.

Furthermore, Fig. 9 shows the relationship between a hardness and a wear amount of the rail steels of the present invention and the comparative rail steels (eutectoid carbon steels: reference numerals of 64 to 67) listed in Tables 5 to 10 to compare the wear test results. Fig. 10 shows instances of the hardness distributions of the head portions of the welded joints of the rail steels

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of the present invention (reference numerals: 41, 44) and the comparative rail steels (reference numerals: 71, 72) shown in the examples in Tables 5 to 10.

5 Still furthermore, Fig. 11 shows the relationship between a hardness and a wear amount of the rail steels of the present invention and the comparative rail steels (eutectoid carbon steels: reference numerals of 112 to 115) listed in Tables 11 to 16 to compare the wear test results. Fig. 12 shows instances of the hardness
10 distributions of the head portions of the welded joints of the rail steels of the present invention (reference numeral: 91) and the comparative rail steel (reference numeral: 120) shown in the examples in Tables 11 to 16.

In addition, the rails used in the examples are as
15 described below.

(Examples in Tables 5 to 10)

* Rails of the present invention (27 pieces) with reference numerals of 37 to 63:

20 the steel rails being heat treated rails each having a chemical composition as mentioned above and a pearlite structure to the depth of at least 20 mm from the rail head portion surface as a starting point, the pearlite structure having a Vickers hardness of at least 320, and the head portion having been subjected to
25 accelerated cooling.

* Comparative rails (21 pieces):

comparative rails (4 pieces) with reference numerals of 64 to 67: prepared from eutectoid carbon steels having chemical compositions outside the scope of
30 the claims of the present invention,

comparative rails (5 pieces) with reference numerals of 68 to 72: prepared from hyper-eutectoid carbon steels having chemical compositions outside the scope of the claims of the present invention, and

35 comparative rails (12 pieces) with reference numerals of 73 to 84: prepared under heat treatment conditions outside the scope of the claims of the present

invention.

(Examples in Tables 11 to 16)

* Rails of the present invention (8 pieces) with reference numerals of 85 to 111:

5 the steel rails being heat treated rails each having a chemical composition as mentioned above and a pearlite structure to the depth of at least 20 mm from the rail head portion surface as a starting point, the pearlite structure having a Vickers hardness of at least 320, and
10 the head portion having been subjected to accelerated cooling.

* Comparative rails (21 pieces):

 comparative rails (4 pieces) with reference numerals of 112 to 115: prepared from eutectoid carbon
15 steels having chemical compositions outside the scope of the claims of the present invention,

 comparative rails (5 pieces) with reference numerals of 116 to 120: prepared from hyper-eutectoid carbon steels having chemical compositions outside the
20 scope of the claims of the present invention, and

 comparative rails (12 pieces) with reference numerals of 121 to 132: prepared under heat treatment conditions outside the scope of the claims of the present invention.

25 As shown in Figs. 5, 7, 9 and 11, any of the rail steels of the present invention shows a decreased wear amount compared with any of the corresponding comparative steels having the same hardness as a result of making the carbon content high compared therewith, and consequently a
30 significantly improved wear resistance even when the rail steel of the invention has the same hardness as the conventional steel. Moreover, a pearlite structure excellent in wear resistance can be stably formed without forming martensite, bainite and proeutectoid cementite
35 detrimental to the toughness, wear resistance and ductility by allowing the chemical composition fall into an appropriate range and selecting appropriate heat

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treatment conditions as shown in Tables 1 to 4.

As shown in Figs. 6 and 10, a decrease in the hardness of the welded joint taking place at the time when the addition amount of Cr is up to 0.50% (comparative rails with reference numerals 17, 71) or formation of abnormal structures such as martensite taking place at the time when the addition amount of Cr is at least 1.00% (comparative rails with reference numerals 18, 72) can be prevented by adding Cr in an amount of more than 0.50 to 1.00%, and the difference in hardness between the rail base steel and the welded joint can be made not more than 30. Partial wear such as a local wear dent caused by the wear of the head top surface of the welded joint in an as-welded state (without heat treatment) can thus be prevented.

As shown in Figs. 8 and 12, a decrease in the hardness of the welded joint taking place at the time when the addition amount of Si is less than 0.40% (comparative rails with reference numerals 35, 120) can be prevented by adding Si in an amount of 0.40 to 1.00%, and the difference in hardness between the rail base steel and the welded joint can be made not more than 30. Partial wear such as a local wear dent caused by the wear of the head top surface of the welded joint in an as-welded state (without heat treatment) can thus be prevented.

Industrial Applicability

As shown in Figs. 5, 7, 9 and 11, any of the rail steels of the present invention shows a decreased wear amount compared with any of the corresponding comparative steels having the same hardness as a result of making the carbon content high compared therewith, and consequently a significantly improved wear resistance. Moreover, a pearlite structure excellent in wear resistance can be stably formed in a rail without forming martensite, bainite and proeutectoid cementite detrimental to the ductility, toughness and wear resistance by allowing the

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chemical composition fall into an appropriate range and selecting appropriate heat treatment conditions as shown in Tables 11 to 16.

Moreover, the present invention has the following advantages as shown in Figs. 6, 8, 10 and 12: a decrease in the hardness on the weld line caused by decarburization is improved; no abnormal structures such as martensite are formed in a welded joint (portion having been reheated to the austenite region); and a difference in Vickers hardness between the base steel and the welded joint is up to 30, and partial wear such as a local wear dent caused by the wear of the head top surface of the welded joint in an as-welded state (without heat treatment) can be prevented.

According to the present invention as described above, a rail excellent in wear resistance and weldability (welding construction, properties of the welded joints) can be provided to heavy load railroads.

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CLAIMS

1. A pearlitic steel rail excellent in wear resistance and weldability, comprising, in terms of weight, more than 0.85 to 1.20% of C, 0.10 to 1.00% of Si, 5 0.20 to 1.50% of Mn, more than 0.50 to 1.00% of Cr, the content sum $Si/4 + Mn/2 + Cr$ being 0.80 to 1.80% in terms of weight, and the balance Fe and unavoidable impurities, the steel rail having a pearlite structure to the depth of at least 20 mm from the head portion corner and the head 10 top surface as a starting point, the pearlite structure having a Vickers hardness of at least 320, and the difference in Vickers hardness between the base steel and the welded joint of the steel rail being up to 30.

2. A pearlitic steel rail excellent in wear resistance and weldability, comprising, in terms of weight, more than 0.85 to 1.20% of C, 0.40 to 1.00% of Si, 15 0.20 to less than 0.40% of Mn, 0.35 to 0.50% of Cr, the content sum $Si/4 + Mn/2 + Cr$ being 0.80 to 0.95% in terms of weight, and the balance Fe and unavoidable impurities, the steel rail having a pearlite structure to the depth of at least 20 mm from the head portion corner and the head 20 top surface as a starting point, the pearlite structure having a Vickers hardness of at least 320, and the difference in Vickers hardness between the base steel and the welded joint of the steel rail being up to 30. 25

3. The pearlitic steel rail excellent in wear resistance and weldability according to claim 1 or 2, wherein the steel rail further comprises, in terms of weight, one or at least two elements selected from the group consisting of 0.01 to 0.20% of Mo, 0.02 to 0.30% of V, 30 0.002 to 0.050% of Nb, 0.10 to 2.00% of Co and 0.0005 to 0.005% of B, and the balance Fe and unavoidable impurities, the steel rail has a pearlite structure to the depth of at least 20 mm from the head portion corner and the head top surface as a starting point, the pearlite 35 structure has a Vickers hardness of at least 320, and the difference in Vickers hardness between the base steel and

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the welded joint of the steel rail is up to 30.

4. A process for producing a pearlitic steel rail excellent in wear resistance and weldability comprising the steps of

5 subjecting the head portion of a hot rolled steel rail having a thermal energy or steel rail heated to a temperature for the purpose of heat treatment which steel rail has the chemical composition according to any one of claims 1 to 3, to accelerated cooling from an austenite
10 region temperature at a cooling rate of 1 to 10°C/sec,

 stopping the accelerated cooling at the time when the steel rail temperature reaches from 700 to 500°C, and

15 allowing the steel rail to cool,
 the steel rail having a pearlite structure to the depth of at least 20 mm from the head portion corner and the head top surface as a starting point, the pearlite structure having a Vickers hardness of at least
20 320, and the difference in Vickers hardness between the base steel and the welded joint of the steel rail being up to 30.

5. A process for producing a pearlitic steel rail excellent in wear resistance and weldability comprising
25 the steps of

 subjecting the head portion of a hot rolled steel rail having a thermal energy or steel rail heated to a temperature for the purpose of heat treatment which steel rail has the chemical composition according to any one of
30 claims 1 to 3, to accelerated cooling from an austenite region temperature at a cooling rate of more than 10 to 30°C/sec,

 stopping the accelerated cooling at the time when the pearlite transformation of the steel rail proceeds in an amount of 70% of the entire transformation,
35 and

 allowing the steel rail to cool,

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the steel rail having a pearlite structure to the depth of at least 20 mm from the head portion corner and the head top surface as a starting point, the pearlite structure having a Vickers hardness of at least 320, and the difference in Vickers hardness between the base steel and the welded joint of the steel rail being up to 30.

6. A process for producing a pearlitic steel rail excellent in wear resistance and weldability comprising the steps of

subjecting the head portion of a hot rolled steel rail having a thermal energy or steel rail heated to a temperature for the purpose of heat treatment which steel rail has the chemical composition according to any one of claims 1 to 3, to accelerated cooling from an austenite region temperature to a temperature from 750 to 600°C at a cooling rate of more than 10 to 30°C/sec, and

consecutively subjecting the head portion thereof to controlled cooling at a cooling rate of 1 to less than 10°C/sec in a temperature region from 750 to 600°C to 550 to 450°C,

the steel rail having a pearlite structure to the depth of at least 20 mm from the head portion corner and the head top surface as a starting point, the pearlite structure having a Vickers hardness of at least 320, and the difference in Vickers hardness between the base steel and the welded joint of the steel rail being up to 30.

Fig. 1 (PRIOR ART)

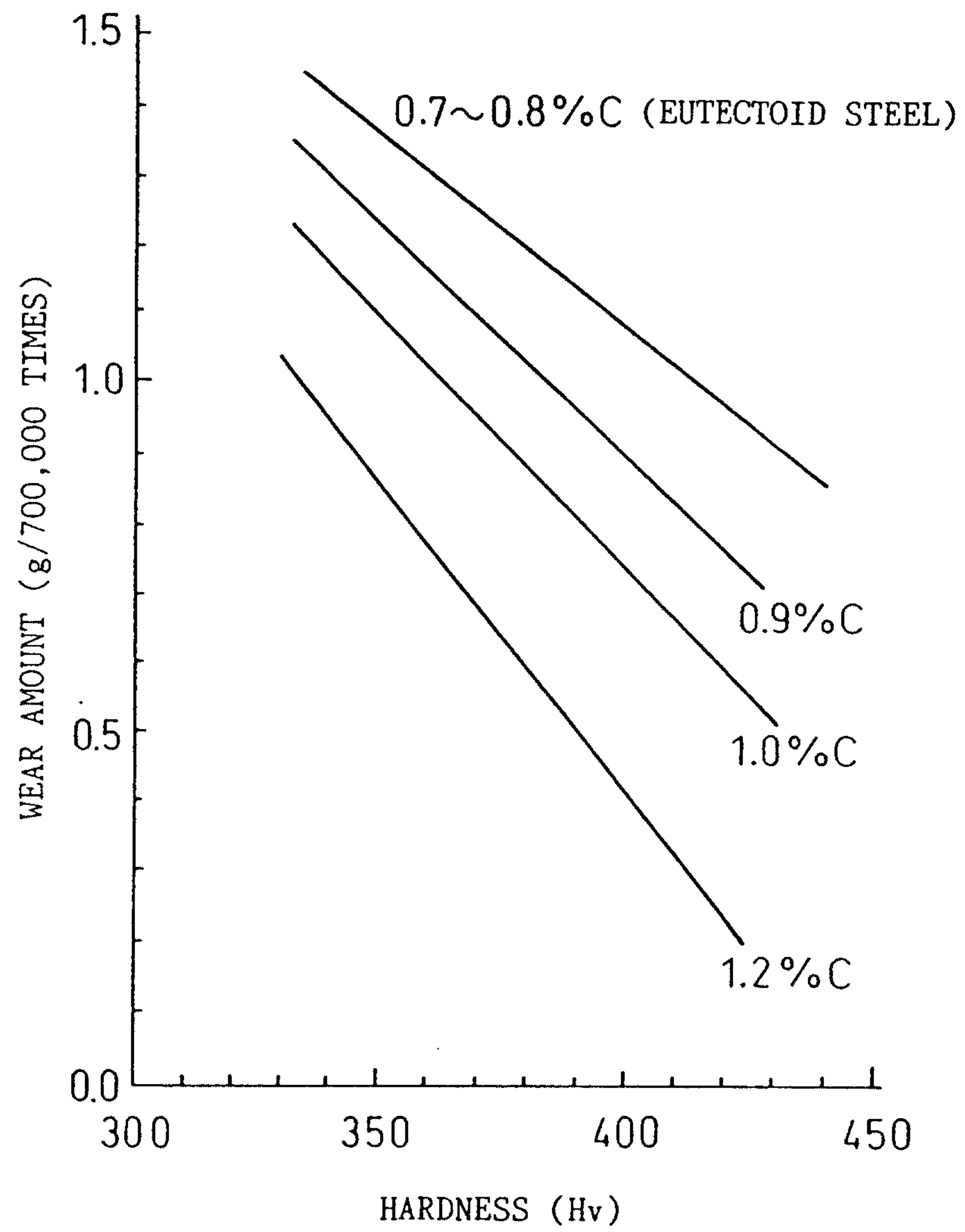


Fig. 2 (PRIOR ART)

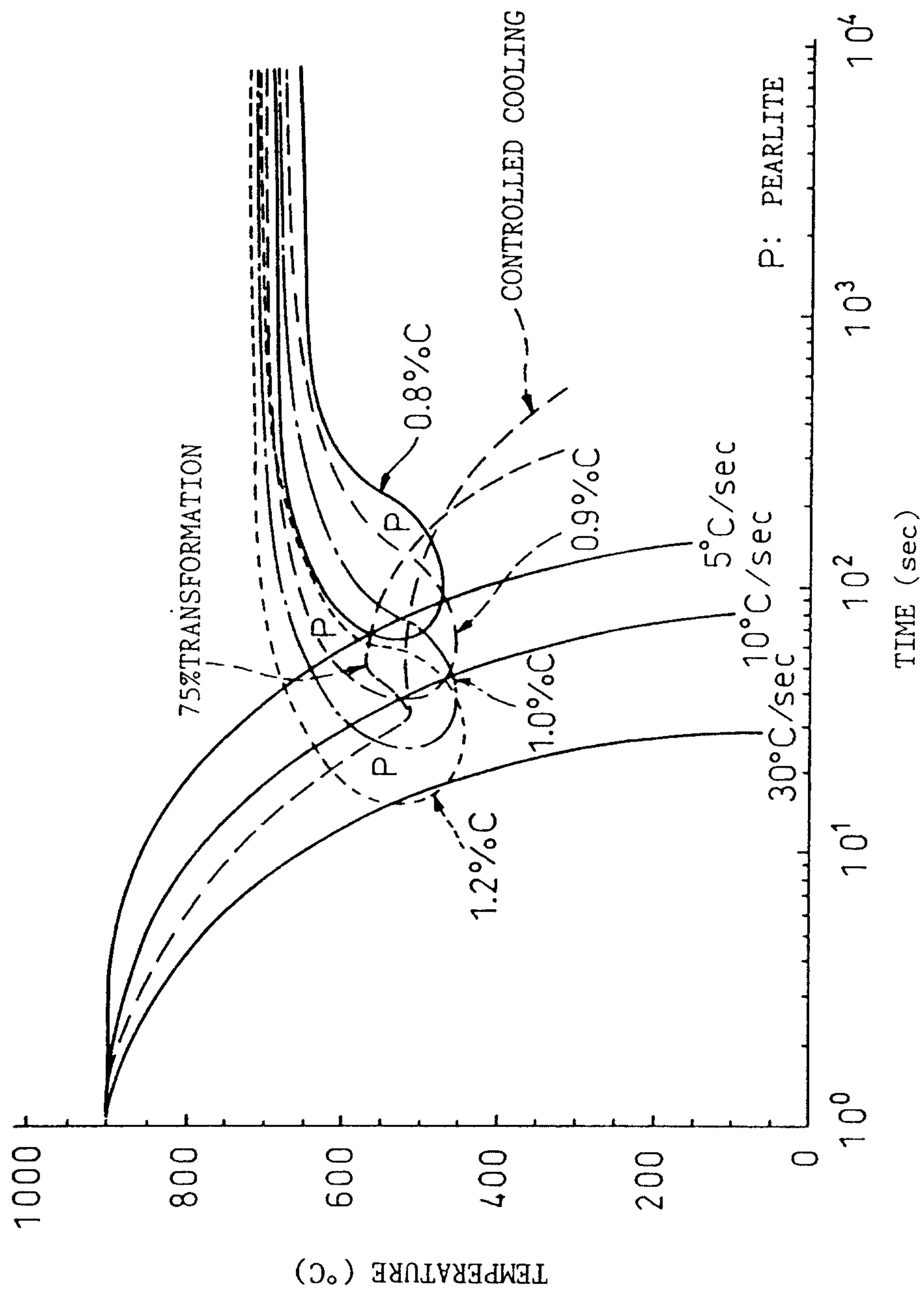


Fig. 3

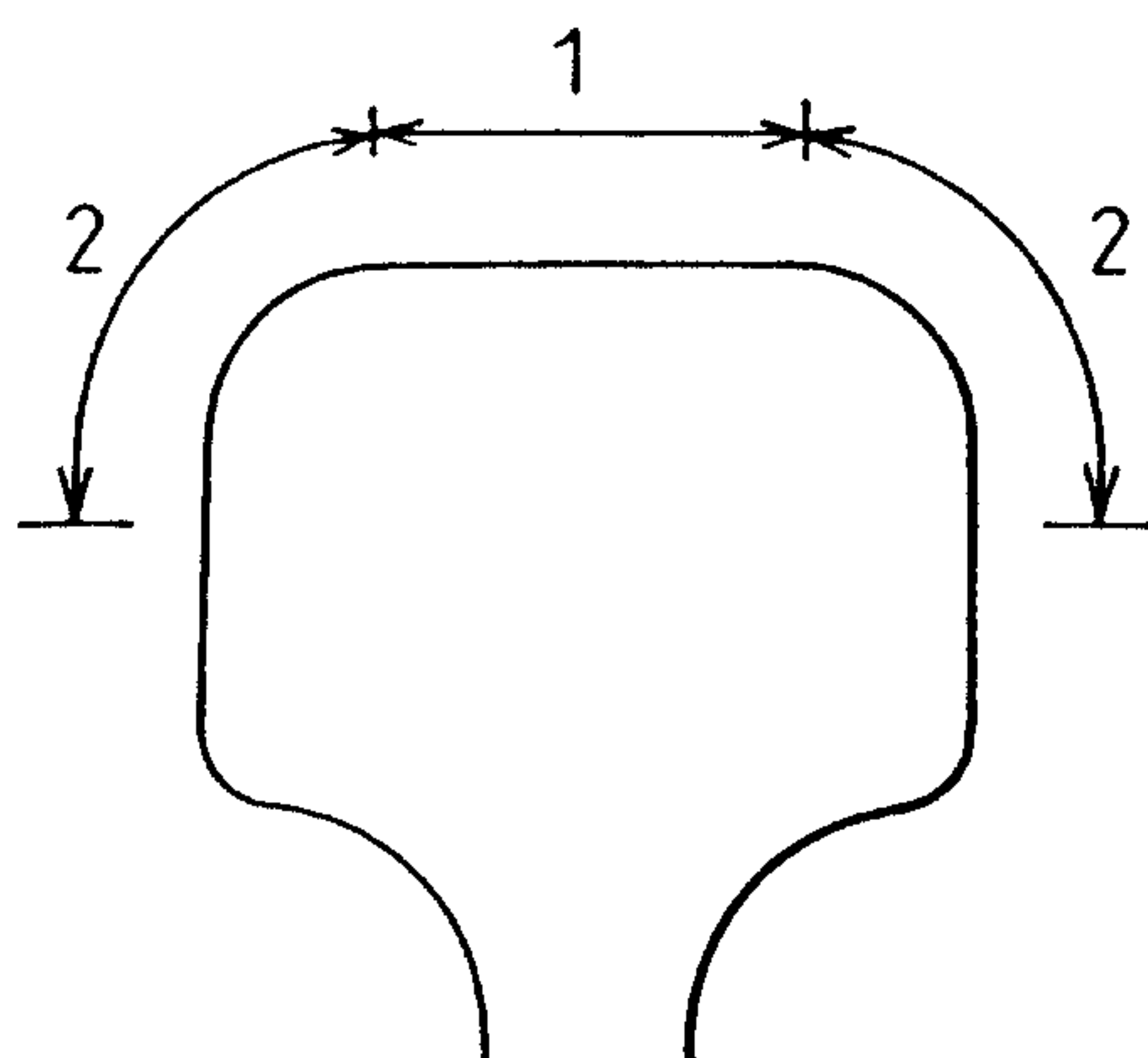
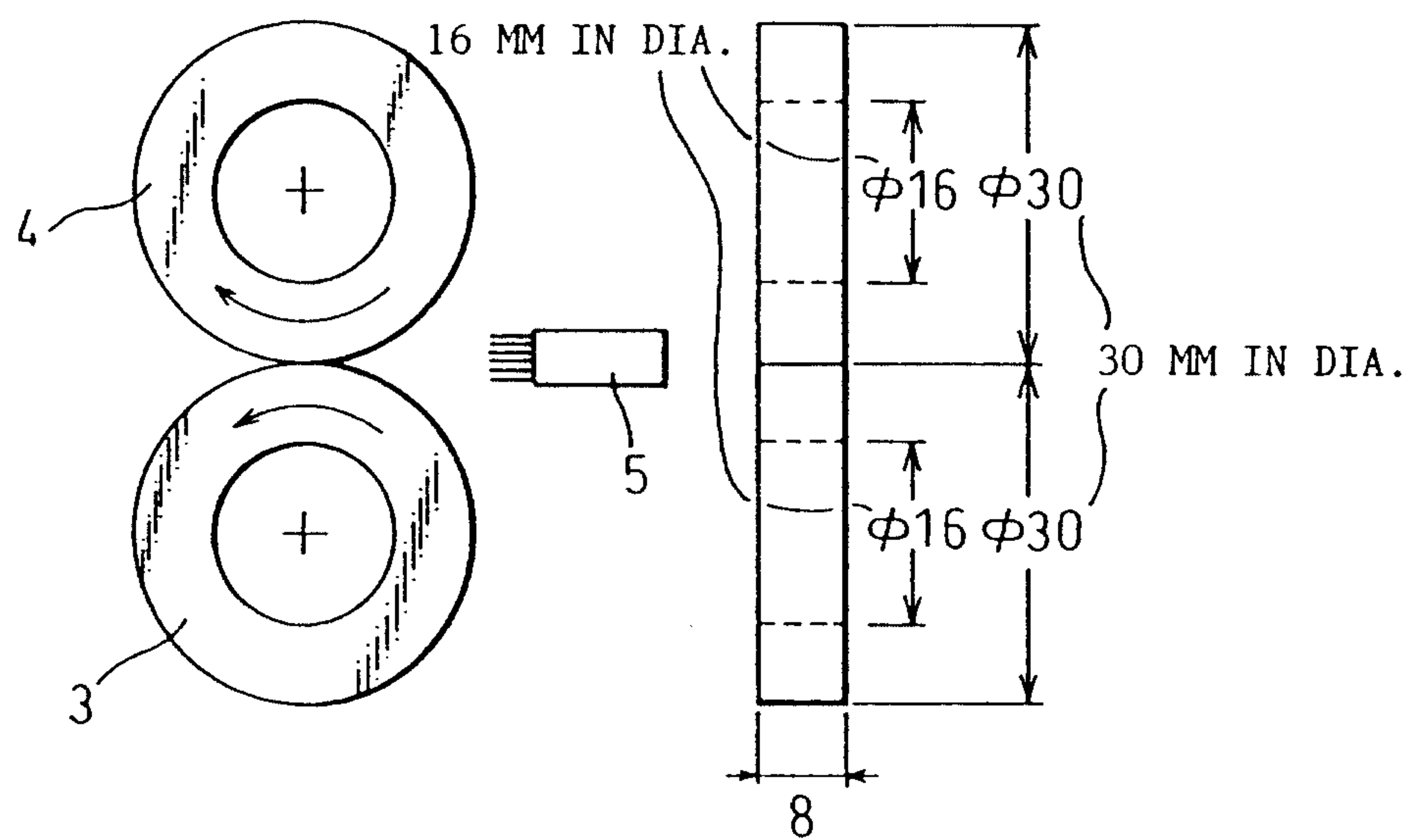


Fig. 4 (PRIOR ART)



F i g . 5

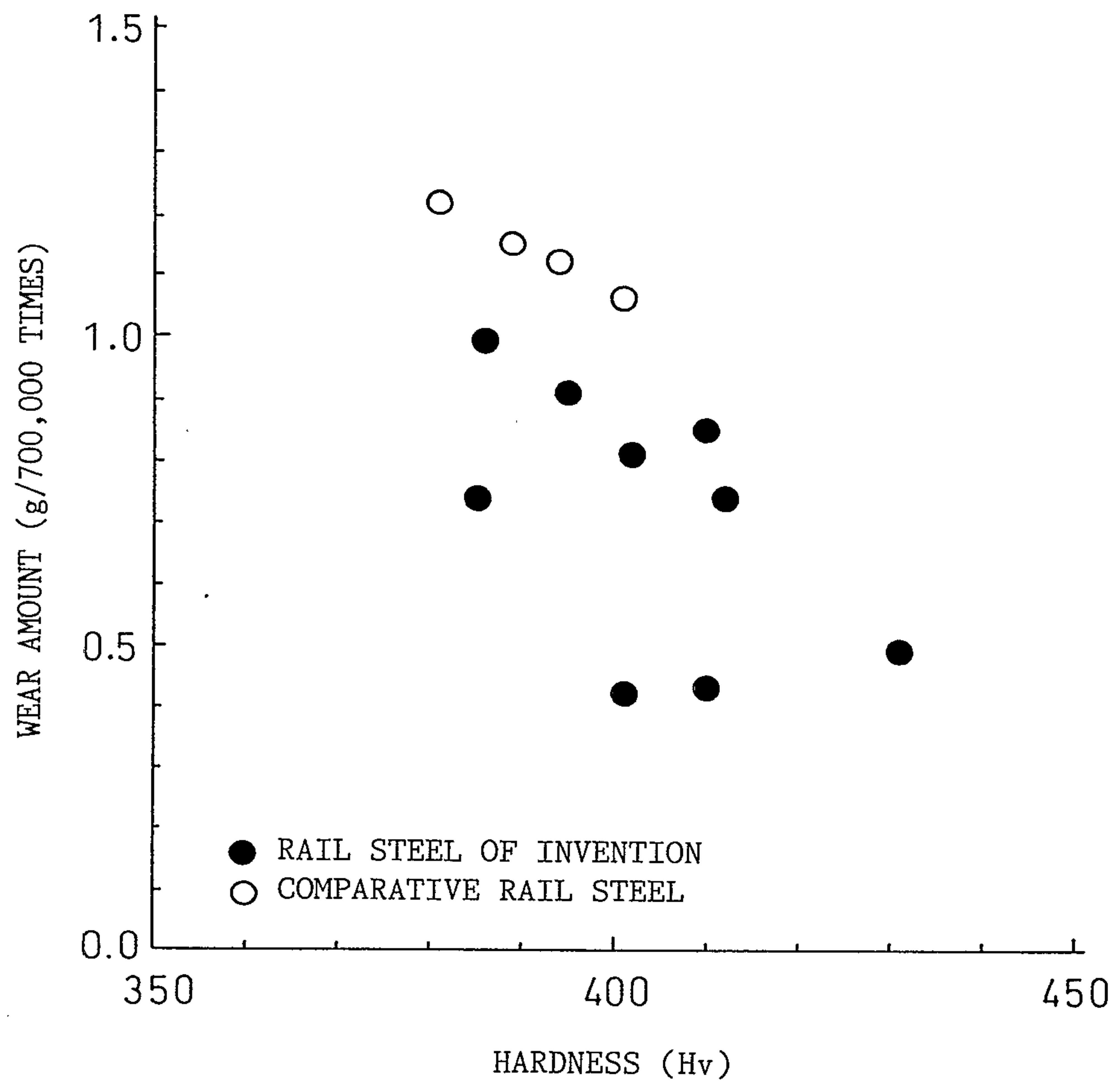
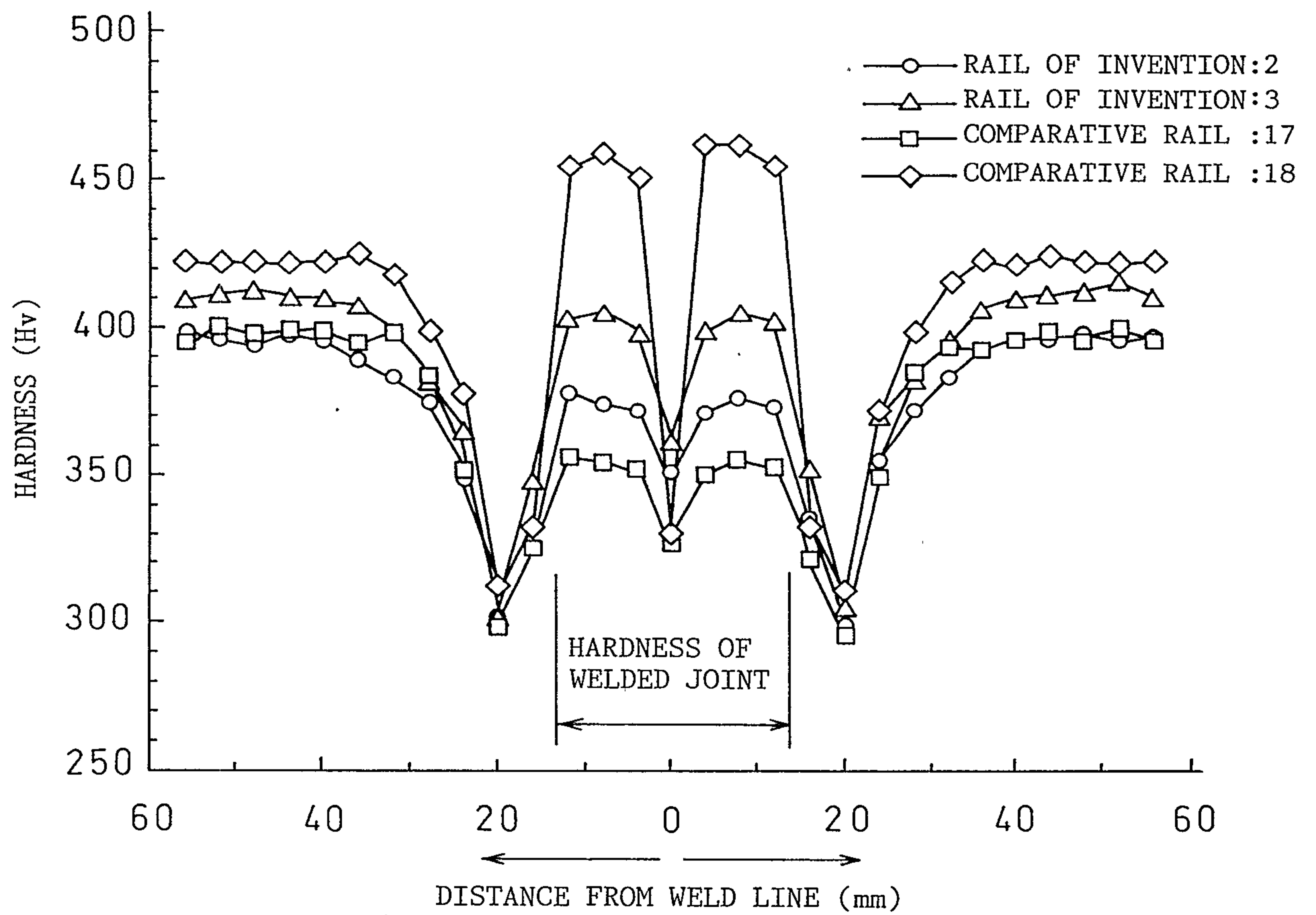


Fig. 6



F i g . 7

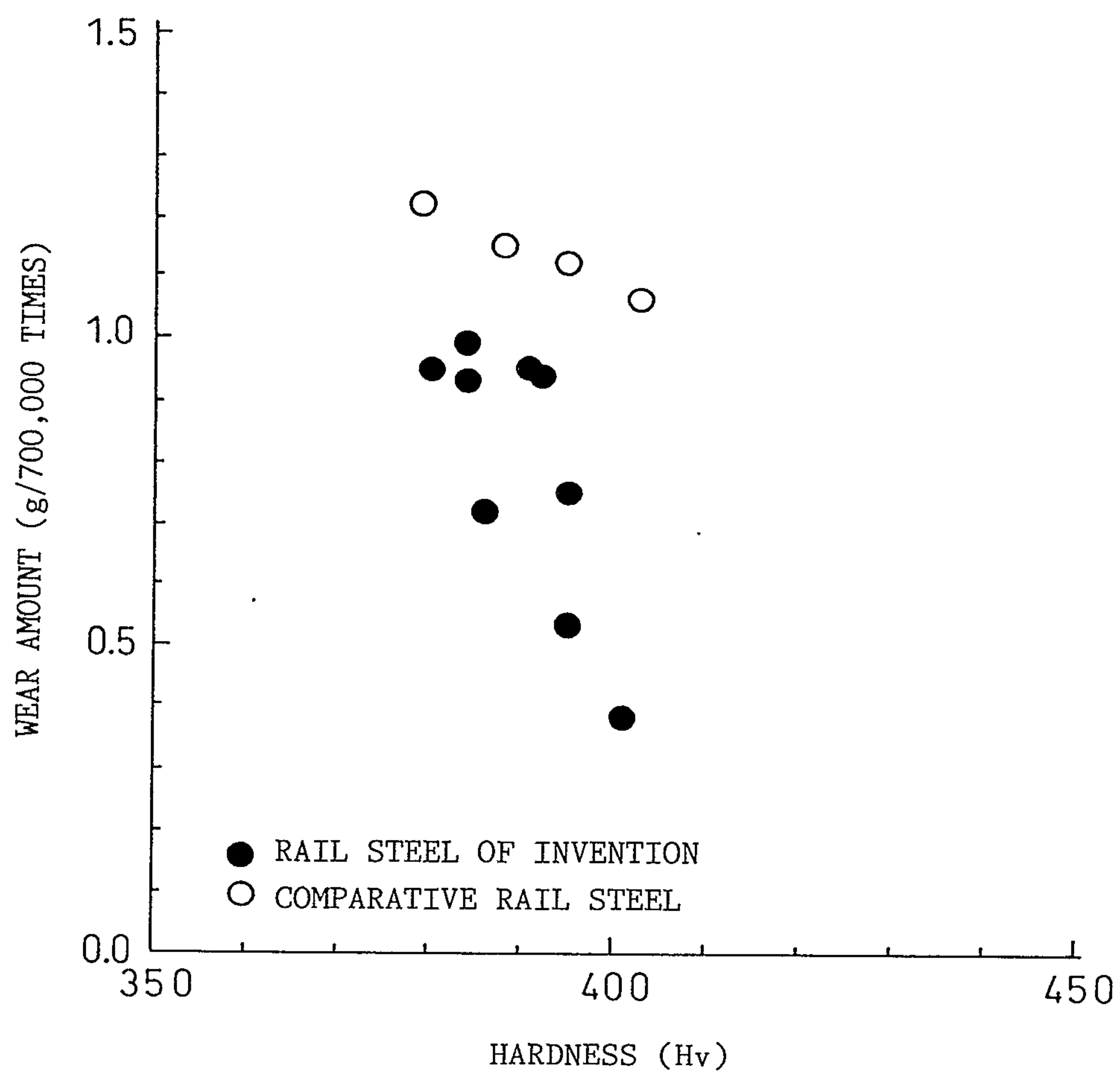


Fig. 8

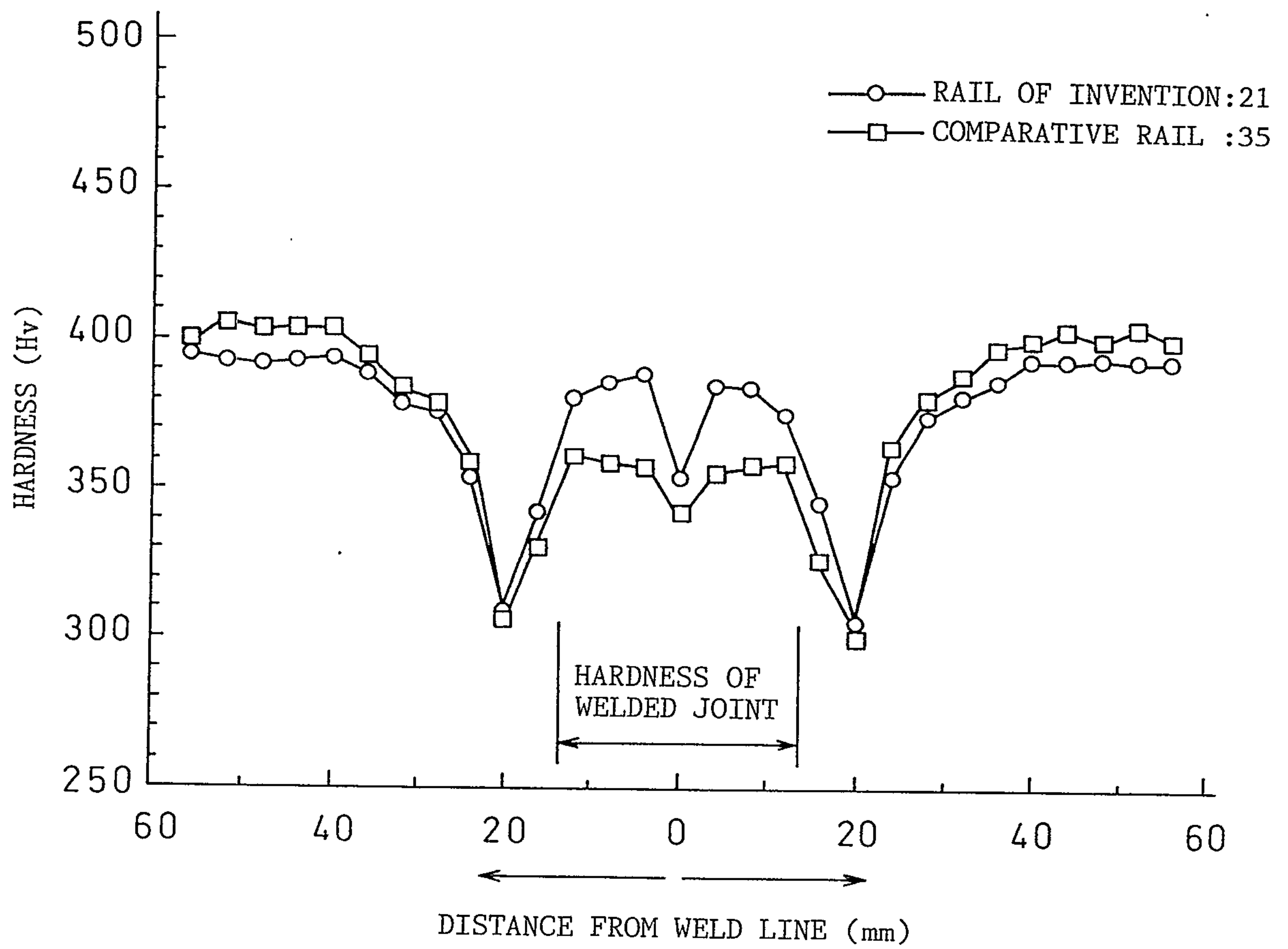


Fig. 9

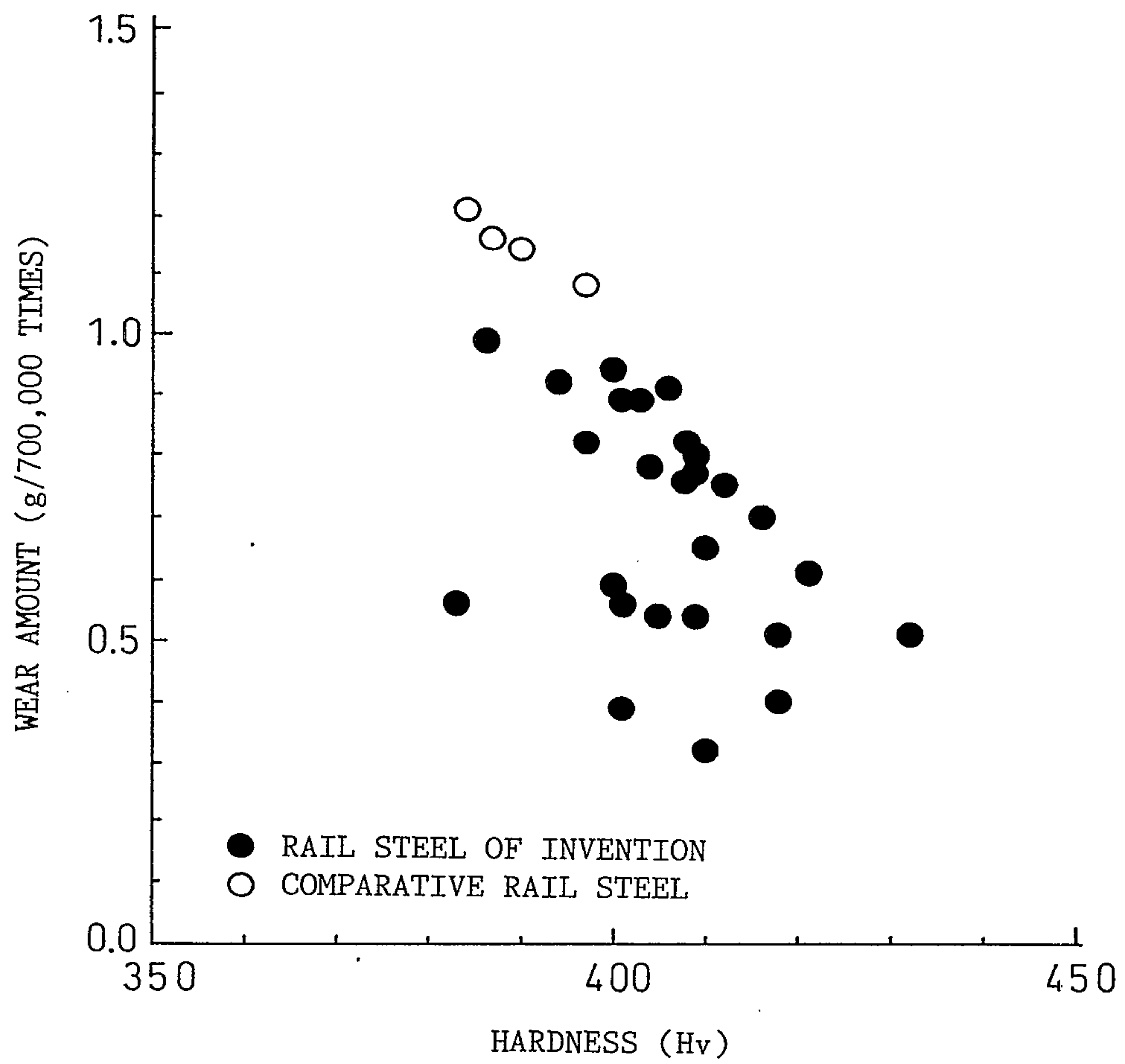
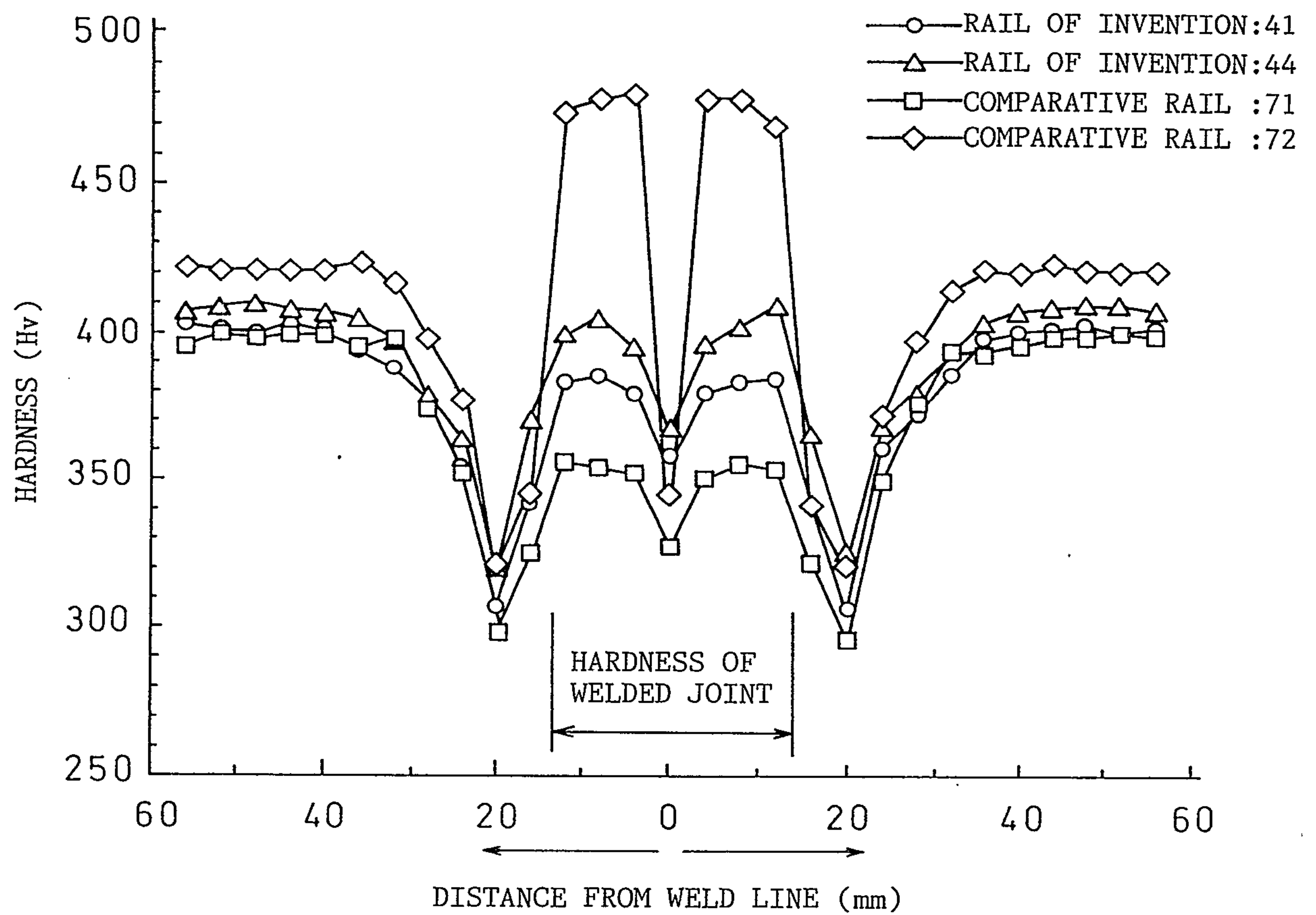


Fig.10



F i g . 11

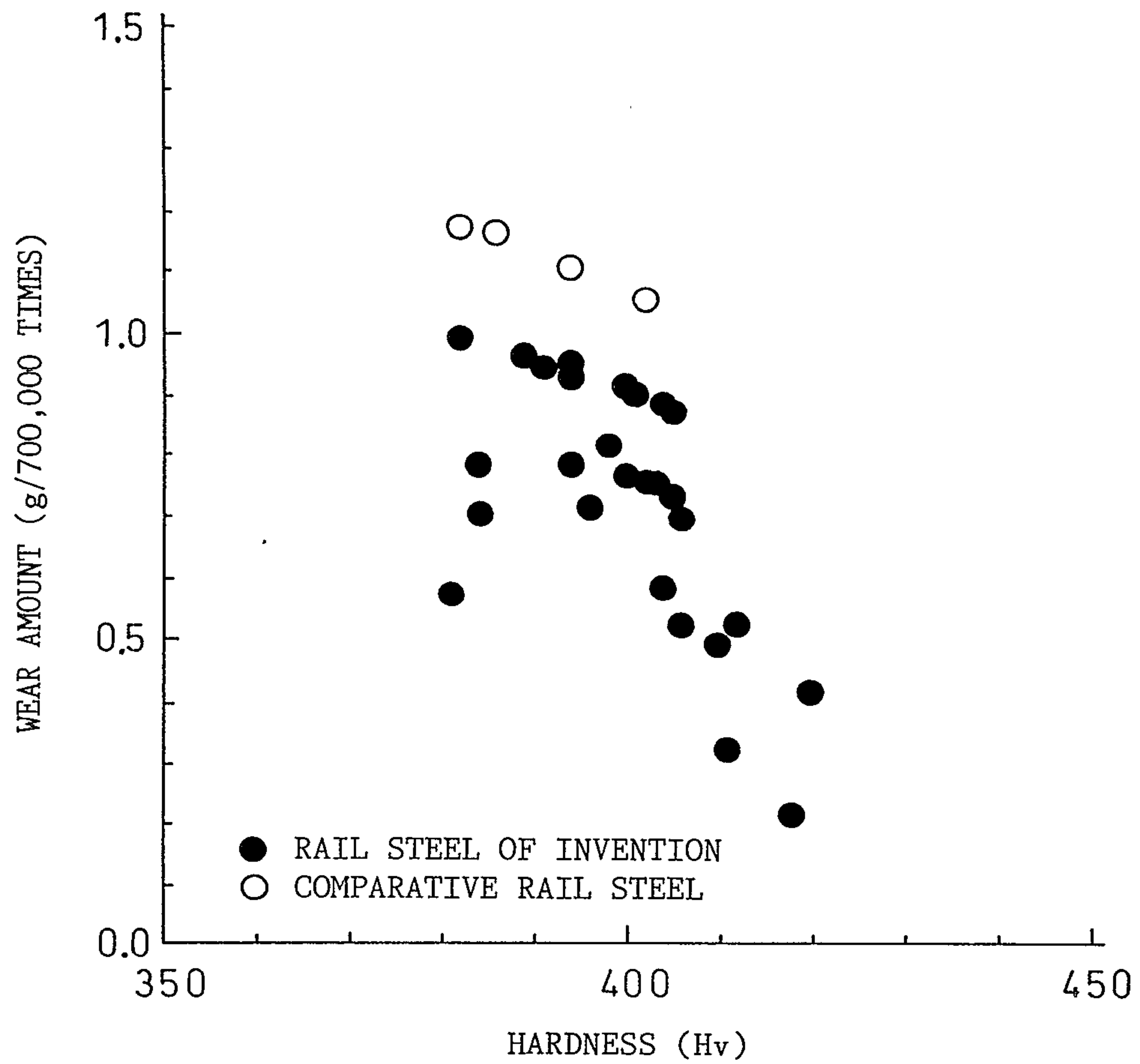


Fig. 12

