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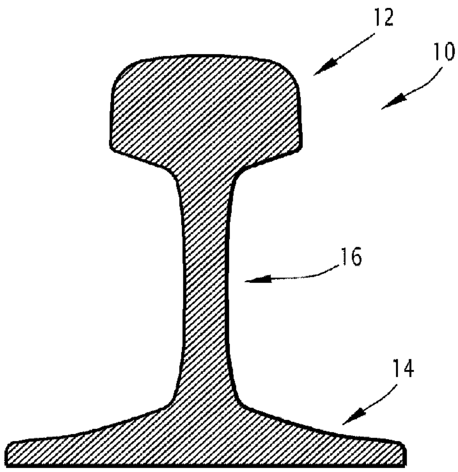
(54) **Titre : PROCEDE DE FABRICATION DE RAIL ET RAIL CORRESPONDANT**
(54) **Title: METHOD FOR MANUFACTURING A RAIL AND CORRESPONDING RAIL**



(57) **Abrégé/Abstract:**
Method for manufacturing a rail, comprising: - casting a steel to obtain a semi-product, said steel having a composition comprising 0.20% ≤ C ≤ 0.60%, 1.0% ≤ Si ≤ 2.0%, 0.60% ≤ Mn ≤ 1.60%and 0.5 ≤ Cr ≤ 2.2%, optionally 0.01% ≤ Mo ≤ 0.3%,0.01% ≤ V ≤ 0.30%; the remainder being Fe and impurities - hot rolling the semi-product into a hot rolled semi-product having the shape of the rail and comprising a head, with a final rolling temperature TFRT higher than Ar3; - cooling the head to a cooling stop temperature T_{CS} between 200°C and 520°C, the temperature of the head over time being comprised between a upper boundary having the coordinates defined by A1 (0 second, 780°C), B1 (50 seconds, 600°C), and C1 (110 seconds, 520°C) and a lower boundary having the coordinates defined by A2 (0 second, 675°C), B2 (50 seconds, 510°C), and C2 (110 seconds, 300°C); - maintaining the head in a temperature range comprised between 300°C and 520°C during a holding time t_{hold} of at least 12 minutes, and; - cooling down the hot rolled semi-product to room temperature to obtain the rail.

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(54) Title: METHOD FOR MANUFACTURING A RAIL AND CORRESPONDING RAIL

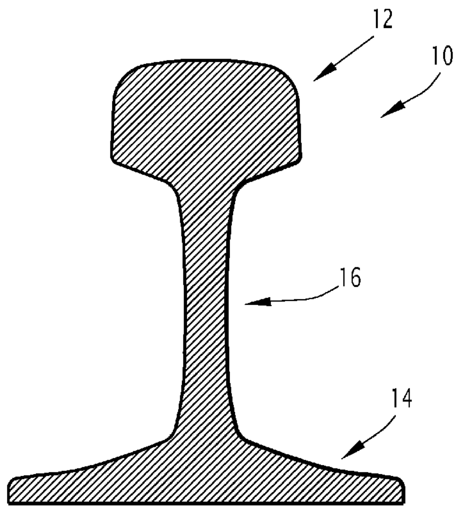

FIG.1

(57) Abstract: Method for manufacturing a rail, comprising: - casting a steel to obtain a semi-product, said steel having a composition comprising $0.20\% \leq C \leq 0.60\%$, $1.0\% \leq Si \leq 2.0\%$, $0.60\% \leq Mn \leq 1.60\%$and $0.5 \leq Cr \leq 2.2\%$, optionally $0.01\% \leq Mo \leq 0.3\%$,$0.01\% \leq V \leq 0.30\%$; the remainder being Fe and impurities - hot rolling the semi-product into a hot rolled semi-product having the shape of the rail and comprising a head, with a final rolling temperature TFRT higher than Ar3; - cooling the head to a cooling stop temperature T_{CS} between 200°C and 520°C, the temperature of the head over time being comprised between a upper boundary having the coordinates defined by A1 (0 second, 780°C), B1 (50 seconds, 600°C), and C1 (110 seconds, 520°C) and a lower boundary having the coordinates defined by A2 (0 second, 675°C), B2 (50 seconds, 510°C), and C2 (110 seconds, 300°C); - maintaining the head in a temperature range comprised between 300°C and 520°C during a holding time t_{hold} of at least 12 minutes, and; - cooling down the hot rolled semi-product to room temperature to obtain the rail.

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Method for manufacturing a rail and corresponding rail

The present invention concerns a method for producing a steel rail having excellent mechanical properties and wear and rolling contact fatigue resistances, as well as a corresponding steel rail.

In recent years, train speed and load have been increased to improve railroad transportation and contact stresses can exceed 2000 MPa. These more severe service conditions require new rails with higher wear and rolling contact fatigue resistance, especially for heavy industrial railway traffic.

Wear and rolling contact fatigue (RCF) are two important factors that may cause a delayed failure in the railway track. Whereas the mechanisms for wear have been fully studied and are well understood, and wear is nowadays managed in the railway system, RCF is still not sufficiently understood to have efficient solutions to prevent the formation of RCF defects, which can cause progressive deterioration and a premature maintenance of the rail.

The traditional approach for the development of new rail steels to address wear and RCF has been to increase steel hardness and strength. In the case of conventional pearlitic grades for railways, this increase has been achieved during the last 40 years by decreasing the interlamellar spacing, by adding costly alloying elements or through head hardening. Nevertheless, this increase in resistance to wear is generally accompanied by a decrease in toughness. The aforementioned challenges are showing that despite all the research that has been taken place to develop new microstructures with enhanced mechanical properties, pearlitic steel grades have already reached their limits in terms of wear and rolling contact fatigue performance, which means that the existing railway grades cannot cope with the most demanding in-service conditions.

Bainitic steels, comprising for example lower bainite microstructure, have been considered as the next generation of advanced high strength steels and candidate materials for heavy-duty rails and railway-crossings due to a good combination of hardness, strength and toughness.

Bainitic steels comprising lower bainite microstructure provide good wear resistance but do not achieve a sufficient RCF resistance.

Especially, WO1996022396A1 discloses a method for producing a high strength wear and rolling contact fatigue resistant rail. The rail is produced from a steel having a composition comprising 0.05% to 0.5% C, 1.00% to 3.00% Si and/or Al, 0.50% to 2.50% Mn and 0.25% to 2.50% Cr. The rail is produced by air cooling the steel from the finish hot rolling temperature.

EP 1 873 262 discloses a method for manufacturing high-strength guide rails, from a steel comprising 0.3% to 0.4% C, 0.7% to 0.9% Si, 0.6% to 0.8% Mn and 2.2% to 3.0% Cr. The manufacturing method comprises air cooling the steel after formation of a bainitic structure. However, EP 1 873 262 does not teach any specific cooling rate.

EP 0 612 852, US2015218759 and US201514702188 disclose methods for producing bainitic rails by accelerated cooling. However, these rails do not show a sufficient Rolling Contact Fatigue resistance.

Therefore, it remains desirable to produce steel rails.

An object of this invention is to provide a method of manufacturing high performance rail having excellent rolling-contact fatigue resistance and wear resistance.

Especially, it is desirable to produce a steel rail wherein the rail head has a tensile strength of at least 1300 MPa, a yield strength of at least 1000 MPa, a total elongation of at least 13 % and a hardness of at least 420 HB and preferably of at least 430 HB together with excellent rolling-contact fatigue resistance and wear resistance.

For this purpose, the invention relates to a method for manufacturing a rail comprising a head, the method comprising the following successive steps:

- casting a steel so as to obtain a semi-product, said steel having a chemical composition comprising, by weight percent:

$0.20\% \leq C \leq 0.60\%$,

$1.0\% \leq Si \leq 2.0\%$,

$0.60\% \leq Mn \leq 1.60\%$,

and $0.5 \leq Cr \leq 2.2\%$,

and optionally one or more elements chosen among

$0.01\% \leq Mo \leq 0.3\%$,

$0.01\% \leq V \leq 0.30\%$;

the remainder being Fe and unavoidable impurities resulting from the smelting;

- hot rolling the semi-product into a hot rolled semi-product having the shape of the rail and comprising a head, with a final rolling temperature T_{FRT} higher than Ar3;

- cooling the head of the hot rolled semi-product from the final rolling temperature T_{FRT} down to a cooling stop temperature T_{CS} comprised between 200°C and 520°C, such that the temperature of the head of the hot rolled semi-product over time is comprised between a upper boundary and a lower boundary, the upper boundary having the coordinates of time and temperature defined by A1 (0 second, 780°C), B1 (50 seconds, 600°C), and C1 (110 seconds, 520°C), the lower boundary having the coordinates of time and temperature defined by A2 (0 second, 675°C), B2 (50 seconds, 510°C), and C2 (110 seconds, 300°C);

- maintaining the head of the hot rolled semi-product in a temperature range comprised between 300°C and 520°C during a holding time t_{hold} of at least 12 minutes, and;
- cooling down the hot rolled semi-product to room temperature to obtain the rail.

The disclosure also relates to a method for manufacturing a rail comprising a head, the method comprising the following successive steps:

- casting a steel so as to obtain a semi-product, said steel having a chemical composition comprising, by weight percent:

$$0.20\% \leq C \leq 0.60\%,$$
$$1.0\% \leq Si \leq 2.0\%,$$
$$0.60\% \leq Mn \leq 1.60\%,$$
$$\text{and } 0.5 \leq Cr \leq 2.2\%,$$

the remainder being Fe and unavoidable impurities resulting from smelting;

- hot rolling the semi-product into a hot rolled semi-product having the shape of the rail and comprising the head, with a final rolling temperature T_{FRT} higher than Ar3;
- cooling the head of the hot rolled semi-product from the final rolling temperature T_{FRT} down to a cooling stop temperature T_{CS} comprised between 200°C and 520°C, such that the temperature of the head of the hot rolled semi-product over time is comprised between a upper boundary and a lower boundary, the upper boundary having the coordinates of time and temperature defined by A1, B1, and C1, the lower boundary having the coordinates of time and temperature defined by A2, B2, and C2;

wherein A1 corresponds to the coordinates 0 second, 780°C,
B1 corresponds to the coordinates 50 seconds, 600°C,
C1 corresponds to the coordinates 110 seconds, 520°C,
A2 corresponds to the coordinates 0 second, 675°C,
B2 corresponds to the coordinates 50 seconds, 510°C,
C2 corresponds to the coordinates 110 seconds, 300°C;

- maintaining the head of the hot rolled semi-product in a temperature range comprised between 300°C and 520°C during a holding time t_{hold} of at least 12 minutes, and;
- cooling down the hot rolled semi-product to room temperature to obtain the rail.

The method for manufacturing a rail may further comprise one or more of the following features, taken along or according to any technically possible combination,

- the microstructure of the head of the rail consists of, in surface fraction:
    - 49% to 67% of bainite;

- 14% to 25% of retained austenite, the retained austenite having an average carbon content comprised between 0.80% and 1.44%;

- 13% to 34% of tempered martensite;

- the surface fraction of bainite in the microstructure of the head is higher than or equal to 56%;

- the surface fraction of retained austenite in the microstructure of the head is comprised between 18% and 23%;

- the surface fraction of tempered martensite in the microstructure of the head is comprised between 14.5% and 22.5%;

- the average carbon content in the retained austenite is higher than 1.3%;

- the cooling stop temperature T_{CS} is comprised between 300°C and 520°C;

- the cooling stop temperature T_{CS} is comprised between 200°C and 300°C, and the method further comprises, after the step of cooling the head of the hot rolled semi-product down to the cooling stop temperature T_{CS} and before the step of maintaining the head in the temperature range, a step of heating the head of the hot rolled semi-product up to a temperature comprised between 300°C and 520°C;

- the step of cooling the head of the hot rolled semi-product is performed through water jets;

- during the step of cooling the head of the hot rolled semi-product, the entire hot rolled semi-product is cooled such that the temperature of the hot rolled semi-product over time is comprised between the upper boundary and the lower boundary;

- during the step of hot rolling the semi-product, the semi-product is hot rolled from a hot rolling starting temperature higher than 1080°C, preferably higher than 1180°C;

- the chemical composition of the steel comprises, the content being expressed by weight percent: 0.30% ≤ C ≤0.60%;

- the chemical composition of the steel comprises, the content being expressed by weight percent:1.25% ≤ Si ≤ 1.6%; and

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- the chemical composition of the steel comprises, the content being expressed by weight percent: 1.09% ≤ Mn ≤ 1.5%.

The invention also relates to a hot rolled steel part having a chemical composition comprising, by weight percent:

0.20% ≤ C ≤ 0.60%,

1.0% ≤ Si ≤ 2.0%,

0.60% ≤ Mn ≤ 1.60%,

and 0.5≤ Cr ≤ 2.2%,

and optionally one or more elements chosen among

0.01% ≤ Mo ≤ 0.3%,

0.01% ≤ V ≤ 0.30%;

the remainder being Fe and unavoidable impurities resulting from the smelting;

the steel rail comprising a head having a microstructure consisting of, in surface fraction:

49% to 67% of bainite,

14% to 25% of retained austenite, the retained austenite having an average carbon content comprised between 0.80% and 1.44%, and

13% to 34% of tempered martensite.

The hot rolled steel part may further comprise one or more of the following features, taken along or according to any technically possible combination:

- the surface fraction of bainite in the microstructure of the head of the rail is higher than 56% ;

- the surface fraction of retained austenite in the microstructure of the head of the rail is comprised between 18 % and 23% ;

- the surface fraction of tempered martensite in the microstructure of the head of the rail is comprised between 14.5% and 22.5% ;

- the average carbon content in the retained austenite is higher than 1.3% ;

- the chemical composition of the steel comprises, the content being expressed by weight percent: 0.30% ≤ C ≤ 0.6% ;

- the chemical composition of the steel comprises, the content being expressed by weight percent: 1.25% ≤ Si ≤ 1.6% ;

- the chemical composition of the steel comprises, the content being expressed by weight percent: 0.9% ≤ Mn ≤ 1.5% ;

- the head of the rail has a hardness comprised between 420 HB and 470 HB, preferably higher than 450 HB ;

- the head of the rail has a tensile strength comprised between 1300 MPa and 1450 MPa ;

- the head of the rail has a yield strength comprised between 1000 MPa and 1150 MPa ; and

- the head of the rail has a total elongation comprised between 13% and 18%.

Other aspects and advantages of the invention will appear upon reading the following description, given by way of example and made in reference to the appended drawings, wherein:

- Figure 1 is a sectional view of the rail, and;

- Figure 2 is a graph showing the upper boundary and the lower boundary of the temperature over time during the step of cooling the head;

- Figure 3 is a graph of the linear thermal expansion coefficients of three samples coefficient of thermal expansion function of the temperature.

An embodiment of a rail 10 according to the invention is depicted in Figure 1.

The rail 10 comprises a head 12 and a foot 14, the foot 14 and the head 12 being connected to each other through a support 16.

As depicted in Figure 1, the support 16 has a maximal width strictly inferior to the maximal width of the head 12, notably at least inferior to 50% to the maximal width of the head 12.

Likewise, the support has a maximal width strictly inferior to the maximal width of the foot, notably at least inferior to 50% to the maximal width of the foot.

The head 12, the foot 14 and the support 16 are made integral.

The rail 10, in particular the head 12 of the rail 10, is manufactured from a steel having a chemical composition comprising, by weight percent:

0.20% ≤ C ≤ 0.60%, and more particularly 0.30% ≤ C ≤ 0.60%,

1.0% ≤ Si ≤ 2.0%, and preferably 1.25% ≤ Si ≤ 1.6%.

0.60% ≤ Mn ≤ 1.60%, and preferably 1.09% ≤ Mn ≤ 1.5%,

and 0.5 ≤ Cr ≤ 2.2%,

and optionally one or more elements chosen among

0.01% ≤ Mo ≤ 0.3%,

0.01% ≤ V ≤ 0.30%;

the remainder being Fe and unavoidable impurities resulting from the smelting.

In this alloy, carbon is the alloying element having the main effect to control and adjust the desired microstructure and properties of the steel. Carbon stabilizes the austenite and thus leads to its retention even at room temperature. Besides, carbon allows achieving a good mechanical resistance and the desired hardness, combined with a good ductility and impact resistance.

A carbon content below 0.20 % by weight leads to the formation of a non-sufficiently stable retained austenite, insufficient hardness and tensile strength, and insufficient rolling-contact fatigue and wear resistances. At carbon contents above 0.60%, the ductility and impact resistance of the steel are deteriorated by the appearance of center-segregation. Therefore, the carbon content is comprised between 0.20% and 0.60% by weight.

The carbon content is preferably comprised between 0.30% and 0.60% by weight percent.

The silicon content is comprised between 1.0% and 2.0% by weight. Si, which is an element which is not soluble in the cementite, prevents or at least delays carbide precipitation, in particular during bainite formation, and allows the diffusion of carbon into the retained austenite, thus favoring the stabilization of the retained austenite. Si further increases the strength of the steel by solid solution hardening. Below 1.0% by weight of silicon, these effects are not sufficiently marked. At a silicon content above 2.0% by weight, the impact resistance might be negatively impacted by the formation of large size oxides. Moreover, an Si content higher than 2.0% by weight might lead to a poor surface quality of the steel.

Preferably, the Si content is comprised between 1.25% and 1.6% by weight.

The manganese content is comprised between 0.60% and 1.60% by weight, and preferably between 1.09% and 1.5%. Mn has an important role to control the microstructure and to stabilize the austenite. As a gammagenic element, Mn lowers the transformation temperature of the austenite, enhances the possibility of carbon enrichment by increasing carbon solubility in austenite and extends the applicable range of cooling rates as it delays perlite formation. Mn further increases the strength of the material by solid solution hardening, and refines the structure. Below 0.6 % by weight, these effects are not sufficiently marked. At contents above 1.6%, Mn favors the formation of too large a fraction of martensite, which is detrimental for the ductility of the product.

The chromium content is comprised between 0.5% and 2.2% by weight. Cr is effective in stabilizing the retained austenite, ensuring a predetermined amount thereof. It is also useful for strengthening the steel. However, Cr is mainly added for its hardening effect. Cr promotes the growth of the low-temperature-transformed phases and allows obtaining the targeted microstructure in a large range of cooling rates. At contents below 0.5%, these effects are not sufficiently marked. At contents above 2.2%, Cr favors the formation of too large a fraction of martensite, which is detrimental for the ductility of the product. Moreover, at contents above 2.2%, the Cr addition becomes unnecessarily expensive.

When present, the molybdenum content is comprised between 0.01% and 0.3% by weight. In the steel of the invention, Mo may be present as an impurity, in a content which is generally of at least 0.01%, or added as a voluntary addition. When added, the Mo content is preferably of at least 0.10%. When added, Mo improves the hardenability of the steel and further facilitates the formation of lower bainite by decreasing the temperature at which this structure appears, the lower bainite resulting in a good impact resistance of the steel. At contents greater than 0.3% by weight, Mo can have however a negative effect on this same impact resistance. Moreover, above 0.3%, the Mo addition becomes unnecessarily expensive.

When present, the vanadium content is comprised between 0.01% and 0.30%. Vanadium is optionally added as a strengthening and refining element. When added, the V content is preferably of at least 0.10%. Below 0.10%, no significant effect on the mechanical properties is noted. Above 0.30%, under the manufacturing conditions according to the invention, a saturation of the effect on the mechanical properties is noted. When V is not added, V is generally present as an impurity in a content of at least 0.01%.

The remainder of the composition is iron and unavoidable impurities. In this respect, nickel, phosphorus, sulfur, nitrogen, oxygen and hydrogen are considered as residual elements which are unavoidable impurities. Therefore, their contents are at most 0.05% Ni, at most 0.025% P, at most 0.020% S, at most 0.009% N, at most 0.003% O and at most 0.0003% H.

The rail 10, in particular the head 12 of the rail 10, has a microstructure consisting of, in surface fractions:

- 49% to 67% of bainite,
- 14% to 25% of retained austenite, and
- 13% to 34% of tempered martensite.

The bainite can include granular bainite and lath-like carbide free bainite. In the frame of the invention, carbide free bainite will designate bainite containing less than 100 carbides per surface unit of 100 square micrometer.

Preferably, the surface fraction of bainite in the microstructure of the head 12 is higher than or equal to 56%.

The retained austenite and the tempered martensite are generally present as M/A constituents, located between the laths or plates of bainite.

The austenite is also contained in the bainite between the laths or plates of bainite.

The retained austenite has an average carbon content comprised between 0.83% and 1.44%, preferably higher than 1.3%.

Preferably, the surface fraction of retained austenite in the microstructure of the head 12 is comprised between 18% and 23%.

The tempered martensite is contained in the bainite between the laths or plates of bainite, and in the M/A components.

The martensite is tempered martensite and preferably self-tempered martensite. Generally, the tempered martensite has a low carbon content, i.e. an average C content strictly lower than the average C content in the steel.

Preferably, the surface fraction of tempered martensite in the microstructure of the head 12 is comprised between 14.5% and 22.5%.

The head 12 of the rail 10 has a hardness of at least 420 HB, generally comprised between 430 HB and 470 HB, a tensile strength of at least 1300 MPa, generally comprised between 1300 MPa and 1450 MPa, a yield strength of at least 1000 MPa, generally comprised between 1000 MPa and 1150 MPa, and a total elongation of at least 13%, generally comprised between 13% and 18%.

The manufacturing of the rail 10 according to the invention can be done by any suitable method.

A preferred method to produce such rail comprises a step of casting a steel so as to obtain a semi-product, said steel having the above chemical composition.

The method further comprises a step of hot rolling the semi-product into a hot rolled semi-product having the shape of the rail 10 and comprising a head 12, with a final rolling temperature T_{FRT} higher than Ar3.

Preferably, during the step of hot rolling the semi-product, the semi-product is hot rolled from a hot rolling starting temperature higher than 1080°C, preferably higher than 1180°C.

For example, before hot-rolling, the semi-product is reheated to a temperature comprised between 1150°C and 1270°C and then hot rolled.

After finishing hot rolling, the rail 10 is passed preferably throughout an induction furnace. This allows avoiding austenite decomposition.

The method for manufacturing a rail 10 comprises then the cooling of the head 12 of the hot rolled semi-product from the final rolling temperature T_{FRT} down to a cooling stop temperature T_{CS} comprised between 200°C and 520°C, such that the temperature of the head 12 of the hot rolled semi-product over time is comprised between a upper boundary and a lower boundary, depicted on Figure 2, the upper boundary having the coordinates of time and temperature defined by A1 (0 second, 780°C), B1 (50 seconds, 600°C), and

C1 (110 seconds, 520°C), the lower boundary having the coordinates of time and temperature defined by A2 (0 second, 675°C), B2 (50 seconds, 510°C), and C2 (110 seconds, 300°C).

The cooling stop temperature T_{CS} is the temperature at which the cooling is stopped.

In a first embodiment, the cooling stop temperature T_{CS} is comprised between 300°C and 520°C.

In this embodiment, the head may reach the cooling stop temperature T_{CS} before or after reaching a point comprised between the points C1 and C2 defined above.

In a second embodiment, the cooling stop temperature T_{CS} is comprised between 200°C and 300°C. In this embodiment, during the cooling, after reaching a point comprised between the points C1 and C2, the head 12 is further cooled to the cooling stop temperature T_{CS}. During the cooling to the cooling stop temperature T_{CS}, a partial transformation of the austenite to bainite and martensite occurs.

If the head 12 of the hot rolled semi-product is cooled such that its temperature over time is higher than the upper boundary, ferrite and pearlite will form and carbides will precipitate upon cooling, so that the desired structure will not be obtained.

If the head 12 of the hot rolled semi-product is cooled such that its temperature over time is lower than the lower boundary, a too high martensite fraction and an insufficient fraction of bainite will be obtained.

More specifically, during this step of cooling the head 12 of the hot rolled semi-product, the entire hot rolled semi-product is cooled such that the temperature of the hot rolled semi-product over time is comprised between the upper boundary and the lower boundary.

The step of cooling the head 12 of the hot rolled semi-product is preferably performed through water jets. Such water jets allow achieving fast cooling rates and controlled heat release and recovery temperatures.

After this step of cooling, the method comprises a step of maintaining the head 12 of the hot rolled semi-product in a temperature range comprised between 300°C and 520°C during a holding time t_{hold} of at least 12 minutes, the holding time t_{hold} being advantageously comprised between 15 min and 23 min.

Preferably, the entire hot rolled semi-product is maintained in a temperature range comprised between 300°C and 520°C during said holding time t_{hold}.

During this step of maintaining, the transformation of the austenite to bainite is completed.

Besides, carbon partitions from the martensite to the austenite, thus stabilizing austenite and tempering the martensite.

If the holding time t_{hold} in the temperature range comprised between 300°C and 520°C is lower than 12 minutes, an insufficient fraction of bainite is formed, so that a too important transformation of the austenite into martensite will occur during the subsequent cooling to room temperature.

For example, the head 12 is held at a holding temperature T_{hold} comprised between 300°C and 520°C.

If the cooling stop temperature is comprised between 300°C and 520°C, the step of maintaining the head 12 in the temperature range comprised between 300°C and 520°C for the holding time t_{hold} is for example performed immediately after the cooling to the cooling stop temperature T_{CS}. In addition, the holding temperature T_{hold} is higher than or equal to the cooling stop temperature T_{CS}.

If the cooling stop temperature is comprised between 200°C and 300°C, the method further comprises, after the cooling of the head to the cooling stop temperature T_{CS} and before the step of maintaining the head in the temperature range, a step of heating the head of the hot rolled semi-product up to a temperature comprised between 300°C and 520°C. In such case, the holding temperature T_{hold} is higher than the cooling stop temperature T_{CS}.

After the maintaining of the head 12 in the temperature range comprised between 300°C and 520°C, the hot rolled semi-product is cooled down to room temperature to obtain the rail 10. The hot rolled semi-product is cooled down to room temperature, preferably through air cooling, and in particular through natural air cooling.

Advantageously, after cooling, the rail 10 has a microstructure consisting of, in surface fractions:

- 49% to 67% of bainite,
- 14% to 25% of retained austenite, and
- 13% to 34% of tempered martensite.

The bainite can include granular bainite and carbide free bainite. Preferably, the surface fraction of bainite in the microstructure of the head 12 is higher than or equal to 56%.

The retained austenite and the tempered martensite are generally present as M/A constituents, located between the laths or plates of bainite.

The austenite is also contained in the bainite between the laths or plates of bainite.

The retained austenite has an average carbon content comprised between 0.80% and 1.44%, preferably higher than 1.3%.

Preferably, the surface fraction of retained austenite in the microstructure of the head 12 is comprised between 18% and 23%.

The tempered martensite is contained in the bainite between the laths or plates of bainite, and in the M/A components.

The martensite is tempered martensite and preferably self-tempered martensite. Generally, the martensite has a low carbon content, i.e. an average C content strictly lower than the average C content in the steel.

Preferably, the surface fraction of tempered martensite in the microstructure of the head 12 is comprised between 14.5% and 22.5%.

The head 12 of the rail 10 has a hardness comprised between 430 HB and 470 HB, a tensile strength comprised between 1300 MPa and 1450 MPa, a yield strength comprised between 1000 MPa and 1150 MPa, and a total elongation comprised between 13% and 18%.

Optionally, the method may further comprise finishing steps, and in particular machining or surface treatment steps, performed for example after cooling down the hot rolled semi-product to room temperature. The surface treatment steps may in particular be a shot peening treatment.

Examples

The inventors of the present invention have carried out the following experiments.

Steels with composition according to Table 1, expressed by weight, were provided under the form of semi-product.

Steel	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Mo (%)	N (ppm)	O (ppm)	H (ppm)
523513-L*	0.300	1.50	1.10	0.017	0.009	1.99	0.12	50	-	1.5
523514-L	0.318	1.52	1.11	0.017	0.011	1.97	0.02	56	-	1.6

Table 1

The semi-products were hot-rolled into hot rolled semi-products having the shape of the rail, with a final rolling temperature T_{FRT} higher than Ar3, then cooled from the final rolling temperature T_{FRT} down to a cooling stop temperature T_{CS}, with a cooling rate such that, from a temperature T0 at an initial cooling time t0=0 s, the hot rolled semi-products reached a temperature T_{50} after 50 s of cooling, and then a temperature T_{110} after 110 s of cooling.

The heads of the rails were then maintained in a temperature range comprised between 300°C and 520°C, at a temperature T_{hold} equal to the cooling stop temperature T_{CS} during a holding time t_{hold}.

The rails were finally cooled down to the room temperature.

The manufacturing conditions of the rails are summarized in Table 2 below.

	Steel	T_{FRT} (°C)	T0 (°C)	T_{50} (°C)	Average cooling rate between T0 and T1 (°C/s)	T_{110} (°C)	Average cooling rate between T1 and T_{CS} (°C/s)	T_{CS} (°C)	t_{hold} (min)
523513-Y208	523513-L*	998	750	592	3.2	481	1.9	434	18
523513-Y308	523513-L*	1012	754	572	3.6	446	2.1	429	20
523514-A208	523514-L	1003	751	563	3.8	467	1.6	423	23

Table 2

Chemical Composition:

Samples for chemical analysis were obtained from tensile test sample location as stated in 9.1.3 in of EN 13674-1:2011, and then polished and analysed by spark emission spectroscopy to determine the average weight percentage (wt %). In addition, several pins of 1 g were extracted, degreased and subjected to a combustion trace elemental analysis to find out the percentage of N, O, S and C in a LECO C/S & LECO N/O analyzer. Hydrogen was also analyzed by IR-absorption. The chemical composition of the steels is shown below in Table 3.

Sample	wt. %							ppm		
	C	Si	Mn	P	S	Cr	Mo	N	O	H
523513-Y208	0.34	1.59	1.09	0.020	0.014	2.07	0.05	65.8	29.1	1.8
523514-A208	0.34	1.58	1.09	0.019	0.016	2.04	0.01	63.9	10.6	1.5
523513-Y308	0.3	1.59	1.1	0.017	0.011	2.05	0.06	NA	NA	NA

Table 3

Fatigue test:

Fatigue samples were extracted from the head of the rail and machined according to ASTM E606-12.

The fatigue tests were performed at room temperature in a hydraulic universal testing machine INSTRON 8801, in strain control with "peak to peak" amplitude of 0.00135 µm. The waveform used was a sine wave, with a symmetrical strain of +0.000675 µm in tension and a strain of -0.000675 µm in compression. The run-out was 5 million cycles, stopping the test at this value.

Three replicates were tested on each sample.

The run-out was 5 million cycles, stopping the test at that value.

Sample	Reps	Cycles (Test stopped at
523513Y208	1	Run out ($5 \cdot 10^6$ cycles)
	2	
	3	
523514A208	1	Run out ($5 \cdot 10^6$ cycles)
	2	
	3	
523513Y308	1	Run out ($5 \cdot 10^6$ cycles)
	2	
	3	

Table 4

Microstructure - Optical microscopy:

Metallographic samples were obtained from rail head according with Clause 9.1.4 in EN 13674-1:2011.

The metallographic samples were grinded, polished and etched with Nital 2% to reveal the microstructure of the rail samples. Microscopic observation was carried out using a Leica DMi4000 microscope.

The overall microstructure appearance in the whole rail head is fully bainitic, i.e. consists of laths or plates of bainite, and martensite and austenite dispersed between the laths or plates of bainite, for all the samples. The nature of the microstructure was analyzed in more detail by high resolution scanning electron microscopy and XR-Diffraction.

Characterization of the microstructure by XR-Diffraction and High Resolution Scanning Electron Microscopy:

A detailed analysis was performed on the sample 523513Y208. Electron microscopy analysis was done by means of a high resolution field-emission gun electron microscope (FEG-SEM) Zeiss Ultra Plus. Diffraction tests were performed on X-ray diffractometer Bruker D8 Advance using CuKα radiation.

Austenite content and its carbon content were measured by XRD following the recommendations of ASTM E975 standard.

The content of the M/A constituent was obtained by manual points count method on SEM images according to ASTM E562 standard. The martensite content is then determined by subtracting from the content of M/A constituent the content of retained austenite measured by XRD. The balance to 100% consists of bainite.

The microstructure comprises 61.3 % of bainite, 20.20 % of retained austenite with a carbon content of 1.38 % and 18.5 % of martensite.

Hardness:

On the one hand, Brinell hardness was evaluated at the rail head rolling surface in compliance with Clause 9.1.8 in EN 13674-1:2011 (mean value out of three measurements).

On the other hand, Brinell hardness was evaluated on cross-section of the rail and using an automatic durometer Leco LV700AT.

Table 5 shows averages values of hardness test in rolling surface (RS) and on different points of the cross section.

Sample	RS	Point 1			Point 2		Point 3	Point 4	
		Left	Centre	Right	Left	Right	Centre	Left	Right
523513 / 208	430	417	438	426	429	432	420	412	420
523514 / 208	431	429	432	420	426	420	426	426	420
523513 / 308	434	461	443	441	440	442	435	433	461

Table 5

Tensile Test:

According to Clause 9.1.9 in EN 13674-1:2011 tensile test was carried out in accordance to ISO 6892-1 using proportional circular test pieces of 10 mm diameter. Test samples (D_0=10 mm, L_0=50 mm) were extracted and tested using an Instron 600DX universal mechanical testing machine.

Three replicates were tested for each sample.

Table 6 shows the results for yield strength (YS), tensile strength (TS) and elongation (A_{50}).

Sample	YS (MPa)	TS (MPa)	A_{50} (%)
523513 / Y208	1089	1440	14
523514 / A208	1098	1452	14
523514 / Y308	1052	1442	14

Table 6

Linear thermal expansion coefficient (LTEC):

LTEC was measured in the rolling direction of the rail. Test samples (4 mm diameter and 10 mm length) were extracted from the tensile sample centre location and coefficient of thermal expansion was evaluated from -70ºC to 70ºC at 2 ºC/min by high resolution dilatometry (BAHR 805A/D).

Relative length change (dL/L_0) and the coefficient of thermal expansion (CTE) for one of the three heating runs performed are depicted in Figure 3.

Next, the technical LTEC, using 25 ºC as reference temperature, is shown in Table 7.

Grade / Heat / Rail	$LTEC_{25/50}$	$LTEC_{25/0}$	$LTEC_{25/-25}$	$LTEC_{25/-50}$
BAM 60E2 / 523513 / Y208	15.1	14.5	11.3	12.0
BAM 60E2 / 523514 / A208	14.6	14.4	11.2	11.9

Table 7

CLAIMS

1.- Method for manufacturing a rail comprising a head, the method comprising the following successive steps:

- casting a steel so as to obtain a semi-product, said steel having a chemical composition comprising, by weight percent:

$$0.20\% \leq C \leq 0.60\%,$$
$$1.0\% \leq Si \leq 2.0\%,$$
$$0.60\% \leq Mn \leq 1.60\%,$$
$$\text{and } 0.5 \leq Cr \leq 2.2\%,$$

the remainder being Fe and unavoidable impurities resulting from smelting;

- hot rolling the semi-product into a hot rolled semi-product having the shape of the rail and comprising the head, with a final rolling temperature T_{FRT} higher than Ar3;
- cooling the head of the hot rolled semi-product from the final rolling temperature T_{FRT} down to a cooling stop temperature T_{CS} comprised between 200°C and 520°C, such that the temperature of the head of the hot rolled semi-product over time is comprised between a upper boundary and a lower boundary, the upper boundary having the coordinates of time and temperature defined by A1, B1, and C1, the lower boundary having the coordinates of time and temperature defined by A2, B2, and C2;

wherein A1 corresponds to the coordinates 0 second, 780°C,
B1 corresponds to the coordinates 50 seconds, 600°C,
C1 corresponds to the coordinates 110 seconds, 520°C,
A2 corresponds to the coordinates 0 second, 675°C,
B2 corresponds to the coordinates 50 seconds, 510°C,
C2 corresponds to the coordinates 110 seconds, 300°C;

- maintaining the head of the hot rolled semi-product in a temperature range comprised between 300°C and 520°C during a holding time t_{hold} of at least 12 minutes, and;
- cooling down the hot rolled semi-product to room temperature to obtain the rail.

2.- Method according to claim 1, wherein the microstructure of the head of the rail consists of, in surface fraction:

- 49% to 67% of bainite;

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- 14% to 25% of retained austenite, the retained austenite having an average carbon content comprised between 0.80% and 1.44%;
- 13% to 34% of tempered martensite.

3.- Method according to claim 2, wherein the surface fraction of bainite in the microstructure of the head is higher than or equal to 56%.

4.- Method according to any one of claims 2 or 3, wherein the surface fraction of retained austenite in the microstructure of the head is comprised between 18% and 23%.

5.- Method according to any one of claims 2 to 4, wherein the surface fraction of tempered martensite in the microstructure of the head is comprised between 14.5% and 22.5%.

6.- Method according to any one of claims 2 to 5, wherein the average carbon content in the retained austenite is higher than 1.3%.

7.- Method according to any one of claims 1 to 6, wherein the cooling stop temperature T_{CS} is comprised between 300°C and 520°C.

8.- Method according to any one of claims 1 to 6, wherein the cooling stop temperature T_{CS} is comprised between 200°C and 300°C, and the method further comprises, after the step of cooling the head of the hot rolled semi-product down to the cooling stop temperature T_{CS} and before the step of maintaining the head in the temperature range, a step of heating the head of the hot rolled semi-product up to a temperature comprised between 300°C and 520°C.

9.- Method according to any one of claims 1 to 8, wherein, the step of cooling the head of the hot rolled semi-product is performed through water jets.

10.- Method according to any one of claims 1 to 9, wherein, during the step of cooling the head of the hot rolled semi-product, the entire hot rolled semi-product is cooled such that the temperature of the hot rolled semi-product over time is comprised between the upper boundary and the lower boundary.

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11.- Method according to any one of claims 1 to 10, wherein, during the step of hot rolling the semi-product, the semi-product is hot rolled from a hot rolling starting temperature higher than 1080°C.

12.- Method according to claim 11, wherein the hot rolling starting temperature is higher than 1180°C.

13.- Method according to any one of claims 1 to 12, wherein the chemical composition of the steel comprises, the content being expressed by weight percent:
0.30% ≤ C ≤0.60%.

14.- Method according to any one of claims 1 to 13, wherein the chemical composition of the steel comprises, the content being expressed by weight percent:
1.25% ≤ Si ≤ 1.6%.

15.- Method according to any one of claims 1 to 14, wherein the chemical composition of the steel comprises, the content being expressed by weight percent:
1.09% ≤ Mn ≤ 1.5%.

16.- Method according to any one of claims 1 to 15, wherein the chemical composition of the steel comprises, the content being expressed by weight percent, one or more elements chosen among:

0.01% ≤ Mo ≤ 0.3%,

0.01% ≤ V ≤ 0.30%.

17.- Steel rail, made of a steel having a chemical composition comprising, by weight percent:

0.20% ≤ C ≤ 0.60%,

1.0% ≤ Si ≤ 2.0%,

0.60% ≤ Mn ≤ 1.60%,

and 0.5≤ Cr ≤ 2.2%,

the remainder being Fe and unavoidable impurities resulting from smelting;
the steel rail comprising a head having a microstructure consisting of, in surface fraction:

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49% to 67% of bainite,
14% to 25% of retained austenite, the retained austenite having an average carbon content comprised between 0.80% and 1.44%,
13% to 34% of tempered martensite.

18.- Steel rail according to claim 17, wherein the surface fraction of bainite in the microstructure of the head of the rail is higher than 56%.

19.- Steel rail according to any one of claims 17 or 18, wherein the surface fraction of retained austenite in the microstructure of the head of the rail is comprised between 18 % and 23%.

20.- Steel rail according to any one of claims 17 to 19, wherein the surface fraction of tempered martensite in the microstructure of the head of the rail is comprised between 14.5% and 22.5%.

21.- Steel rail according to any one of claims 17 to 20, wherein the average carbon content in the retained austenite is higher than 1.3%.

22.- Steel rail according to any one of claims 17 to 21, wherein the chemical composition of the steel comprises, the content being expressed by weight percent:
$0.30\% \leq C \leq 0.6\%$.

23.- Steel rail according to any one of claims 17 to 22, wherein the chemical composition of the steel comprises, the content being expressed by weight percent:
$1.25\% \leq Si \leq 1.6\%$.

24.- Steel rail according to any one of claims 17 to 23, wherein the chemical composition of the steel comprises, the content being expressed by weight percent:
$0.9\% \leq Mn \leq 1.5\%$.

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25.- Steel rail according to any one of claims 17 to 24, wherein the chemical composition of the steel further comprises, the content being expressed by weight percent, one or more elements chosen among:

$$0.01\% \leq Mo \leq 0.3\%,$$

$$0.01\% \leq V \leq 0.30\%.$$

26.- Steel rail according to any one of claims 17 to 25, wherein the head of the rail has a hardness comprised between 420 HB and 470 HB.

27.- Steel rail according to claim 26, wherein the head of the rail has a hardness higher than 450 HB.

28.- Steel rail according to any one of claims 17 to 27, wherein the head of the rail has a tensile strength comprised between 1300 MPa and 1450 MPa.

29.- Steel rail according to any one of claims 17 to 28, wherein the head of the rail has a yield strength comprised between 1000 MPa and 1150 MPa.

30.- Steel rail according to any one of claims 17 to 29, wherein the head of the rail has a total elongation comprised between 13% and 18%.

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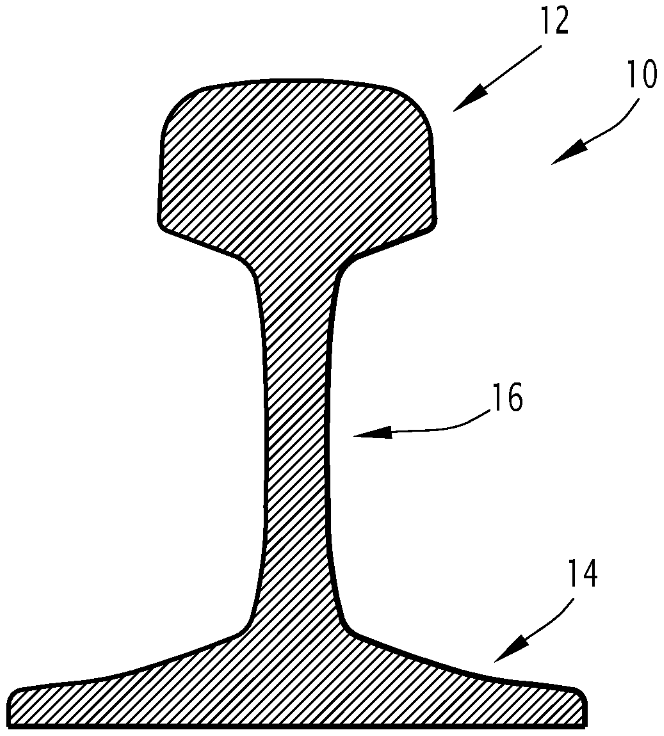


FIG.1

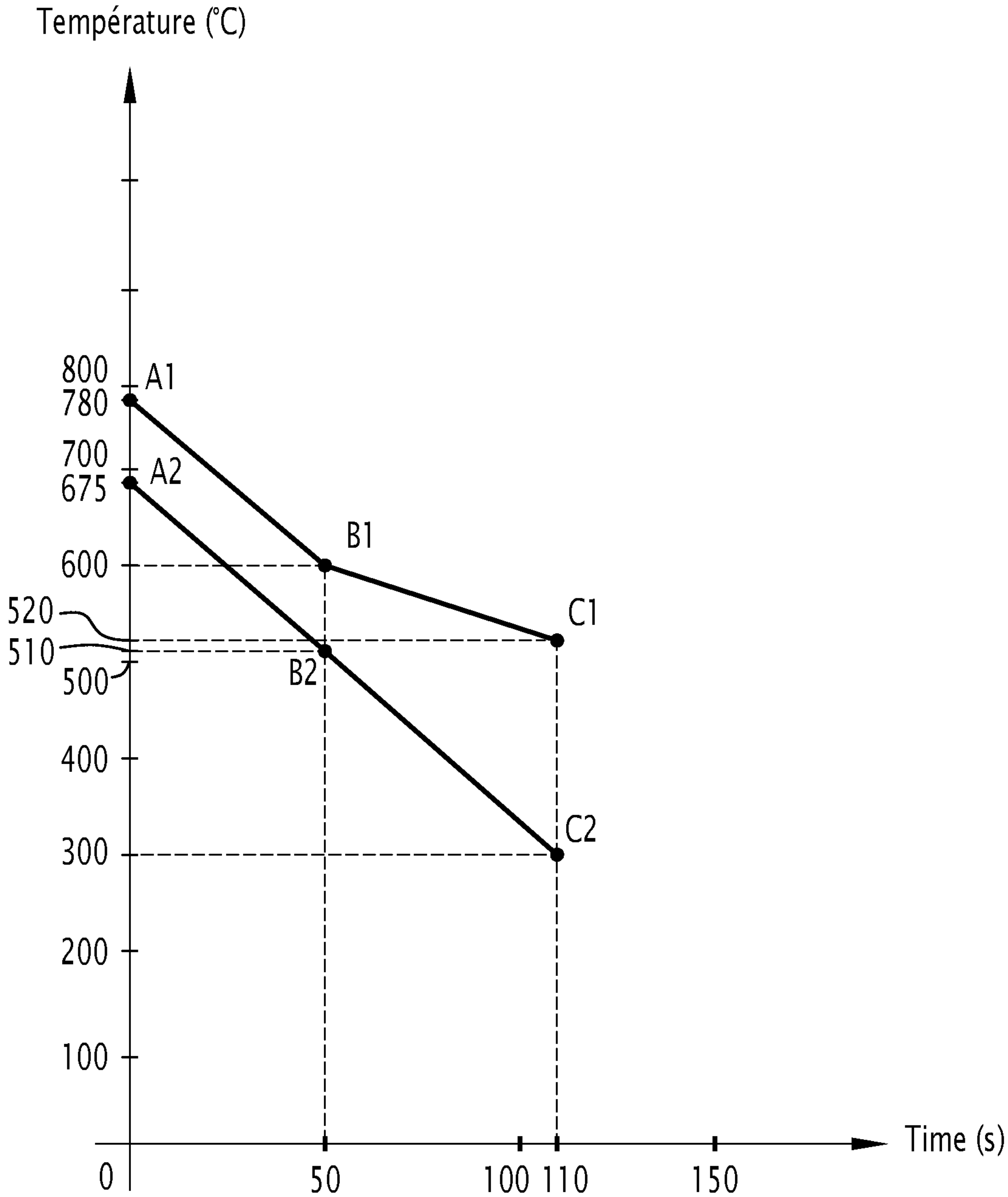

Température (°C)
800
780
A1
700
675
A2
600
B1
520
510
500
B2
C1
400
300
C2
200
100
0
50
100
110
150
Time (s)

FIG.2

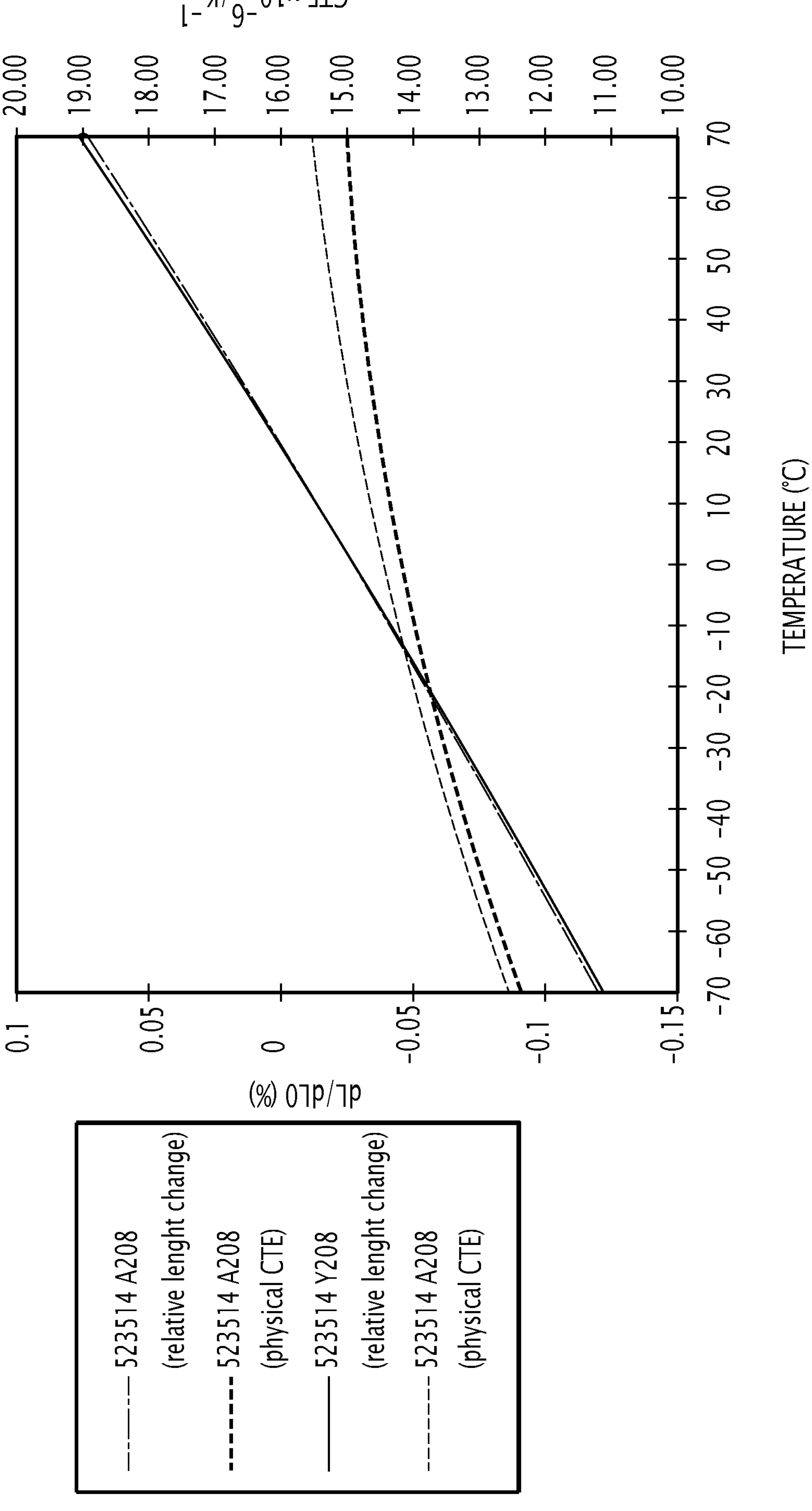
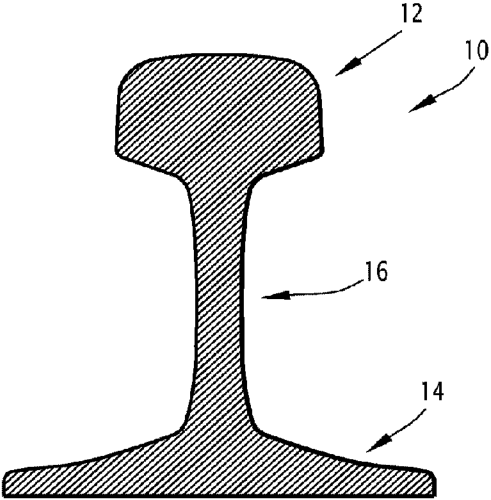

CTE x10^-6/K^-1
20.00
19.00
18.00
17.00
16.00
15.00
14.00
13.00
12.00
11.00
10.00
dL/dL0 (%)
0.1
0.05
0
-0.05
-0.1
-0.15
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
TEMPERATURE (°C)
523514 A208 (relative lenght change)
523514 A208 (physical CTE)
523514 Y208 (relative lenght change)
523514 A208 (physical CTE)

FIG.3



12
10
16
14