Rail Materials - Alternatives and Limits

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Abstract

DB Systemtechnik has for years been investigating operationally induced flaws to rails and wheels in order to arrive at means of slowing down or actually preventing damage processes. One option here is to use rail materials of greater strength that accordingly have a higher resistance to rolling contact fatigue (RCF). Over recent years, DB Systemtechnik has been investigating the suitability of pearlitic and bainitic rail steels for use on lines with rolling contact fatigue problems with the aim of cutting track maintenance input without increasing the level of vehicle maintenance due to increased wheel wear. The present findings indicate that, as well as reducing wear, higher-strength pearlitic grades also result in shallower head checks, enabling them to at least delay the attendant damage done to the rail. Furthermore, with suitable alloying and control of the form that sulphides take, non heat-treated, naturally hard steels could well be developed as an alternative to the head-hardened rail, especially since the wear at weld joints to which head-hardened rails are subject would cease to exist. Bainitic rail steels may produce a balance between the processes of wear and rolling contact fatigue at a low level. However, minimum strengths need to be observed when using them, though, due to the altered wear mechanisms of pearlitic steels. The present findings indicate that high-chromium steels with a medium carbon content and hence of considerably greater strength deliver better wear behaviour than high-manganese steels with a low carbon content.

1 Introduction

Given the increase in traffic volumes over recent years, the service life of rails in the track and in switch systems is now determined less by wear-related attrition and increasingly by rolling contact fatigue that can lead to surface damage in the form of head checks and squats or, indeed, complete impairment of a rail’s functional properties. Ever since high-speed services were introduced, therefore, an intensive search has been on for means of extending the service life of rails. DB Systemtechnik has for years been dealing with investigating operationally induced flaws to rails and wheels, departing from an analysis of the causal mechanisms, to arrive at means of slowing down or actually preventing damage processes. One option is to use rail materials of greater strength that accordingly have a higher resistance to rolling contact fatigue (RCF).

It is possible with pearlitic rail steels to either reduce the lamellar spacing in the pearlite through heat treatment (head-hardened rail), add alloying elements or raise the carbon content in the steel (hypereutectoid steels). All these measures lead to an increase in material strength and hence of resistance to wear and RCF.

One alternative pursued in recent years is the use of bainitic rail steels. In conjunction with the appropriate alloying additions and, if need be, a suitable form of heat treatment, these can attain even greater strengths than pearlitic steels.

Over recent years, DB Systemtechnik has been investigating the suitability of pearlitic and bainitic rail steels for use on lines with rolling contact fatigue problems with the aim of cutting track maintenance input without increasing the level of vehicle maintenance due to increased wheel wear. The present paper reports on these findings.¹

¹ Some of the findings are from OPTIKON - Optimising Materials Involved in Wheel/Rail Contact in High-Speed Services, a composite project funded by the German Transport Ministry (1998-2001).
2 Stressing of rail as cause of RCF

A railway wheel rolling along a rail gives rise to high surface stresses in the generally elliptical contact area between wheel and rail. Besides the vertical stress component, traction load locally produces additional transverse stresses beneath the wheel tread and the running surface of the rail respectively. Such stresses lead to local plastic deformations of the materials in the surface area if the yield strength of the rail steel is exceeded. Recurrent plastic deformation of the rail surface induces residual compressive forces. Plastic deformation causes strain hardening to occur on the surface, moreover, that leads to the yield strength being raised locally. As a result, the material is initially able to absorb further strains by purely elastic means. This is a precondition for the materials being able to withstand such high stresses in the contact area. Recurrent loading cycles on the rail produces cumulative plastic deformations (ratcheting) as a function of the vertical stress exerted and the friction coefficient. Once the limit of strain hardening (critical deformation) is achieved and adhesive wear on the rail surface is low relative to the degree of ratcheting, cracks form on the surface. These may subsequently lead to flaking or spalling. To prevent this occurring, the cracks can be removed through grinding (artificial wear) [1, 2]. As well as needing to have a sufficient strength, the rail material also has to deliver high resistance to wear whilst also being sufficiently tough if the danger of brittle fracture is to be avoided - especially when there are cracks in the rail.

3 Standard materials

Given the principal requirements involved, the steels generally used for wheels and rails have a predominantly pearlitic microstructure incorporating hard cementite lamellae that guarantees high resistance to wear. The microstructure produced by transformation close to thermodynamic equilibrium simultaneously ensures more sluggish transformation in operation than, for instance, a bainitic or martensitic microstructure [3]. Material designations and the properties of rails requiring verification are set forth in UIC Leaflet 860V as well as in DIN EN 13674-1. DIN EN 13674-1 exclusively covers pearlitic steels for rails, those being R220, R260, R320Cr and R350HT, whose carbon content lies between 0.6 and 0.8 %. These steels primarily differ as regards:

- their heat-treatment condition
  - “naturally hard” for R220, R260 and R320Cr, “head-hardened” (finely pearlitised) for R350HT
- their minimum hardness
  - 220, 260 and 320 HB for grades R220, R260 and R320Cr and 350 HB for grade R350HT.

Use is made at Deutsche Bahn AG of steel R260 as the regular grade and of grade R350HT for curves ≤ 700m.

4 Testing new rail steels

4.1 Basic considerations

The focus when testing new material concepts for rails has always been on reducing rolling contact fatigue damage without significantly increasing wear on the side of the rail or wheel. Wear-related material attrition is invariably accompanied by deterioration of profile accuracy which, in turn, would cause contact stresses to rise. In the ideal rail steel, processes of wear and rolling contact fatigue in the material are kept at as low a level as possible so that wear-related material degradation is sufficient to speedily remove any rolling contact fatigue cracks that appear. This property has always been attributed to bainitic steels.
As a means of limiting processes of rolling contact fatigue in the material, steels with a higher yield strength are an option, since they display a lower susceptibility to ratcheting.

The yield strength of pearlitic rail steels can be increased in the following ways:
- by raising the carbon content to > 0.8 % [4] so as to attain solid-solution strengthening and precipitation hardening
- by adding alloying elements so as to attain solid-solution strengthening and, first and foremost, to reduce the lamellar spacing in the pearlite
- heat treatment so as to reduce the lamellar spacing in the pearlite (fine pearlitisation2)

There is a simultaneous increase in resistance to wear, though this is generally accompanied by a fall in toughness. As a result, such steels are only conditionally capable of fulfilling the ideal of keeping wear and rolling contact fatigue at as low a level as possible.

The yield strength of bainitic steels is likewise influenced by carbon content, alloying elements and heat treatment. Notwithstanding many years of trials [e.g. 5, 6], however, their use has remained the exception in the rail domain. Assuming steels of comparable strength, the resistance to wear of bainitic steel is inevitably lower than that of pearlitic steel, as the cementite lamellae in pearlite offer far higher resistance to shearing than do finely distributed or coarsely precipitated carbide platelets in bainite. By designing the microstructure so as to achieve adequate plasticity, furthermore, the toughness of bainitic steel can far exceed that of pearlitic steel. The greater input required for welding rails has to be regarded as a drawback, however.

### 4.2 Steel grades examined

With a view to optimising material properties in the wheel/rail contact area, several rail steel concepts underwent comparative appraisal to enable their suitability for use under differing line conditions (curve radii, traffic tonnage, running speeds) and their impact on wheel wear to be assessed.

The following material concepts for pearlitic steels were scrutinised and included in the study schedule:

<table>
<thead>
<tr>
<th>Steel type</th>
<th>Material concept</th>
<th>Tensile strength (MPa)</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>R260</td>
<td>naturally hard, 0.6 ≤ C ≤ 0.8%</td>
<td>≥ 880</td>
<td>Standard grade as reference</td>
</tr>
<tr>
<td>R220 Is</td>
<td>naturally hard, 0.4 ≤ C ≤ 0.6%, S ≤ 0.005%</td>
<td>≥ 770</td>
<td>To reduce RCF damage relative to higher-strength pearlitic steels by means of greater wear that is nevertheless confined due to a lower S content and sulphide spheroidisation</td>
</tr>
<tr>
<td>R320Cr (a)</td>
<td>naturally hard, 0.6 ≤ C ≤ 0.8%, 0.8-1.2 %Cr</td>
<td>≥ 1,080</td>
<td>To optimise wear/RCF correlation: (a) standard grade (b) with lower S content and sulphide spheroidisation</td>
</tr>
<tr>
<td>R320Cr ls (b)</td>
<td>finely pearlitised, 0.6 ≤ C ≤ 0.8%</td>
<td>1,175</td>
<td>To define the line parameters under which head-hardened rails are beneficial</td>
</tr>
</tbody>
</table>

Table 1: Material concepts tested for rails - Pearlitic steels

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2 Such heat treatment of the rail head is usually termed “head hardening” despite its not constituting standard steel hardening in the sense of martensitic transformation.
The following material concepts for bainitic steels were scrutinised:

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</thead>
<tbody>
<tr>
<td>1000B</td>
<td>tempered C ≤ 0.1%; 3.5% Mn</td>
<td>≥ 1,000</td>
<td>To identify an optimum relation between wear and RCF by setting a variety of strengths</td>
</tr>
<tr>
<td>1100B</td>
<td>tempered C ≤ 0.1%; 3.5% Mn</td>
<td>≥ 1,100</td>
<td></td>
</tr>
<tr>
<td>1400B</td>
<td>tempered C ≤ 0.4%; 2.8% Cr</td>
<td>≥ 1,400</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Material concepts tested for rails - Bainitic steels

4.3 Rig tests

The suitability of a given rail steel is invariably also influenced by actual conditions in the track and hence it was first planned to investigate the steels’ basic behaviour under completely comparable conditions on a twin-disk test machine (Amsler principle). Samples (disks) with an external diameter of 46 mm and an internal diameter of 20 mm and made of the respective wheel and rail steel were used. The wheel sample rotated at a speed of 436 min⁻¹, the rail sample at 450 min⁻¹. Hence, the rolling motion occurred under a slip of 3 % and a standard force of 3,935 N, yielding a surface pressure of 1,250 N/mm². A drop of water was introduced to the contact area between the wheel and rail samples at 20 s intervals. At the beginning of testing and at intervals 20,000 cycles, the mass of each sample was established. At the end of testing, the wear value was taken as being the cumulative material loss after 140,000 cycles. In order to obtain statistically safe results, three trials were conducted per material pairing. The values cited here accordingly constitute medians of three separate readings.

The steel types enumerated in Table 1 (except R220 ls and R320Cr ls) and Table 2 were used for rails. Two typical representatives of solid and tyred wheels, R7 and B6, were chosen as the other wearing party. Whilst R7 solid wheels with a tensile strength of between 820 and 940 MPa are used in freight and passenger operations, B6 tyres with a tensile strength of between 920 and 1050 MPa are frequently used on locomotives or powered axles in passenger operations. It was additionally possible by varying the hardness of wheel and rail to make pronouncements on wear in the system as a whole, i.e. the extent to which harder rails may increase wear on the wheel.

- Appraisal of wear behaviour
  
  Figs. 1 and 2 summarise material loss on wheel and rail samples after 140,000 cycles separately for the two wheel steels R7 and B6. Owing to tests on material pairings R7/1000B, B6/1000B and B6/1100B having to be aborted after just 100,000 cycles due to heavy wear on the rail sample, material loss after 100,000 roll-overs was additionally evaluated for all material pairings (Figs. 3 and 4).
  
  In the case of naturally hard pearlitic rail grades R260 and R320Cr, there is no significant difference in wear regardless the wheel steel. Only when the transition is made to head-hardened grade R350HT is there a drop in wear over the standard grade. This shows that the tighter spacing of ferrite and cementite lamellae in the finely pearlitised microstructure of steel R350HT has a greater strength-enhancing effect than adding 1 % Cr, something that is also reflected in the far higher yield strength for grade R350HT. Remarkably, in the case of higher-strength grade R350HT, there is a drop in wear on both the rail sample and the R7 wheel sample (Figs. 1 and 3).
Material pairing R7 - Rail steel

Fig. 1: Material loss on wheel (R7) and rail in Amsler test after 140,000 roll-overs

Material pairing B6 - Rail steel

Fig. 2: Material loss on wheel (B6) and rail in Amsler test after 140,000 roll-overs

Material pairing R7 - Rail steel

Fig. 3: Material loss on wheel (R7) and rail in Amsler test after 100,000 roll-overs
Where use is made of higher-strength wheel steel B6, there is a drop in wear not only on the wheel but also on pearlitic rail steels (cf. Figs. 1/2 and 3/4), presumably attributable in the first instance to profile stability being retained. It is to be assumed that, owing to its greater degree of wear, the softer wheel steel is susceptible to surface roughening and alteration of contour, which is in turn likely to raise contact stresses locally. As expected, the use of bainitic grades 1000B and 1100B escalates the level of wear compared to pearlitic grades of the same strength, notably in conjunction with higher-strength wheel steel B6. Moderate wear values, lower even than those for the pairing of head-hardened grade with R7 wheel steel (Fig. 1), are only achieved with bainitic rail steel 1400B.

**Appraisal of RCF behaviour**

Eddy-current testing was implemented to check the rail samples for cracking in the contact area at intervals of 20,000 cycles and at the end of testing. This facilitated the detection of surface areas prone to cracking. The findings allowed inferences to be drawn regarding the susceptibility to cracking of the various rail grades.

The pearlitic rail steels revealed a pronounced change between crack formation/growth and material removal by wear in the course of tests on samples in wheel steel R7. Within a short period of exposure to stressing, a higher susceptibility to cracking became discernible in the head-hardened rail steel than in naturally hard grades. At the end of testing, however, the samples in grades R320Cr and R350HT revealed significantly fewer cracks than standard grade R260, with the two higher-strength steel types no longer differing greatly from one another. Qualitatively speaking, the trend with regard to the higher-strength wheel steel B6 was the same except that there were fewer indications of cracking on all the rail samples. Given that wear was also lower when higher-strength wheel steel B6 was used, this wheel steel is evidently the most favourable wearing component from a whole-system point of view.

Bainitic rail steels 1000B and 1400B produced remarkably few indications of cracking in tests involving both R7 and B6 over the entire duration of testing. Samples in grade 1100B, by contrast, revealed a large number of cracks; indeed, by the end of testing, the total was on a par with that for higher-strength pearlitic rail steels.

**4.4 Track tests**

Trials on the steel types detailed in Tables 1 and 2 were conducted on seven track curves, having radii of between 520 and 1570 m and daily loadings of from 25,000 to 55,000 tonnes (mixed traffic), on which there are frequent changes of rails in practice due to the pronounced appearance of head checks. Test rails (15 m long) made of the rail steels summarised in Tables 1 and
2 were welded to form a length of rail that was then laid as the outside rail in a curve of constant radius. The track was completely overhauled and the inner rail replaced by standard rails of grade R260. All lines were reground once the rails had been installed. This ensured uniform conditions for all test rails.

Track inspections conducted once every six months for the first 3 years and annually thereafter enabled the extent of wear and any head checks arising to be assessed. To this end, the transverse profile of each test rail was measured at two points using a Miniprof system to ascertain the degree of wear at the gauge corner as a function of the rail steel used. In addition, the length of head checks was documented photographically as well as following magnetic particle testing under UV light. To conclude, the depth of head checks was established by means of eddy-current testing.

The results of this long-term testing reveal significant differences as regards wear and the depth of head checks between the various steel types, as illustrated in Fig. 5 for a curve radius of 791m.

![Results after 105 MGT](image-url)

**Fig. 5: Gauge corner wear and depth of head checks on pearlitic and bainitic rail steels in a track curve (R = 791m) after 105 million traffic tonnes**

This confirms the test rig results, in which bainitic rail steels 1000B and 1100B reveal no head checks but a high degree of wear. Here, too, bainitic grade 1400B is characterised by low wear, by contrast, and suffers no head checks whatsoever. Clearly, the goal involved in developing materials for rail steels as set out in Subsection 4.1 - processes of wear and rolling contact fatigue in the material ought to balance out at as low a level as possible - is achieved with this steel type.

Fig. 5 additionally demonstrates that, as expected, higher-strength pearlitic steel types R350HT and R320Cr incur less wear than the standard R260 grade. The head checks on head-hardened grade R350HT are significantly shallower than on naturally hard pearlitic grades, moreover, something that is in the first instance attributable to the higher yield strength of grade R350HT (cf. 4.1). Worthy of note here, however, is the behaviour of modified steel type R320Cr ls, whose sulphur content has been cut considerably and which has been specially treated for the spheroidisation of sulphides. These rails revealed the lowest level of wear, though it was not possible to avoid head checks completely. Their depth is comparable with those on grade R350HT, however.

Despite evaluations still being underway for all sections of line, it is already possible to derive the following universally applicable insights from the track tests:
All pearlitic rail steels reveal head checks to a greater (R220, R260, R320Cr) or lesser degree (R320Cr Is, R350HT). The higher-strength pearlitic give rise to a finer crack pattern with smaller intervals between cracks. The R220 Is grade trialled here, with its lower S content and simultaneous spheroidisation of sulphides, is not an alternative to the standard R260 grade on account of its high degree of wear and pronounced head checks. By contrast, the modified, naturally hard grade R320Cr Is represented a significant improvement over steel type R260 on all test lines. This shows the influence a steel's yield strength has on its behaviour when subjected to wear and rolling contact fatigue on the one hand and reveals the strong influence of sulphides on crack growth in rails on the other hand.

None of the bainitic rail steels trialled suffered head checks on the test lines. The high-manganese bainitic rail steels 1000B and 1100 B with their low C content nevertheless give rise to too much wear to be an alternative to the standard R260 grade. By contrast, the high-Cr bainitic steel 1400B with its medium C content displayed optimum behaviour in terms of its resistance to both wear and rolling contact fatigue on all lines. This may indicate that bainitic steels ought to have a specified minimum carbon content so as to guarantee sufficient strength and hence high resistance to wear. It is evident in this respect that the alloying element Cr is more effective than Mn. However, the welding expenses are higher.

5 Conclusion & Summary

Trialling pearlitic and bainitic rail steels to establish their suitability for use on track curves with rolling contact fatigue problems has shown that, as well as reducing wear, higher-strength pearlitic grades also result in shallower head checks, enabling them to at least delay the attendant damage done to the rail. The present findings indicate that, with suitable alloying and control of the form sulphides take, non heat-treated, naturally hard steels could well be developed as an alternative to the head-hardened rail, especially since the wear at weld joints to which head-hardened rails are subject would cease to exist.

Regardless of its lower sulphur content and its spheroidised sulphides, the R220 grade is unsuitable for lines with RCF problems, because its low yield strength encourages ratcheting and though level of wear is higher than that of the standard R260 grade, it does not suffice to prevent the propagation of head checks.

Bainitic rail steels allow a low-level balance between the processes of wear and rolling contact fatigue to be ensured. However, minimum strength values need to be observed when using them due to the altered wear mechanisms compared to pearlitic steels. The present findings indicate that high-chromium steels with a medium carbon content and hence of considerably greater strength deliver better wear behaviour than high-manganese steels with a low carbon content. The welding technique for these steels is more demanding and they are more expensive to buy, hence this is a type of steel that can only be recommended for lines where serious RCF problems necessitate considerable maintenance input.

With regard to the wheel/rail interaction, emphasis needs to be given to the finding that, in Amser tests, the higher-strength pearlitic rail steel did not manifest a higher degree of wear than the two standard-wheel steels of differing strength tested. Conversely, the wheel steel of greater strength actually induced lower wear on the rail steel samples. This suggests that using higher-strength steels for both wheels and rails impacts favourably on wear in the system as a whole in that it ensures more sustained profile stability.

6 Bibliography
