Life Cycle Cost considerations on high strength rail steels

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Abstract
Voestalpine Schienen developed advanced rail steels with both pearlitic and bainitic microstructure and hardness up to 450 BHN with the aim to meet nowadays demands of railroads for components with longer service life time and reduced needs for maintenance at the same time. The paper demonstrates the life cycle cost (LCC) based solution concept of voestalpine Schienen including an approach to understand damage pattern ("damage map") and also latest results of the ongoing track tests with DBAG. Significant savings in LCC due to the superior track performance of high strength rail steels are presented exemplary by a life cycle cost evaluation with the dynamic software model LCC Rail, developed in a joint project with University of Graz.

Introduction
In the 21st century railways are challenged when performing their task to fulfil demanding customer requirements. They have to increase productivity by maximising the availability of their network. In Germany for example, prognosis on rail transportation development show an increase of 10 % in passenger transport and 41% in freight transport until 2015 [1]. In order to fulfil future requirements, passenger trains run with higher speeds and higher train frequencies. An increase in axle load is discussed currently in Europe (from 22.5 to 25 tons), too. The extremely growing demand of raw materials for the steel industry enforces heavy haul railroads to increase their productivity, demonstrated also by the trend to increase axle loads up to 40 tons. All this leads to steadily increasing loads, which favours wear and rolling contact fatigue defects (RCF).

The experience of many railways shows that wear can be controlled with highest possible rail hardness combined with lubrication techniques. It was proven many times that Head hardened rails exhibit better resistance to wear and corrugation than softer grades [2, 3]. In the last decade RCF is becoming the dominant problem and thus the management of rolling contact fatigue accounts for a significant proportion of railways maintenance costs. Rails with RCF defects must be maintained properly to avoid a risk of a sudden rail breakage. Grinding or milling machines are used, where the fatigued material is – ideally – taken off completely.

Due to the fact that a lot of capital is bound in the infrastructure assets, the longest possible service lifetime is expected from all infrastructure components in order to reduce the annual financial costs. Ideally components do not only perform well over a long service life time, but they should require minimum maintenance as well. Maintenance is on one hand expensive, costs for hindrances are high and on the other hand time windows for maintenance are becoming fewer and shorter.

Therefore railways look more and more on advanced track components that promise longer service life time due to better track performance and require less maintenance thereby maintaining the highest level of safety.

The solution concept based on life cycle cost considerations
The rail as a central track component is an important cost-driver. Railways, no matter if state owned or privatized are forced more and more to operate low cost oriented, thus life cycle cost (LCC) considerations are becoming an essential part of the purchasing business [4]. The following saying bears some logic:

"If you pay too much, you loose money, that’s all. If you paid to few, you loose sometimes everything because the thing you bought does not fulfil the requirements. The law of economy makes it impossible to get high value for little money. If you accept the cheapest offer, you must add something for the risk you take. And if you do this, you should have enough money to buy something better.” [5]
Reducing LCC is not only a strategic goal of modern railways, but also for rail manufacturers with the capability to produce premium products, i.e. heat treated rails with better track performance. Only the sustained reduction of LCC by premium products creates customer benefit and satisfaction, which is exactly the motivation of voestalpine Schienen to develop advanced pearlitic and bainitic rail grades with longest possible service life time with the minimum maintenance requirements for the given service conditions. The approach of voestalpine Schienen GmbH to this solution concept is a “development cycle” starting with the basic development of advanced rail steels with the aim to increase damage resistance to both wear and RCF, figure 1.

The next step is then testing under practical conditions in track together with our customers. Therefore the rails are installed in various tests sites with different loading conditions to investigate and evaluate the technical track performance. Following the “old way”, new rail grades were homologated when they proved superior performance compared to the actual standard technology. Nowadays, following the “new way”, economical evaluations of the track performance are an essential part in product development. Finally, only when the validation of the new technology is superior in comparison to the current state of the art technology in terms of track performance, economy and safety, the last logical step has to be the implementation of the new technology in standards and specifications of railways.

The concept of a “damage map”

A very important part of rail steel development is the understanding of damage pattern in track. There are two main reasons for re-railing: wear and RCF. Wear is predominant in tight curves and the parameters influencing the amount of wear are well investigated. The RCF-problem, which is very specific to the wheel–rail–system is subject of intense investigations for some decades already. The best known examples being Head Checks and Spalling which occur at a further stage. It is evident to see that also wheels are subjected to this damage modes, figure 2.

Head Checks and local Spalling on the rail…

…...and the wheel.

Figure 1: Circle of development

Figure 2: Head Checks and Spalling, on rails and wheels
The requirement for material development is to understand these mechanisms in a way that pragmatic solutions are possible.

The first step is to see, that a small element view is necessary to figure out the elementary contributions to damage generation. Investigations on the whole contact patch will not lead to a solution, because in the contact patch are different damage modes – for a clear attenuation to the damage generating parameters pointing on a small contact zone is necessary.

The second step is to understand, what kind of parameters can cause these damage modes. Investigations on specimens indicate that in principle two main parameters can generate these damages: Mechanical shifting of material in longitudinal direction and the relative movement between wheel and rail in the spot of contact. These two parameters are described best by the:

Longitudinal stress $\sigma_T \,[\text{N/mm}^2]$ 

and the speed difference between the wheel- and the rail-patch, the 

slip speed $v_{\text{slip}} \,[\text{m/s}]$.

The third step is investigating the meaning of a combination of these two parameters. Rearranging the units of STRESS and SPEED result in:

$$
\left[ \frac{N}{mm^2} \right] \times \left[ \frac{m}{s} \right] = \left[ \frac{N \times m}{s} \right] \times \left[ \frac{1}{mm^2} \right]
$$

**STRESS x SPEED = POWER / AREA**

The combination of Stress x Speed can be transformed to Power / Area: This might be a damage – determining factor in the wheel rail contact.

A pragmatic combination of these two parameters may provide the possibility to include both damage modes, Wear and RCF, in one diagram. Physically, the tangential stress describes the mechanical contribution and the slip speed describes the thermal component to the damage. **Figure 3** shows a first draft of a “damage – map” which tries to show qualitatively the impact of the forces between the wheel and rail on the damage modes. This approach has been described in [6, 7] more detailed.

![Figure 3: The “Damage – Map”](image-url)
The concept of increasing damage by increasing tangential stress and/or slip speed gives the possibility to gain some quantitative knowledge. Modern locos are able to transfer power of approximately up to 5 kW/mm² into the contact patch [8]. A rough estimation of the power needed to induce damage to the material indicates 1 kW/mm² [7]. It is evident that the operation of modern loco technology needs to consider these forces and their impacts. The increasing track damage indicates that there is considerable need for action in this area. One way of improving the situation is providing materials which offers higher resistance against both wear and RCF.

The solution concept – Development of advanced rail steels

Voestalpine Schienen offers a range of high strength rail steels, see table 1, with both improved wear- and RCF-resistance, properties which are of equal importance to railways nowadays.

<table>
<thead>
<tr>
<th>rail grade</th>
<th>hh micro-structure</th>
<th>chemical composition</th>
<th>( R_{m, \text{min}} )</th>
<th>( A_{s, \text{min}} )</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>conventional grades acc. to EN13674</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R220</td>
<td>pearlite</td>
<td>( 0.50-0.60 )</td>
<td>( 0.20-0.60 )</td>
<td>( 1.00-1.25 )</td>
<td>( \leq 0.15 )</td>
</tr>
<tr>
<td>R260</td>
<td>pearlite</td>
<td>( 0.62-0.80 )</td>
<td>( 0.15-0.58 )</td>
<td>( 0.70-1.20 )</td>
<td>( \leq 0.15 )</td>
</tr>
<tr>
<td>R260Mn</td>
<td>pearlite</td>
<td>( 0.55-0.75 )</td>
<td>( 0.15-0.60 )</td>
<td>( 1.30-1.70 )</td>
<td>( \leq 0.15 )</td>
</tr>
<tr>
<td>R320Cr</td>
<td>pearlite</td>
<td>( 0.60-0.80 )</td>
<td>( 0.50-1.10 )</td>
<td>( 0.80-1.20 )</td>
<td>( \leq 0.15 )</td>
</tr>
<tr>
<td>R350HT</td>
<td>pearlite</td>
<td>( 0.72-0.80 )</td>
<td>( 0.15-0.58 )</td>
<td>( 0.70-1.20 )</td>
<td>( \leq 0.15 )</td>
</tr>
<tr>
<td>R350LHT</td>
<td>pearlite</td>
<td>( 0.72-0.80 )</td>
<td>( 0.15-0.58 )</td>
<td>( 0.70-1.20 )</td>
<td>( \leq 0.30 )</td>
</tr>
<tr>
<td>new rail grades from VAS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>370LHT</td>
<td>pearlite</td>
<td>( 0.70-0.82 )</td>
<td>( 0.40-1.00 )</td>
<td>( 0.70-1.10 )</td>
<td>( \leq 0.40 )</td>
</tr>
<tr>
<td>380UHC</td>
<td>pearlite</td>
<td>( 0.90-0.95 )</td>
<td>( 0.20-0.35 )</td>
<td>( 1.20-1.30 )</td>
<td>( \leq 0.25 )</td>
</tr>
<tr>
<td>400UHC</td>
<td>pearlite</td>
<td>( 0.90-0.95 )</td>
<td>( 0.20-0.35 )</td>
<td>( 1.20-1.30 )</td>
<td>( \leq 0.25 )</td>
</tr>
<tr>
<td>DOBAIN 380</td>
<td>bainite</td>
<td>( 0.76-0.84 )</td>
<td>( 0.20-0.35 )</td>
<td>( 0.80-0.90 )</td>
<td>( \leq 0.40 )</td>
</tr>
<tr>
<td>DOBAIN 430</td>
<td>bainite</td>
<td>( 0.76-0.84 )</td>
<td>( 0.20-0.35 )</td>
<td>( 0.80-0.90 )</td>
<td>( \leq 0.40 )</td>
</tr>
</tbody>
</table>

hh..head hardened / heat treated

The grade 370LHT has approx. 0.5% chromium to further increase the hardness limits; the typical hardness as delivered is 390-400BHN. This grade is used regularly in the Netherlands at ProRail for all curves with a max. radius of 3000 m and is also the standard grade at Ofotbahn in Norway. The hyper-eutectoide grade 400UHC is based on R350LHT, but uses approx. 1% carbon to further increase the hardness limits of the pearlitic microstructure to approx. 440BHN. The typical running surface hardness as delivered is approx. 420BHN. This steel is tested at different sides of Europe showing further improvements in track performance.

The optimal solution for the fight against RCF will be the Bainitic Rail Steels DOBAIN380 and DOBAIN430. Track tests up to now already proofed that these steels have an intrinsic capability to avoid RCF-cracks caused by the special structures of these steels. There is still a lot of effort in research and development work to find the best combination between the “right” bainitic structure (there are several different structures which are accounted to bainitic structures) and the most economical way to produce these rails.

Track testing and results

By track tests, which are carried out in joint projects with various railways worldwide, the track performance under different loading conditions ranging from high speed via mixed traffic to heavy haul is evaluated. voestalpine is doing more than 20 track tests with different heat treated rail steels worldwide. The so developed data base for rail degradation pattern is the basis for LCC analysis.

All tests that were carried out and are still running indicate that wear, corrugation and RCF defects can be significantly reduced by the use of head hardened (HSH®) rails [2, 3]. The most astonishing result was that a comparison test to the rail grade R220 showed that the softest rail grade had not only the highest wear rates (six times more than R350HT) but also 6 times deeper cracks. This result
proved that harder rail grades do not only increase wear resistance but also crack resistance at the same time. The results proved for R350HT in average a three-fold improvement in efficiency compared to standard grade R260 rails. Motivated by these results the track tests were extended with advanced rail steels 370LHT and 400UHC as well as bainitic rail grades DOBAIN®. In the following the results from one of the most interesting and sophisticated track test, which is carried out together with DBAG in Germany will be presented exemplary as a base for LCC considerations.

In Kerzell, a track test on the medium speed line Frankfurt-Göttingen for mixed traffic with axle loads of max. 22.5 to and max. speed of 160 km/h was started in November 2003. In a 1.400 m radius curve six rail types (four pearlitic and two bainitic steel grades in 60E2 profile, see also table 1) are laid in an alternating order with the aim to avoid the position in curve effect. The typical damage pattern in this radius class at DBAG is RCF, i.e. Head Checks. The total accumulated load so far is 135 Mio to. An extensive monitoring program is carried out by DB Systemtechnik in half year intervals: Eddy Current testing (ET) and Magnetic particle inspection (MPI) for the classification of Head Checks and determination of the crack depths. Wear measurement is done using the Miniprof device.

The worn profiles at Kerzell do not show much wear after the last measurement in autumn 2007 at 125 Mio tons. Figure 4 shows the development of the gauge corner wear of the grades R260 and R350HT. For the grade R260, the gauge corner loss is still less than 1 mm. All head hardened rails and also the bainitic rails have wear figures below 0.3 mm, confirming an improvement by a factor of three and larger. Especially when the accumulated load increases over more than 40 MGT’s, the gauge corner wear of the R260 grade increases exponentially, whereas the gauge corner wear of R350HT remains almost linear. Thus resulting in a improvement factor of 5 at 125 MGT’s. The difference in wear between the 370LHT, 400UHC and DOBAIN is only some hundreds of a millimetre, and consequently we can not give precise wear improvement factors for the different heat treated steels at this stage of the test. While this is a disadvantage for the rail testing evaluation, the low wear rates of the heat treated rail steels guarantee a proper shape of the railhead profile for a long time. The rail head profile does not change from the chosen geometry, which was produced by grinding, supporting good running behaviour and controlled low wheel-rail forces. And again, wear is not the real issue on this track, but more RCF.

![Figure 4: Wear data over accumulated load at Kerzell](image-url)

The results regarding damage depth by Head Checking, measured by eddy current testing, are presented in figure 5. The results are principally similar as for wear, showing a strong increase in damage depth for R260 after a certain load whereas the damage by Head Checks for the head hardened grades are only slightly increasing. After 125 MGT’s, the softest steel grade showed the
longest and thus deepest cracks, slightly above 1 mm. The harder pearlitic steel grades R350HT and 370LHT show 67 % and 87 % less damage depth, which proved the results obtained from various other track tests.

Currently the advanced rail steels 370LHT®, 400UHC® and DOBAIN® are tested in various other lines. In general, the results obtained so far show for 400UHC a further 30% improvement in wear resistance compared to 370LHT. Bainitic high strength rail steels are currently under practical tests in Austria and Germany, promising significant better resistance against RCF-defects compared to pearlitic steels. If more significant actual results are available at the time of the conference, they will be presented.

**Maintenance**

The track tests also include investigations regarding maintenance, grinding in particular. As mentioned above, maintenance windows are very short and rare and therefore railroads require rails that need less maintenance. Grinding tests showed that R350HT rails needed only half the number of grinding passes to remove the head checks and produce the required profile compared to the R260 rails. With constant grinding intervals, the amount of material which has to be removed is much lower with R350HT rails. Alternatively, longer grinding cycles are possible – both options help to cut track maintenance costs. **Figure 6** shows the principle of the life cycle of the three steel grades in comparison, the black boxes being grinding actions. While the rail grade R260 has to be ground yearly, the grinding cycles for R350HT can be tripled and even extended to 5 years intervals for the grade 370LHT. This is possible because of the much better damage resistance of the harder rail steels. The technical service life time can be tripled for R350HT and even sextupled for 370LHT.

**Figure 5:** RCF data over accumulated load at Kerzell

![RCF data over accumulated load at Kerzell](image)

**Figure 6:** Life cycle scheme (exemplary) of various rail rail grades

![Life cycle scheme](image)
Welding procedures

In parallel with the rail steel development, welding procedures for the harder rail steels are developed together with welding experts. The weld performance is evaluated at the same time by visual inspection and profile measurements (determination of battering of the heat affected zone HAZ). Principally all procedures regarding flash-butt welding, aluminothermic welding and repair welding are performing well and are available on the market.

LCC analysis

In order to quantify the economic impact of advanced rail steels, voestalpine Schienen works since 1997 on different projects to evaluate life-cycle-costs (LCC). Together with ÖBB (Austrian federal Railways) and the Technical University of Graz, Institute for Railway Engineering, a dynamic LCC model was developed. This model compares the annuities of to technologies along their entire service life, i.e. a new technology with the existing one. Input data are the costs for the individual maintenance activities and financial data like the rates for interest and inflation. The LCC calculation is started with the prognosis for the life cycles of the different test candidates. The lifetime model is simple, considering the “natural” wear and the material removal by grinding until the wear limit of the profile is reached. Based on this service life prognosis, and with the costs for rail replacement and grinding, the LCC calculation is also done easily.

The worn profiles at Kerzell do not show much wear at 125 Mio tons. For the lifetime calculation presented here, we used the wear data from other track tests done at severe wear conditions. The wear improvement factor for R350HT and DOBAIN 430 is approx. three, as confirmed also for the Kerzell test. For the 370LHT and 400UHC, we considered conservative wear improvement factors of five and six, respectively.

The grinding intervals for the advanced rail steels are based on the results from the head check field survey. For the softest grade R260, grinding should be done once per year with a material removal of 0.3 mm in order to achieve the “magic wear rate” [9].

Considering the depth of the Head Checks as measured in Kerzell, the grinding cycle can be stretched to three years for R350HT, five years for 370LHT and six years for the 400UHC.

The service life of the R260 for the 1400 m curve is approx. 13 years. Due to the lower wear rate and less frequent grinding, the heat treated grades achieve a lifetime beyond 45 years. The LCC comparison is cut at 40 years according to the agreements on LCC modelling of the integrated European project “Innotrack”. Figure 7 shows the life cycles for the four different grades considered.

<table>
<thead>
<tr>
<th>Year</th>
<th>R260</th>
<th>R350HT</th>
<th>370LHT</th>
<th>400UHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>3</td>
<td>4</td>
<td>-</td>
<td>-</td>
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<tr>
<td>4</td>
<td>5</td>
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</tr>
<tr>
<td>5</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 7: Life cycle prognosis for the 1400 m curve at Kerzell

Along the 40 years of service life, the R260 rail must be replaced twice. A third replacement in year 40 and also some of the grinding cycles were omitted because practical procedures do not foresee any grinding actions at the end of the service life time. All heat treated grades achieve the 40 year service life easily and the harder the steel, the less number of grinding actions are required. The LCC cost calculation reflects these different maintenance requirements, showing the tremendous potential of heat treated rails to save costs. Table 2 summarizes the annuities and the total costs for the 40 years service life. While the annuities drop to less then 50 % for all head hardened rails, the total costs are less than a third as compared to the R260 steel grade.
<table>
<thead>
<tr>
<th>Steel grade</th>
<th>R260</th>
<th>R350HT</th>
<th>370LHT</th>
<th>400UHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>annuities [€/y]</td>
<td>14.555</td>
<td>6.793</td>
<td>5.646</td>
<td>5.398</td>
</tr>
<tr>
<td>total costs [€]</td>
<td>654.774</td>
<td>196.187</td>
<td>148.683</td>
<td>140.207</td>
</tr>
</tbody>
</table>

Table 2: Life Cycle Cost comparison for the 1400 m curve at Kerzell

LCC - Rail Length and Welding

The failure statistics of railways prove that still a lot of failures arise from bad welds. The statement “The best weld is no weld” is very well known and therefore it is understandable that ultra long rails (up to 120 meters) are a very important contribution to the reduction of weld failures and thus an important contribution to the decrease of life cycle costs.

Summary

High strength rail steels proved to contribute to a significant prolongation of service life-time and at the same time reduction in maintenance costs. Depending on the rail hardness, improvement factors in wear and RCF resistance of 3 to 8 can be achieved compare to the standard carbon grade R260.

The exemplary life cycle cost analysis presented here demonstrated that using head hardened steel grades offers cost advantages of up to 50 % and improved availability by a reduction of the track maintenance possession time. voestalpine Schienen uses LCC calculations routinely as a proof for the validation of the benefit of innovations. The software model LCC Rail offers opportunities to offer comparative cost evaluations and determine optimum fields of application and maintenance procedures of different rail profiles and steel grades. With the know-how concentrated at voestalpine Schienen, the added value can be demonstrated, according to the individual case of the customer.

Outlook

Voestalpine will emphasize further on developing and testing advanced rail steels with the aim to increase both wear and RCF resistance. Reducing the LCC of components and products must be a strategic aim of both railways and their suppliers. This requires the identification and quantification of cost saving potential over the life cycle of the available technical opportunities. RAMS and LCC analysis are used to quantify the benefits perceived by customers, i.e. savings due to increased service life time and reduced maintenance costs of components [10]. The dynamic software model LCC Rail is a very suitable tool for this task and is used therefore regularly for technical customer consultancy by voestalpine Schienen. Value to customers is achieved by providing assistance for railroaders in terms of minimal LCC based decisions for investment and maintenance.

A new application field for advanced rail steels is currently investigated together with partners. The idea is to benefit from the advantages in track performance also in switches and crossings (S&C). Currently three projects are carried out with the application of the grades 370LHT and also bainitic rails in components of S&C’s. Results will be presented at a later stage.

References

[1] ProNetz; Information from DBAG 2007
[5] John Ruskin; British social reformer, 1819-1900