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(54) RAIL STEEL WITH AN EXCELLENT COMBINATION OF WEAR PROPERTIES, ROLLING CONTACT FATIGUE RESISTANCE AND WELDABILITY

SCHIENENSTAHL MIT HERVORRAGENDER KOMBINATION AUS VERSCHLEISSEIGENSCHAFTEN, ERMÜDUNGSBESTÄNDIGKEIT UND SCHWEISSBARKEIT

ACIERS POUR RAILS AVEC EXCELLENTE COMBINAISON DE PROPRIÉTÉS D'USURE, DE RÉSISTANCE À LA FATIGUE EN CONTACT ROULANT ET DE SOUDABILITÉ

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(56) References cited:
EP-A2- 1 241 277
WO-A1-02/08482
WO-A1-2009/103565
US-A- 4 895 605
US-A- 5 830 286
US-A- 5 899 516
US-A1- 2009 051 182
US-A1- 2009 134 647

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Description

[0001] This invention relates to a rail steel, particularly for use as a grooved rail such as those used for tramway track, having an excellent combination of properties, in particular, the resistance to both wear and rolling contact fatigue and at the same time being capable of being weld restored without the need for high temperature preheat.

[0002] Cost effectiveness of rail transport has become a significant issue in recent years. Replacing an embedded rail in a tramway network causes service disruptions; not only for the rail traffic, but also for other users of the shared infrastructure as such networks are installed in city centres. Tramway networks are often characterised by very tight track radii that inevitably experience high rates of side wear and hence can be the factor dictating rail life. Thus a key first requirement of a cost effective rail steel grade for tramway applications is its ability to be weld restored without the need for high temperature preheat that damages the surrounding polymer in which the rail is embedded. However, even with this attribute, the factor determining the life of the rail is the rate of vertical head wear and hence the second key requirement of a cost effective rail steel grade is its wear resistance. Moreover, increasing passenger numbers mean that rail traffic has become more intense over the years, causing more wear of the rails. Further improvements in rail material properties are required to make them more tolerant and resistant to the damage resulting from the increased stresses and stress cycles imposed. Although developments in rail metallurgy and heat treatment technology have refined the pearlitic microstructure to increase wear resistance, the need for greater reductions in life cycle costs continues to drive further improvements in the metallurgy of rails.

[0003] Another rail degradation mechanism often encountered on tramway and metro networks is railhead corrugation. Although the development of corrugation is influenced by a variety of system characteristics, it is widely acknowledged that an increase in hardness and yield strength of rail steels slows down the development and growth of corrugation. Consequently a third requirement of cost effective rail steel for tramways and metro networks is an increase in hardness and yield strength.

[0004] US2009/0134647 refers to a railroad wheel steel with a pearlitic structure, and contains (in weight%) carbon (0.65-0.80), silicon (0.90-1.10), manganese (0.85-1.15), phosphorus (0.001-0.030), niobium (0.009-0.013), sulfur (0.005-0.040) and remainder of iron and unavoidable impurities. The steel further contains chromium (0.10-0.25), nickel (0.050-0.150), molybdenum (0.20-0.30) and vanadium (0.10-0.30).

[0005] In straight and gently curved parts of railroads where the experienced rates of wear are generally lower, rail life and associated maintenance costs are also dictated by the need to control the initiation and growth of Rolling Contact Fatigue (RCF) cracks whose origins are either at, or very close to, the rail head surface. RCF can occur in various forms but are commonly referred to as Head Checks (HC), Gauge Corner Cracking (GCC), or as Squat defects. Hence, a fourth requirement of cost effective rail steel for tramways and metro networks is its resistance to the initiation of Rolling Contact Fatigue (RCF).

[0006] Optimisation of wheel and rail profiles to minimise the damaging stresses and the use of regular grinding to maintain the desired profiles while, at the same time, removing the remaining damaged surface layers has become the proven method of control for RCF and corrugation affected track. However, the cost of rail grinding is high and it consumes the time available for running scheduled services. Hence the driver for the development of a more cost effective metallurgical solution remains.

[0007] In addition to the improved resistance to wear, RCF, and corrugation, a further requirement for the design of a novel rail steel is the ability to be repeatedly weld restored in-situ as a mitigation measure to the high rates of side wear experienced in tight curves of tramway networks. The low preheat weld restoration technology, as laid down in Tata Steel patent GB2443494, provides a proven methodology of repeated weld restoration of high carbon steels. However, the use of this technique imposes two key metallurgical requirements of an upper limit on the Martensite start (M_s) temperature of less than 200°C and that on Martensite finish (M_f) temperature of not greater than 50°C and preferably much less. Thus the composition of the new rail steel needs to be designed to not only meet the requirements of resistance to wear, RCF, and corrugation but also to ensure that the transformation to martensite occurs over such a range that it prevents completion of transformation when using the low preheat weld restoration technology. The critical success factor for such a weld restoration process is the absence of any hard brittle microstructure or incipient cracks within the weld metal, weld metal-parent rail interface, or within the heat affected zone, all of which would subsequently lead to spalling of the deposit from the propagation of the incipient cracks through fatigue.

[0008] Therefore it is an object of this invention to provide high-strength rails that are highly resistant to wear, rolling contact fatigue, and corrugation while retaining the ability to be repeatedly weld restored.

[0009] It is also an object to provide high-strength rails in which side wear can be easily and robustly restored in-situ by means of a weld deposition treatment.

[0010] It is also an object to provide high-strength rails with a hardness of at least 330 HV, a tensile strength of at least 1000 MPa and yield strength of at least 600MPa.

[0011] One or more of the objects of the invention was achieved with a high-strength pearlitic rail steel having an excellent combination of wear properties, rolling contact fatigue resistance and weld restorability, containing (in weight %):

- 0.70% to 0.85% carbon,
- 0.65% to 1.00% silicon,
- 1.1% to 1.4% manganese,
- 0.07% to 0.15% vanadium,
- up to 0.008% nitrogen,
- up to 0.025% phosphorus,
- 0.008 to 0.030% sulphur,
- at most 2.5 ppm hydrogen,
- at most 0.10% chromium,
- at most 0.010% aluminium,
- at most 20 ppm oxygen,
- the remainder consisting of iron and unavoidable impurities.

[0012] The efficacy of the chemical composition of steels according to the invention is best demonstrated through an explanation of the reasons for the addition of various elements and comparison of the key properties for grooved rail steels.

[0013] Carbon is the most cost effective strengthening alloying element in rail steels as it provides the most cost effective addition to achieve the hardness and strength in fully pearlitic steels. In an embodiment the maximum value of carbon is 0.8%. This reduces the risk of formation of a cementite network at the grain boundaries. More preferably the range of carbon content is from 0.735% to 0.785%. This range provides the optimal balance between the volume fraction of hard cementite and the prevention of the formation of a deleterious network of embrittling cementite at grain boundaries. Carbon is also a potent hardenability agent that facilitates a lower transformation temperature and hence finer interlamellar spacing. The high volume fraction of hard cementite and fine interlamellar spacing provides the wear resistance and contributes towards the increased RCF resistance of the composition included in an embodiment of the invention. Furthermore, as demonstrated by the Tata Steel low preheat weld restoration process[1], it is essential to lower the Martensite Start (Ms) temperature of the steel to ensure a robust weld deposit. The prescribed range of carbon is essential to achieve this objective. The following widely accepted methodologies for the calculation of M_s temperature, clearly identify the efficacy of carbon in reducing the magnitude of this parameter. In effect, carbon is between 13 to 17 times more potent in reducing the M_s temperature compared to manganese. According to Andrews (J. Iron & Steel Inst., 183 (1965), pp. 721-727) the M_s Temperature in °C is given by 539 - 423 x % Carbon - 30.4 x % Mn (eq. 1'a) and according to Steven and Haynes (J. Iron & Steel Inst., 183 (1956), pp. 349-359) by 561 - 474 x % Carbon - 33 x % Mn (eq. 1 b). Both regression equations provide slightly different values for M_s. In the context of this invention the average value of these two equations was used as a the approximation of the actual M_s. M_f is then determined from M_s by subtracting 150°C from M_s.

$$M_s\ (°C) = 0.5 \times (M_{s,\ Andrews} + M_{s,\ Stevens\&Haynes}) \qquad \text{<eq. 1>}$$

$$M_f\ (°C) = M_s - 150 \qquad \text{<eq. 2>}$$

[0014] It is preferable that the Martensite Start (M_s) temperature of the steel is below about 160°Cto ensure a robust weld deposit.

[0015] In this invention the addition of Silicon is an integral and essential part of the design of the steel to engineer the resulting microstructure and properties and not, as in most other rail steels, a reflection of the manufacturing process route rather than an intentional alloying addition. Silicon is often used as a deoxidising element and as such the addition of silicon is usually intended for that purpose only. As the invention refers to a broadly eutectoid composition, the microstructure contains little or no proeutectoid ferrite. Instead it is primarily the interlamellar spacing of the pearlite that dictates the resulting properties. Traditionally, the refinement of the pearlitic microstructure in grooved rail compositions has been achieved trough the use of accelerated cooling. The novelty of the approach in this invention is to treat the pearlitic microstructure as a three-dimensional entity in which the behaviour at the wheel-rail interface is governed by the properties of the two components of pearlite, ferrite and cementite laths, rather than just the bulk properties of hardness and tensile strength. Consequently, the novelty in this invention lies in the use of silicon to strengthen the pearlitic ferrite through solid solution strengthening which in turn imparts an increased resistance to ratchetting, wear, and rolling contact fatigue. A minimum Silicon content of 0.65% is essential for the steel according to the invention to attain the required mechanical property values, wear resistance and RCF resistance. Although Silicon additions have a very limited effect on hardenability of steel and this is reflected in the equations for the calculation of M_s temperature, the addition of up to 1.0% Silicon is acknowledged to make a small contribution to the lowering of the M_s temperature.

Silicon content between 0.65% and 0.80% was found to provide a good balance of the required mechanical properties without any adverse effect on weld restorability.

[0016] Manganese is a key alloying element in all grooved rail steels to provide the required hardenability to ensure a relatively fine interlamellar spacing following natural or accelerated cooling of such steels. This purpose remains valid for the current invention. In the current invention, which does not rely on accelerated cooling for its properties, a higher manganese content is considered desirable to impart sufficient hardenability to achieve a pearlitic microstructure with fine interlamellar spacing. A manganese content of less than 1.1 %Mn was found to be insufficient to achieve the desired hardenability at the chosen carbon content while at levels above 1.4%, the increased risk of formation of martensite, particularly in areas of segregation of manganese, was considered unacceptable. A higher level of manganese is also considered undesirable from a welding perspective because of the increased risk of formation of hard and embrittling martensite. In a preferable embodiment, the manganese content is at most 1.35%. A suitable minimum value for the manganese would be 1.20% or even 1.25%.

[0017] The efficacy of vanadium as a precipitation strengthening alloying element has been utilised in this invention to strengthen the pearlitic ferrite and thereby increase the resistance to ratchetting, wear, and rolling contact fatigue. Vanadium forms vanadium carbides or vanadium nitrides depending on the amount of nitrogen present in the steel and the temperature. Therefore, it is necessary to examine the level of vanadium addition together with the magnitude of nitrogen in the steel as the efficacy of precipitation strengthening in eutectoid pearlitic steels decreases with increasing levels of nitrogen, which leads to coarser precipitates of vanadium nitride at higher temperatures. Furthermore, such high temperature precipitates do not strengthen the pearlitic ferrite nor do they leave sufficient vanadium in solution to impart increased hardenability to achieve a finer interlamellar spacing. The additions of vanadium to eutectoid steels do not appreciably affect the M_s temperature. The inventors found that the proportion of vanadium precipitated as carbides was near maximum when the nitrogen content was restricted to 0.003% and this decreased proportionately with increasing nitrogen content. The knowledge of these metallurgical principles has been applied in an innovative manner to arrive at the ideal contents of 0.08% V with 0.003% Nitrogen. Hence, for reasons of cost effective manufacturability, minimum nitrogen content of 0.003% is considered a practical lower limit while a higher limit of 0.007% is considered desirable to ensure best returns from the additions of costly vanadium. However, although not desirable from the point of view of cost effectiveness, higher nitrogen contents could be tolerated provided they are accompanied by proportionately higher vanadium contents.

[0018] In an embodiment of the invention, the minimum amount of nitrogen is 0.003% coupled with minimum vanadium content of 0.07%. Preferably nitrogen is at most 0.007% while the corresponding figures for vanadium are 0.07% minimum and 0.12% maximum. Although these maximum contents could be exceeded, they are non-ideal and economically unattractive.

[0019] Because of the tailored additions of silicon, manganese and vanadium the aimed properties are achieved not only near the surface but also in the head bulk, with a high consistency. This consistency is difficult to achieve in a heat treated rail whereas in the steel according to the invention this consistency is achieved in the as-hot rolled rail. Higher strengths and/or yield strength and/or hardness can be achieved from this steel by subjecting it to accelerated cooling in an in-line or off-line heat treatment facility employing forced air, water, air mist, or polymer quenchants.

[0020] The wear resistance obtained with the steel according to the invention in the as-rolled condition, accelerated cooling condition or heat treated condition is such that this will reduce the need for the application of a preventive high cost hard facing for rails to be laid in tight curves.

[0021] Preferably, the phosphorus content of the steel is at most 0.015%. Suphur values must be between 0.008 and 0.030% because it forms MnS inclusions. These inclusions act as sinks for any residual hydrogen that may be present in the steel. This hydrogen can result in shatter cracks which can be the initiators of fatigue cracks in the head (also known as tache ovals) under the high stresses from the wheels. The addition of at least 0.008% sulphur prevents the deleterious effects of hydrogen, whereas a maximum value of 0.03% is chosen to avoid embrittlement of the structure. Preferably the maximum value is 0.025%. Boron, although not a mandatory alloying element, could be used to improve the properties of the steel according to the invention and amounts up to about 60 ppm could be used. Boron is a strong promoter of the formation of microstructural components such as bainite or martensite, particularly when the nitrogen in the steel is bound by titanium. If not, BN-precipitates may be formed. In the steel according to the invention it is important that the microstructure is substantially pearlitic and preferably fully pearlitic and that the amount of bainitic or martensitic microstructural components is kept as low as possible and preferably are absent. Preferably there is no boron in the steel according to the invention as an alloying elements, but it may be present as an inevitable impurity. A boron content of below 0.0005% (i.e. < 5ppm) is generally considered ineffective as an alloying element and is therefore considered as an impurity in the context of this application.

[0022] The maximum recommended level of unavoidable impurities are based on EN13674-I:2003, according to which the maximum limits are Mo 0.02%, Ni 0.10%, Sn - 0.03%, Sb - 0.020%, Ti - 0.025%, Nb - 0.01%.

[0023] The wear resistance of the steel from the current invention has been established employing the proven comparative "Twin Disk" testing procedure. The test is undertaken using a laboratory twin-disc facility similar to the facility described in 'Wear', 162-164 (1993), Microstructure and wear resistance of pearlitic rail steels, Albert J. Perez-Unzueta & John H. Beynon[5]. This equipment simulates the forces arising when the wheel is rolling and sliding on the rail. These assessments are not part of the formal rail qualification procedure but have been found to provide a good indicator as to the relative in-service performance of different rail steel compositions. The test conditions for wear testing involve the use of a 560 MPa contact stress and 25% slip while those for RCF utilise a higher contact stress of 900 MPa, 5% slip and water lubrication. The results are shown in Figure 1 where the wear rate in mg/m slip is plotted against the hardness (in HV).

[0024] It is apparent that wear rate decreases as a function of hardness and that beyond a hardness level of 330 Hv30 (~313HB), there is little or no measurable further reduction in the rate of wear. Consequently, one of the objects of the invention was to achieve the wear resistance equivalent to hardness level of at least 330 HV30. The optimised compositions of the invention in both the laboratory and commercial casts have achieved the desired wear resistance. The inventors have found that the balanced chemical composition produces very wear resistant pearlite as a result of the strengthening of the pearlitic ferrite through solid solution strengthening by silicon additions and very finely dispersed vanadium carbides within the pearlitic ferrite laths. Furthermore, by restricting the nitrogen to < 0.007%, the inventors have managed to capitalise on the well known potent hardenability effect of vanadium in solution which enhances the strength, hardness, and wear resistance of the optimised composition of the invention by refining the interlamellar spacing of the pearlite.

[0025] Although, the lower operational speed of tramways in embedded track makes them less susceptible to Rolling Contact Fatigue (RCF), the strengthening of the pearlitic ferrite resulting from the composition of the invention has also improved the resistance of the steel to RCF. An improvement of at least 20% in the resistance to RCF-initiation has been established through comparative laboratory twin disk testing of the composition of the invention and the standard R260 grade.

[0026] A number of factors come together to bring about these improvements. Firstly, increasing the carbon content with respect to the typical lower carbon rail steel grades for grooved rails whilst remaining within the hypo-eutectoid region of the iron-carbon phase diagram, increases the volume fraction of hard cementite in the microstructure. As the carbon content does not encroach into the hyper-eutectoid range of compositions, the risk of forming deleterious networks of embrittling cementite at grain boundaries under the relatively slow cooling experienced by rails during production is avoided. As an additional precautionary measure, the intentional additions of higher silicon and vanadium to the composition have been designed to prevent grain boundary cementite within the segregated portions of the rail section. These additions also have a second, and equally important, function. Silicon is a solid solution strengthener and increases the strength of the pearlitic ferrite, thereby increasing the resistance of the pearlite to both wear and RCF initiation. Similarly, the precipitation of fine vanadium carbides within the pearlitic ferrite increases its strength, in particular the proof strength, and thereby the resistance to both wear and RCF. A further feature of the compositional design is to limit the nitrogen content in order to prevent the premature formation of relatively coarse precipitates of vanadium nitride, as they are significantly less effective in increasing the strength of the pearlitic ferrite. This ensures that the vanadium additions remain in solution within the austenite to lower temperatures and, therefore, result in finer precipitates. A proportion of the vanadium also remains in solution, thereby acting as a hardenability agent to refine the pearlite spacing. Thus the specific design of the composition claimed in this embodiment utilises the various attributes of the individual elements to produce a microstructure with a highly desirable combination of wear and RCF resistance. The mechanical properties and the resistance to both wear and RCF initiation of the steels in accordance with the invention are better than most conventional heat treated pearlitic rail grades and similar to the hardest heat treated grade (Grade R340GHT) included in the Euro norm for grooved rails (EN 14811:2006 + A1: 2009). Although not essential for the current intended application of grooved rails for embedded street running track, further improvements to tensile properties and resistance to wear, plastic deformation, and RCF could be obtained by subjecting the compositions of the invention to accelerated cooling after hot rolling or follow up heat treatment employing a reheating stage.

[0027] Another and equally significant additional attribute of the steels in accordance with the invention is their ability to be weld restored without the need for high temperature preheat. The proprietary Tata Steel weld restoration process specifies low preheat temperatures of about 60°C to 80°C. The fundamental principle on which this process is based is the avoidance of the completion of transformation to martensite within the heat affected zone created by the deposited weld bead. Thus, in this invention, the design of the steel composition has had two challenging objectives: firstly to meet the property requirements described in preceding paragraphs and secondly to ensure the martensite start (M_s) and martensite finish (M_f) transformation temperatures are such that they do not permit the transformation to martensite to go to completion during the weld restoration process. Consequently, the M_f temperature, needs to be below about 60°C and preferably much below this temperature to maximise the volume of untransformed retained austenite that is key to the prevention of the formation of incipient cracks at the weld-parent metal interface or within the heat affected zone formed by the deposition of the weld bead. In general, the M_f temperature is considered to be about 150°C below the M_s temperature which can be calculated using the equations (1), (1a), (1b) and (2) as given above. The M_s and M_f temperature of a range of rail steels available is shown in Figure 2 against the required minimum hardness of the grade.

The temperatures are the average of those calculated by the two equations given in paragraph 0012 and the concentrations of carbon and manganese used in the calculations are the midpoint values of the range specified in EN 14811:2006 +A1: 2009. The M_s temperature is the upper value, the M_f temperature is the lower value of the depicted range.

[0028] It is apparent that the steel of this invention, referenced as "Invention" in figure 2, has the lowest M_f temperature and hence is capable of retaining the maximum proportion of austenite and therefore most resistant to the formation of incipient cracks. In contrast, the other grooved rail steel grades have undesirably higher M_f temperatures implying completion of martensite transformation during weld restoration and a much higher risk of the formation of cracks.

[0029] The excellent wear resistance of the rail ensures that it takes a long time before the rail is worn down in a vertical direction. The weld restorability and the fact that the steel according to the invention does not require a heat treatment to achieve its properties ensures that the rail can be repaired in situ, so the rail does not have to be taken out of the street but can be repaired overnight. This involves less road works and less inconvenience for inner city traffic. This combination of properties achievable by engineering the microstructure and the chemistry of the rail means that the rail is not only cost effective, but also provides a more ecological solution because rails can be easily repaired and do not have to be replaced by new rails as often. Moreover, careful compositional design, thereby eliminating the need for a heat treatment step during rail manufacture, also ensures a greener rail product in comparison with steels which derive their properties from a heat treatment after rolling the rail.

[0030] Although the steel according to the invention is suitable for purposes such as crane rails or flat-bottomed rails, it has been found that the rail steel is exceptionally suitable for the production of grooved rails that benefit from the combined key attributes of wear resistance and weld restorability.

[0031] Laboratory casts of steels C1-C4 and of the inventive steel A were produced as 60 kg ingots. Casts C1 to C4 are preliminary casts that were made to establish the balance amongst the sometimes conflicting requirements of achieving the required hardness, tensile properties, and the resulting wear resistance on one hand with the requirements of a low enough M_s temperature to ensure weld restorability using the low preheat process. The results from these investigations culminated firstly into a laboratory cast of the composition of cast A. The ingots were rolled to 30 mm thick plate and subjected to natural air cooling to accurately simulate the cooling conditions in the head of an as-rolled rail. A 300 t commercial BOS cast (steel B) was produced of the inventive steel based on the chemistry of lab cast A, and subsequently continuously cast to a 355 x 305 mm bloom section. The blooms were rolled to various rail sections and were allowed to cool on the rail cooling bank under the standard cooling conditions as for conventional as-rolled commercial rail grades. All rail lengths were produced free from any internal or surface breaking defects. The rails were tested in the as-hot-rolled condition.

[0032] The chemical compositions of steels A and B are given in Table 1. The comparative examples C1-C4 are also given in table 1.

Table 1: Chemical composition, wt%

Steel	C	Si	Mn	P	S	Cr	V	Al	N
A	0.76	0.76	1.23	0.016	0.012	0.04	0.08	< 0.005	49
B	0.76	0.75	1.22	0.018	0.013	0.03	0.09	< 0.005	32
C1	*0.61*	0.82	1.40	0.018	0.014	*0.62*	*< 0.01*	0.010	70
C2	0.72	0.83	*0.95*	0.016	0.011	<0.01	0.13	0.008	40
C3	*0.65*	0.72	1.25	0.015	0.013	<0.005	0.13	*0.012*	60
C4	*0.44*	0.70	1.21	0.015	0.010	<0.005	0.12	*0.014*	60

[0033] The hardness of the steels A and B was found to be between 330 and 335 HV30. The inventors found that by selecting a steel in the narrow chemistry window in accordance with the invention that both wear resistance and RCF resistance are excellent and match the performance of a heat treated Grade 350HT whilst showing similar mechanical properties. In comparison to some grades our inventive steels do not require heat treatment to obtain the desired properties.

Table 2: Hardness & tensile property data for the inventive steels and current pearlitic rail grades (R260 and R350HT).

Steel	Condition	0.2% PS (MPa)	TS (MPa)	El (%)	Hardness (HV30)
R260	As-rolled	494	907	12.5	290
R350HT	Heat treated	763	1210	14.0	375

(continued)

Steel	Condition	0.2% PS (MPa)	TS (MPa)	El (%)	Hardness (HV30)
A	As-rolled	646	1089	10.0	331
B	As-rolled	629	1100	9.8	335

Claims

1. Steel for the manufacture of rails, particularly of grooved rails, having a hardness of at least 330 HV30, a tensile strength of at least 1000 MPa and a yield strength of at least 600 MPa consisting of in weight %,

    - 0.70% to 0.85 carbon,
    - 0.65% to 1.00% silicon,
    - 1.1% to 1.4% manganese,
    - 0.07% to 0.15% vanadium,
    - up to 0.008% nitrogen,
    - up to 0.025% phosphorus,
    - 0.008 to 0.030% sulphur,
    - at most 2.5 ppm hydrogen,
    - at most 0.10% chromium,
    - at most 0.010% aluminium,
    - at most 20 ppm oxygen,
    - the remainder consisting of iron and unavoidable impurities.

2. Steel according to claim 1 wherein the martensite start transformation temperature (M_s) as determined by eq. 1 is below 190°C and wherein martensite finish transformation (M_f) according to eq. 2 is below 40°C.

$$M_s\ (°C) = 0.5 \times (M_{s,\ Andrews} + M_{s,\ Stevens\&Haynes}) \qquad \text{<eq. 1>}$$

$$M_{s,\ Andrews}\ (°C) = 539 - 423 \times \%\ Carbon - 30.4 \times \%\ Mn \qquad \text{<eq. 1a>}$$

$$M_{s,\ Stevens\&Haynes}\ (°C) = 561 - 474 \times \%\ Carbon - 33 \times \%\ Mn \qquad \text{<eq. 1b>}$$

$$M_f\ (°C) = M_s - 150 \qquad \text{<eq. 2>}$$

3. Steel according to claim 1 comprising a carbon content of at least 0.735%C, preferably of at least 0.75%.

4. Steel according to claim 1 or 2 comprising a manganese content of at least 1.20%.

5. Steel according to any one of claims 1 to 3 comprising a silicon content of at least 0.75%.

6. Steel according to any one of claims 1 to 5 comprising a combination of a vanadium content of at least 0.08% V and a nitrogen content of at most 0.005%.

7. Steel according to any one of claims 1 to 5 comprising a combination of a vanadium content of at least 0.10% V and a nitrogen content of at most 0.007%.

8. Steel according to any one of claims 1 to 7 wherein the martensite start transformation temperature as determined by eq. 1 is below 175°C and wherein martensite finish transformation according to eq. 2 is bellow 25°C.

9. Steel according to any one of claims 1 to 8 wherein heat affected zone of the weld restoration bead comprises at least 50% in volume of retained austenite.

10. Rail, such as grooved rail, crane rail or flat bottomed rail, made from the steel according to any one of claims 1 to 9 having a hardness of at least 330 HV, a tensile strength of at least 1000 MPa and a yield strength of at least 600 MPa.

Patentansprüche

1. Stahl zur Herstellung von Schienen, insbesondere von Rillenschienen, mit einer Härte von wenigstens 330 HV30, einer Zugfestigkeit von wenigstens 1000 MPa und einer Streckgrenze von wenigstens 600 MPa, bestehend aus (in Gewichtsprozent):

- 0.70 % bis 0.85 % Kohlenstoff,
- 0.65 % bis 1.00 % Silizium,
- 1.1 % bis 1.4 % Mangan,
- 0.07 % bis 0.15 % Vanadium,
- bis zu 0.008 % Stickstoff,
- bis zu 0.025 % Phosphor,
- 0.008 % bis 0.030 % Schwefel,
- höchstens 2.5 ppm Wasserstoff,
- höchstens 0.10 % Chrom,
- höchstens 0.010 % Aluminium,
- höchstens 20 ppm Sauerstoff,
- wobei der Rest aus Eisen und unvermeidbaren Verunreinigungen besteht.

2. Stahl nach Anspruch 1, wobei die gemäß Gl. 1 ermittelte Starttemperatur der Martensitumwandlung (M_s) unter 190 °C liegt und wobei die gemäß Gl. 2 ermittelte Endtemperatur der Martensitumwandlung (M_f) unter 40 °C liegt.

$$M_s\ (°C) = 0.5 \times (M_{s,\ Andrews} + M_{s,\ Stevens\&Haynes}) \qquad \text{<Gl. 1>}$$

$$M_{s,\ Andrews}\ (°C) = 539 - 423 \times \%\ \text{Kohlenstoff} - 30.4 \times \%\ \text{Mn} \qquad \text{<Gl. 1a>}$$

$$M_{s,\ Stevens\&Haynes}\ (°C) = 561 - 474 \times \%\ \text{Kohlenstoff} - 33 \times \%\ \text{Mn} \qquad \text{<Gl. 1b>}$$

$$M_f\ (°C) = M_s - 150 \qquad \text{<Gl. 2>}$$

3. Stahl nach Anspruch 1, umfassend einen Kohlenstoffgehalt von wenigstens 0.735 % C, bevorzugt wenigstens 0.75 %.

4. Stahl nach Anspruch 1 oder 2, umfassend einen Mangangehalt von wenigstens 1.20 %.

5. Stahl nach einem der Ansprüche 1 bis 3, umfassend einen Siliziumgehalt von wenigstens 0.75 %.

6. Stahl nach einem der Ansprüche 1 bis 5, umfassend eine Kombination aus einem Vanadiumgehalt von wenigstens 0.08 % V und einem Stickstoffgehalt von höchstens 0.005 %.

7. Stahl nach einem der Ansprüche 1 bis 5, umfassend eine Kombination aus einem Vanadiumgehalt von wenigstens 0.10 % V und einem Stickstoffgehalt von höchstens 0.007 %.

8. Stahl nach einem der Ansprüche 1 bis 7, wobei die gemäß Gl. 1 ermittelte Starttemperatur der Martensitumwandlung unter 175 °C liegt und wobei die gemäß Gl. 2 ermittelte Endtemperatur der Martensitumwandlung unter 25 °C liegt.

9. Stahl nach einem der Ansprüche 1 bis 8, wobei die Wärmeeinflusszone der Instandsetzungsschweißnaht wenigstens 50 Vol.-% Restaustenit umfasst.

10. Schiene, wie z. B. Rillenschiene, Kranschiene oder Vignolschiene, hergestellt aus dem Stahl nach einem der Ansprüche 1 bis 9 mit einer Härte von wenigstens 330 HV, einer Zugfestigkeit von wenigstens 1000 MPa und einer Streckgrenze von wenigstens 600 MPa.

Revendications

1. Un acier pour la fabrication de rails, en particulier de rails à gorge, avec une dureté minimale de 330 HV30, une résistance à la traction d'au moins 1000 MPa, et une limite élastique minimale de 600 MPa, et dont la composition en % de poids est la suivante :

- 0.70% à 0.85% de carbone,
- 0.65% à 1.00% de silicium,
- 1.1% à 1.4% de manganèse,
- 0.07% à 0.15% de vanadium,
- jusqu'à 0.008% d'azote,
- jusqu'à 0.025% de phosphore,
- de 0.008% à 0.030% de soufre,
- au maximum 2.5 ppm d'hydrogène,
- au maximum 0.10% de chrome,
- au maximum 0.010% d'aluminium,
- au maximum 20 ppm d'oxygène,
- le restant étant composé de fer et d'impuretés inévitables.

2. Un acier selon la revendication 1, dans lequel la température de départ de la transformation martensitique (M_s), déterminée par l'équation 1, est inférieure à 190°C, et la température de fin de la transformation martensitique (M_f), déterminée par l'équation 2, est inférieure à 40°C.

$$M_s\ (°C) = 0.5 \times (M_{s,\ Andrews} + M_{s,\ Stevens\ \&\ Haynes}) \qquad \text{< éq. 1>}$$

$$M_{s,\ Andrews}\ (°C) = 539 - 423 \times \%\ \text{de carbone} - 30.4 \times \%\ Mn \qquad \text{< éq. 1a>}$$

$$M_{s,\ Stevens\ \&\ Haynes}\ (°C) = 561 - 474 \times \%\ \text{de carbone} - 33 \times \%\ Mn \qquad \text{< éq. 1b>}$$

$$M_f\ (°C) = M_s - 150 \qquad \text{< éq. 2>}$$

3. Un acier selon la revendication 1, ayant une teneur en carbone d'au moins 0.735% C, de préférence au moins 0.75%.

4. Un acier selon la revendication 1 ou 2, ayant une teneur en manganèse d'au moins 1.20%.

5. Un acier selon une quelconque des revendications 1 à 3, ayant une teneur en silicium d'au moins 0.75%.

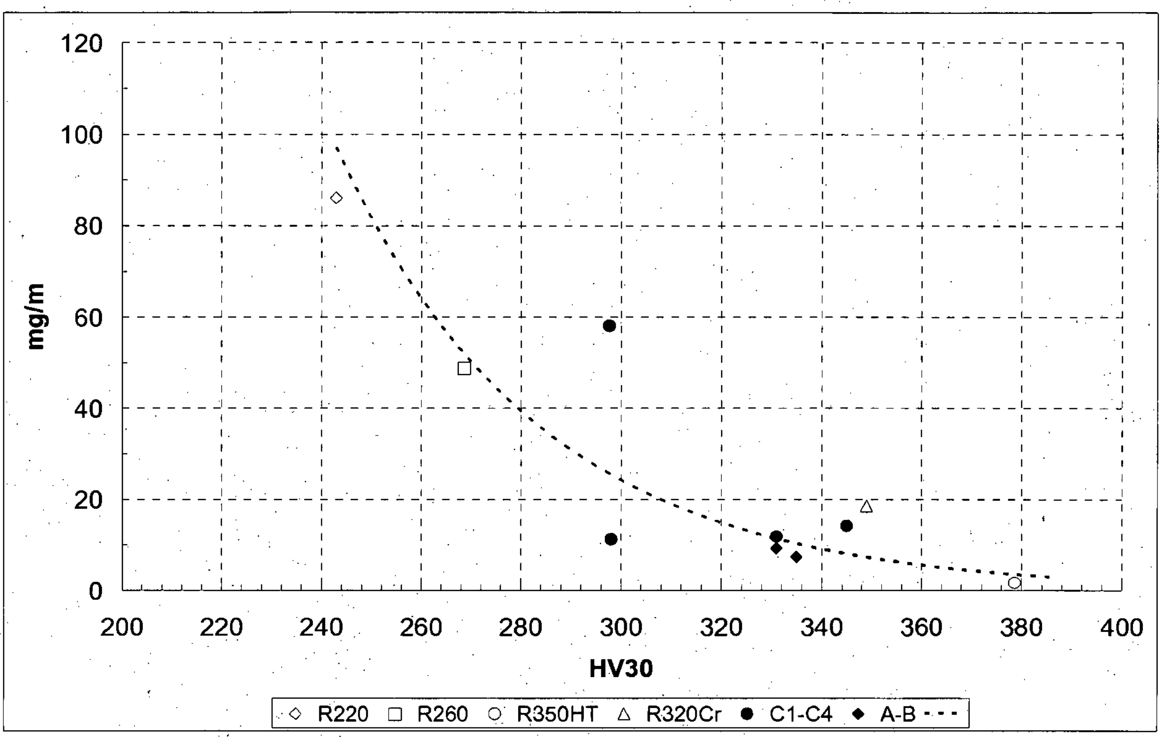
6. Un acier selon une quelconque des revendications 1 à 5, comprenant une combinaison d'une teneur en vanadium d'au moins 0.08% V et d'une teneur en azote d'au moins 0.005%.

7. Un acier selon une quelconque des revendications 1 à 5, comprenant une combinaison d'une teneur en vanadium d'au moins 0.10% V et d'une teneur en azote d'au moins 0.007%.

8. Un acier selon une quelconque des revendications 1 à 7, dans lequel la température de départ de la transformation martensitique, déterminée par l'équation 1, est inférieure à 175°C, et la température de fin de la transformation martensitique, déterminée par l'équation 2, est inférieure à 25°C.

9. Un acier selon une quelconque des revendications 1 à 8, dans lequel la zone affectée par la chaleur du cordon de restauration de soudure comprend au moins 50% d'austénite retenue.

10. Un rail, par exemple un rail à gorge, un rail pour grues, ou un rail Vignole, fabriqué en acier selon une quelconque des revendications 1 à 9, avec une dureté égale au moins à 330 HV, une résistance à la traction d'au moins 1000 MPa, et une limite élastique minimale de 600 MPa.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100
80
60
40
20
0
mg/m
200
220
240
260
280
300
320
340
360
380
400
HV30
R220
R260
R350HT
R320Cr
C1-C4
A-B

Figure 1

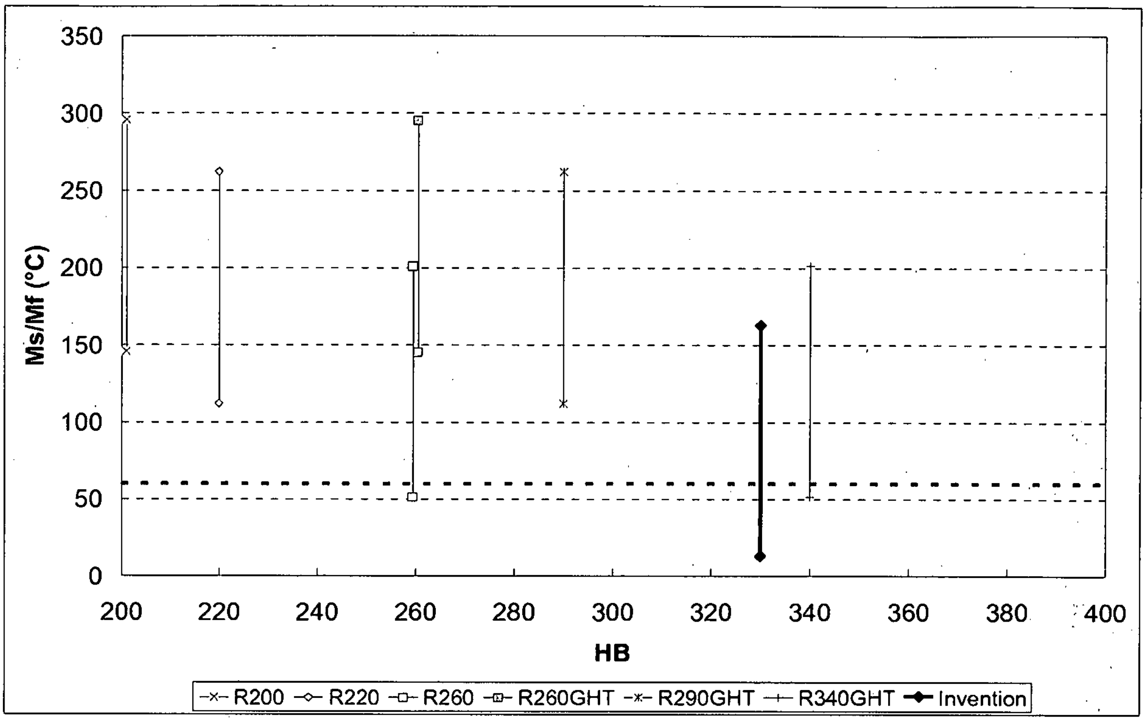
350
300
250
200
150
100
50
0
Ms/Mf (°C)
200
220
240
260
280
300
320
340
360
380
400
HB
R200
R220
R260
R260GHT
R290GHT
R340GHT
Invention

Figure 2

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 20090134647 A **[0004]**
- GB 2443494 A **[0007]**

Non-patent literature cited in the description

- **ANDREWS.** *J. Iron & Steel Inst.,* 1965, vol. 183, 721-727 **[0013]**
- **STEVEN ; HAYNES.** *J. Iron & Steel Inst.,* 1956, vol. 183, 349-359 **[0013]**
- *Wear,* 1993, 162-164 **[0023]**