Advanced rail steels for Heavy Haul application – track performance and weldability

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Summary: Heavy Haul railroads focus on the long term on increasing the annual throughput by raising axle loads and train frequencies. Shorter time windows for maintenance make it increasingly difficult to achieve their goal of maximizing track availability. Therefore they require advanced track components, especially rails, as well as improved welding techniques that require less maintenance. This report represents an overview of such advanced high strength rail steels, their track performance in conjunction with applicable rail maintenance strategies (grinding in particular) as well as welding techniques that need less maintenance and promise to prolong service life time significantly. Since life cycle costing is becoming an integral part of the purchasing process of modern railways, an example life cycle cost analysis is presented.

Index Terms: premium rail steels, track performance, flash butt welding, aluminothermic welding, life cycle costing

1. Introduction

Although some Heavy Haul railroads have recently reduced shipment volumes due to the existing worldwide economic crisis, they must continue to replace worn and unsafe components and will still be required over the long term to maximize productivity and track availability in order to satisfy customer requirements. At the same time railroads have to improve economic performance and maintain the highest levels of safety.

Increasing axle loads – nominal 42 metric tons are already in service – and train frequencies create greater damage in the rail/wheel system, e.g. wear and rolling contact fatigue defects (RCF).

Track assets are costly, and therefore a lot of capital is bound in the infrastructure. These capital costs account for around half of the total track related costs. Therefore it makes sense for railways to require rails with the longest possible service life in order to reduce depreciation cost. The other half of the total costs is maintenance and track down time or hindrance costs, because these activities are not only costly themselves but also do influence track availability and downtime, respectively. In North America alone, railroads spend more than $2 billion a year on rail repair and replacement [1]. Control of RCF defects accounts for a significant proportion of the overall maintenance costs and is catalysed by high operation hindrance costs incurred by maintenance interventions. Therefore track components and rail in particular shall require the lowest maintenance and be as reliable and durable as possible.

Weldability is becoming of increasing importance to railways and thus welding techniques with advanced and cost effective procedures that ensure safe and reliable rail joints are a major concern for them.

These are the reasons why life cycle cost (LCC) considerations are becoming an essential part of the procurement process. Therefore railways are increasingly looking for advanced track components and procedures for installation, welding and maintenance that promise to reduce LCC.

2. The LCC-optimized solution concept

Reducing LCC is not only a strategic goal pursued by railways, but must also be the target for the manufacturing industry, because only the sustained reduction of LCC by premium products and advanced procedures creates customer benefit and satisfaction.

The LCC optimized solution concept adopted by voestalpine Schienen entails a combination of development and application of premium rail steels together with optimized welding procedures and maintenance concepts. In contrast to the usual pure technological performance evaluation, the new or advanced product is benchmarked with the actual “best practice product” currently considered by the railroad.

2.1 Premium rail steels

voestalpine Schienen offers a range of high strength premium rail steels, ranging from 350 to more than 400 Brinell hardness (BHN), see table 1. Increasing hardness results in both improved wear and RCF-resistance, two properties that are of equal importance to Heavy Haul railways.

Historically, the way to increase hardness in order to reduce wear was by increasing the Carbon content and alloying elements such as Chromium and Manganese. However, alloying limited the achievable hardness level to approx. 350 BHN. Since the 1990´s, heat treatment processes provide a solution for further increasing hardness. Premium rail steel producers currently achieve hardness levels above 400 BHN through the combination of metallurgical and heat treatment processes.

The rail grade R350HT is the basic heat treated steel grade according to the European rail standard EN13674 with a minimum hardness of 350 BHN. It is used in all types of rail traffic systems in Europe in tight curves to enable reasonable service life against wear.

The steel grade R350LHT is a Cr-alloyed (0,25 wt%) version of the R350HT and provides approximately 10 BHN higher hardness. Further

Rail Grade	Steel design	Tensile strength min. MPa	Elongation min. %	Hardness BHN	Properties and Application
R350HT	acc. to EN13674 Traditional HSH® rail	1175	9	350-390	3-fold wear and RCF resistance compared to R260 used in all European railway systems
R350LHT	acc. to EN13674 HSH® with 0,25 % Cr	1175	9	350-390	increased wear and RCF resistance for all application fields well established Heavy Haul grade in the 90´s
370LHT	acc. to voestalpine HSH® with 0,5 % Cr	1175	9	370-440	further increased wear and especially RCF resistance increasing application for heavy loaded tracks
400UHC	acc. to voestalpine HSH® with 0,95 % C	1240	9	400-440	highest wear resistance best choice for heavy haul application
UHC+	new steel design	1240	9	420-440	currently in test at HH application

Table 1: premium rail steels from voestalpine Schienen

increasing the Cr-content to approx. 0,5 wt% allows a rail hardness of 370-410 BHN to be achieved with a fully pearlitic microstructure.

Heavy Haul railways running with axle loads higher than 30 tons require the hardest rail steels because they provide the highest wear resistance currently possible. By combining carbon contents up to 1 wt% with the in-line head hardening treatment, a fully pearlitic microstructure with a hardness of more than 400 BHN can be produced. This hyper-eutectoid rail steel from voestalpine is called 400UHC ("ultra high carbon") and is used today by Heavy Haul railroads in Australia and Brazil.

Further developments to achieve hardness above 420 BHN on everyday production are going on.

2.2 Track performance

The track performance of these high strength rail steels has been evaluated in joint track test projects with various railways worldwide under a range of loading conditions. In general, all these tests prove that harder pearlitic rail steels show higher resistance against both wear and RCF.

The steel grade R350HT proved in various track tests, mainly conducted in light rail, mixed and high speed traffic systems, in average a threefold improvement regarding both wear and RCF resistance compared to the standard grade R260 [2,3].

This superior track performance together with significant reductions of life cycle costs of 35 % [4] encouraged European railways to increase the application fields for this grade. For example, Europe´s largest railway, Deutsche Bahn, revised its internal regulation for the use of the head hardened grade R350HT at the beginning of 2009. Before, their application was foreseen in curves with radii up to 700 m – according to the UIC leaflet 721 – and has been extended now to 1500 m radius thereby replacing the standard carbon grade R260 [5]. Austrian railways apply the R350HT grade up to 3000 m radius [6].

The grade 370LHT fulfilled the expectation of improved wear and especially RCF resistance in various tests on medium and high speed lines in Europe. Track tests on mixed traffic lines in Germany showed that the grade 370LHT achieves – depending on the specific loading conditions in certain track locations – a three to five times better Head Check resistance compared to the standard carbon grade R260 [7].

Tests in the Netherlands showed for 370LHT significantly better crack resistance compared to the grade R260Mn, too [8]. The results are not published yet. Thus this grade is implemented in the Dutch regulations for the use in curve radii up to 3000 m.

Tests with regards to Heavy Haul operations have been conducted at the Ofot Line in Norway, where iron ore is hauled with 25 to 30 tons axle load trains over curvy and steep tracks (20 ‰ inclination, Radius < 500 m). With 370LHT the lifetime has been doubled with respect to wear as compared to R350HT. In addition, the RCF damage by head checking and spalling was significantly lower for the harder rail steel, figure 1. It is noticeable that that there is more RCF damage on the R350HT after one year in service, than there is on the 370LHT two years of service.

This significant improvement was the reason for the Norwegian Railway Jernbaneverket to establish this grade as the standard grade on this heavy haul line.

On a Heavy Haul line with 36 tons axle load, rails with two different hardness levels, 370 and 400 BHN were tested in tight curves with less than 300 m radius. The results showed so far that a 30% improvement in wear resistance was realized by the 30 BHN increase in hardness.

Figure 1: rail surface of R350HT and 370LHT as observed at the Ofot Line.

Comparative test of the grades R350LHT, which were widely used by heavy haul railroads, and 400 BHN grades showed that a doubling of overall track performance due to increased wear resistance of 400UHC is possible. It should be noted that this improvement was achieved even when extensive grinding is included. Even greater improvement factors could be realized if rail grinding cycles were optimized.

A comprehensive comparative wear test has been conducted at FAST TTCI [1, 9], between high-end premium grades of different suppliers. In general, the test confirmed that the current generation of rail steels with hardness beyond 420 BHN showed an improvement in rail life of approx. 15 % as compared to 400 BHN rails.

Figure 2 displays possible improvement factors that can be achieved by using these premium rail steels based on results from track testing

2.3 Rail maintenance

Rails are ground or milled in order to maintain the target profile and control the extent of RCF damage. Modern railways try to implement preventive rail machining based on the "magic wear rate" [10]. These cycles should be the best fit

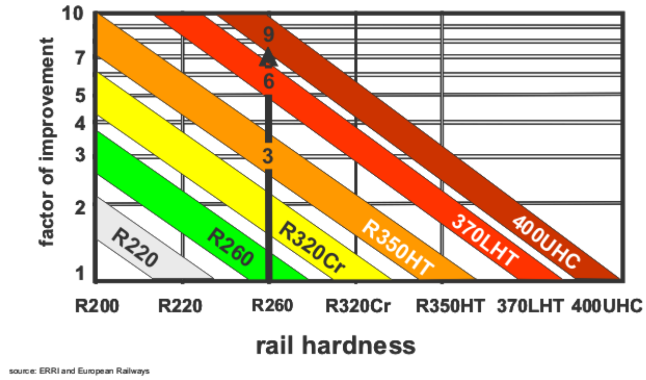

Figure 2: Improvement factors for various rail steels.

between metal removal rates, target profile and intervention cycle.

Higher hardness rail steels, new designs for the rail/wheel contact and lubrication/friction modifier techniques have led to a reduction in wear rates. Thus RCF has become the main issue for rail maintenance and of greater significance in determining rail life.

Unfortunately, the target grinding cycle is often not met because grinding trains are not available at a certain time or logistic issues increase the costs of rail grinding. Instead of preventive grinding, the rail surface is then ground in a corrective mode, when safety thresholds regarding depth of corrugation and cracks or deviation from the target profile are reached. Common preventive rail machining strategies of Heavy Haul railways nowadays foresee a grinding frequency of 40 to 60 MGT in larger curves (approx. 1000 m radius), 20 to 40 MGT in medium curves (approx. 700 m radius) and 10 to 20 MGT for curves below 300 m.

It was previously mentioned that premium rail steels need less maintenance due to their better track performance. To evaluate the needs for maintenance, quantitative figures were obtained from tests with the head hardened rail grade R350HT in comparison to the standard grade R260. R350HT rails need only half the number of grinding passes as compared to R260 to remove the head checks and produce the required rail profile [2]. In the same way, with a constant time-based grinding interval (due to availability and logistics), the amount of metal removal is much lower for the grade R350HT. Both described options help to cut rail maintenance costs.

Quantifying the potential of high strength rail steels to reduce maintenance and total cost is the main target of all voestalpine track tests. The cost impact of any reduction in maintenance efforts is the key factor of the LCC-optimized solution concept.

2.4 Welding technology

Weldability is one of the most important properties of a rail. Whether it is joint welding or repair welding, a rail has to be weldable. As a consequence, any testing or introduction of new rail metallurgy must be accompanied by extensive welding tests.

The quality of a weld is usually proven by three tests:

- Bending test
- Hardness test
- Microstructural examination

For the different welding methods, flash-butt, aluminothermic and electric arc welding, different limits for each test are applied in various standards around the world.

The bending test is done mainly as a pragmatic method for quality control, i.e. to recheck if the product quality is stable and consistent throughout time. Limits are different for flash-butt and for the aluminothermic process, which confirms that this is not a performance parameter during service.

The hardness across the joint should ideally be the same as the rail hardness. For all head hardened rail steels, a hardness drop can technically not be avoided at the limits of the heat affected zone (HAZ) by a law of nature. The hardness measured in this so-called spherodized zone is below 300 BHN no matter what rail metallurgy is used. In order to avoid battering at these points, the welding process must be adjusted so that these hardness valleys are as short as possible in the longitudinal direction along the rail.

In any case, the microstructure shall be pearlitic as the rail steel is. A brittle microstructure like martensite forms if the cooling after welding is too quick. If present, the risk of failure depends both on the martensite content and the location inside the rail.

2.4.1 Flash-Butt welding

Some 20 years ago, when the R350HT rail was introduced, it was recommended to apply forced cooling of the rail head after welding in order to achieve an appropriate hardness at the weld centre. For all new high strength rail steels, this must not be done in order to prevent martensite formation.

As mentioned before, adding alloying elements to the rail steel requires modification of the welding process. The most effective countermeasure for flash-butt welding is to apply additional heat input to slow down the cooling rate after welding. The higher the carbon-equivalent, the more heat has to be put in during the post-weld treatment process to support an appropriate cooling rate.

Tests done on different flash-butt welding machines showed that welding of the high-strength rail steels can be adapted easily by the number of pre- and post-heating impulses. We like to note that each welding machine must be studied individually because of its peculiar setup and characteristics.

2.4.2 Aluminothermic welding

The overall performance of thermite welds has improved during the recent years but rail fracture statistics [11] indicate that there is still potential for improvement. These improvements have been initiated by the introduction of single use crucibles and better control of the thermite consumables.

Further enhancements have been made by improving welder training and more stringent monitoring of welder skills. The weld quality depends strongly on the ability of the welder and the circumstances for the execution of the weld. In many cases, the superstructure maintenance and operator working conditions are under-appreciated factors affecting the weld quality.

The quality of thermite welds suffers under bad track quality and time pressure during the installation of the weld. Furthermore, thermite weld statistics are typically compared with those of flash butt welds that normally originate from new tracks or bigger track renewal sites where new rails and ideal working conditions can be found more often. Thus thermite welds are often not assessed correctly.

The Thermit® welding technology of Elektro-Thermit GmbH has monitored the rail grade developments and is already adapting to grades reaching hardness levels above 400 BHN.

This is shown by the plot of figures 3 and 4 that show the hardness distribution in the longitudinal direction along the running surface of welds, For standard rail grades and head hardened rails, standard aluminothermic welding processes can easily be used (Fig. 3). Advanced welding techniques can be applied for rails of higher hardness like 370LHT and 400UHC, see Fig. 4.

Elektro-Thermit has developed welding processes, e.g. SkV-Elite [12], which reduce the susceptibility to failures in execution. This has been realized with the shortest possible preheating duration and an optimized casting system that result in robust welds with the smallest possible heat affected zone.

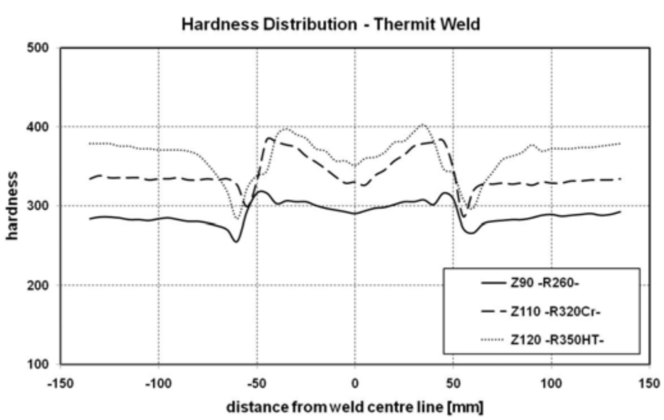

Figure 3: Hardness distribution in longitudinal direction of the weld (standard process).

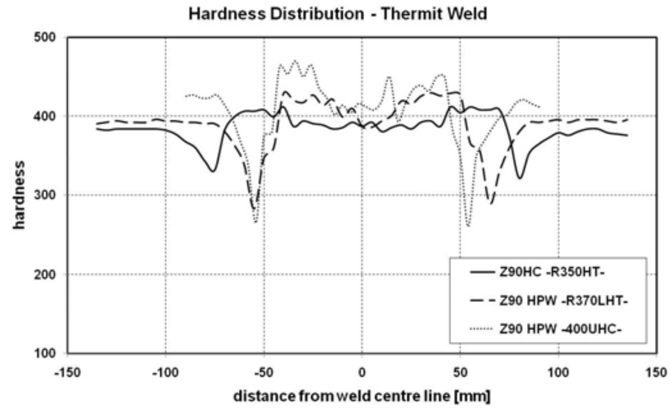

Figure 4: Hardness distribution in longitudinal direction of the weld (HC-procedure, HPW).

Besides providing a robust welding process, the properties of the weld become more and more important in the case of high strength rails. From Fig. 4 it can be seen that the drop of hardness in the HAZ is gaining more significance compared to welds of standard rail grades like R260. A small HAZ must be achieved in order to avoid defects in the weld and HAZ due to the pronounced variation of hardness.

Advanced techniques like the post heat treatment (HC) and High Performance Weld (HPW) processes offer a customized welding technology for all different traffic conditions and rail grades.
The basic idea behind the development of the HC-process and the HPW welding process is that the weld should obtain similar properties to the rail: a comparably soft and ductile foot and web, and the same hardness as the rail in the head with a high resistance against wear and rolling contact fatigue.

The HC-process is a post heat treatment that is applied to the finished weld. A Thermit® portion is used with slightly increased carbon content that achieves a low hardness in the weld metal after welding. Upon application of the HC post heat treatment on the running surface of the weld, the hardness of weld metal increases and reaches the

Figure 5: Principle of HPW – alloying elements are dissolved in weld head.

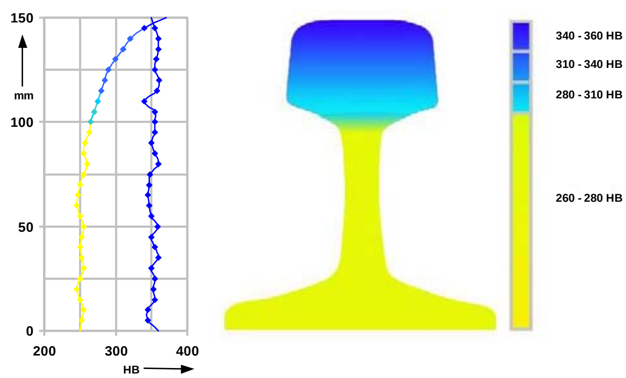

Figure 6: Hardness distribution within an HPW weld (vertical direction).

same level as the rail. The advantage of this process is that the original rail hardness of the weld HAZ is recovered and a new HAZ is formed outwards. Typically, the width of the new HAZ caused by the HC-process is much smaller (see figures 3 and 4) and less susceptible to battering.

Another advanced welding technique is the HPW process. This process provides a selective alloying system at the weld head with the use of comparably low alloyed Thermit® portions to generate a soft web and foot of the weld. Figure 5 shows schematically that alloying elements are dissolved in the head of the weld resulting in an increase of hardness (shown in figure 6 for rail grade R350HT in comparison with the hardness distribution of a standard weld providing a constant hardness of about 350 HBN).

However, the applicability of a welding process must finally be proven during the service in track. The HPW welding process has been successfully used at the Ofot Line in Norway for more than eight years. The first test welds were executed in 2000; the applied axle loads have since increased from about 25 to approx. 30 tonnes [13].
Figures 7 and 8 show hardness measurements on HPW welds performed in track immediately after installation and after 10 months. The hardness distribution in the initial state has the typical appearance shown previously.

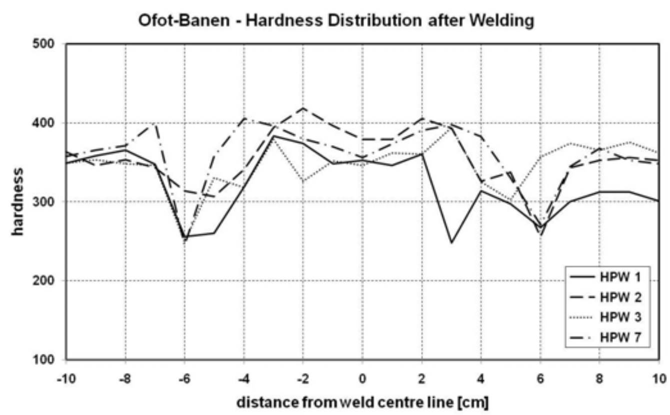

Figure 7: Ofot Line; In-track hardness measurement of HPW-welds (after installation)

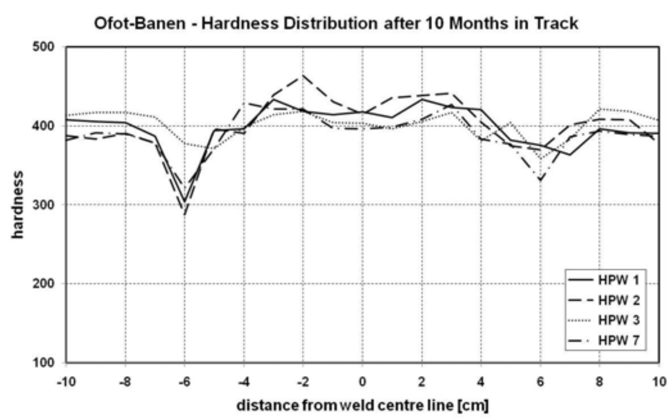

Figure 8: Ofot Line; In-track hardness measurement of HPW-welds (after 10 months exposed to traffic)

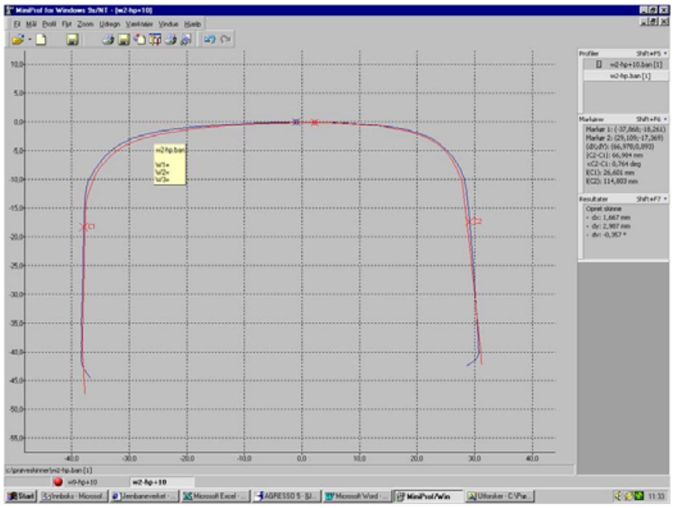

Figure 9: Ofot Line; Cross profile record (after weld installation)

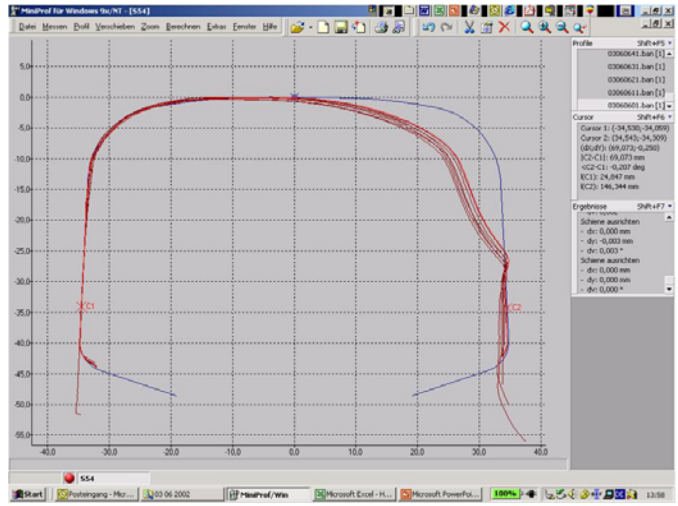

Figure 10: Ofot Line; HPW at 7,50 km; Cross profile record (after 22 months exposed to traffic)

After 10 months the hardness increases by about 50 BHN along the complete weld (including the HAZ), but the general appearance remains the same. The increase of hardness is caused by plastic deformation of the rail steel on the running surface and is a natural response of the steel to the applied load.
In figure 9 and 10, cross section profiles of HPW welds after installation and after 22 months exposure to traffic are shown. The profiles have been recorded in a curve (300 m radius) and exhibit severe wear of the rail during 22 months traffic. The measurements show that the performance of these HPW welds is nearly the same as the rail steel not exhibiting dipping or higher wear.

These results from Norway give evidence that advanced aluminothermic welding procedures are capable of producing reliable welds of high strength rail steels with significantly improved performance results.

2.5 LCC Considerations

Life Cycle Costing has already become a standard requirement in the railway business for the last decade. In order to quantify the economic impact of advanced rail steels, voestalpine Schienen has been participating in a number of LCC evaluation projects over the last ten years.

Together with ÖBB (Austrian Federal Railways) and the Technical University of Graz, Institute for Railway Engineering, a dynamic LCC software tool was developed “LCC RAIL” [14]. Using LCC RAIL, the annual expenses for financing the investments and also for maintenance and operational hindrance during the entire service life time of a new rail grade can be compared to those of the current best available solution. Thus two technical alternatives can be compared economically, based on the technical performance data obtained from in-track testing. LCC RAIL also enables a sensitivity analysis to be performed to safeguard the results of best/worst case scenarios.

The LCC calculation begins with the service life prognosis of the different rail grades under test. The service life model is simple in that it considers the “natural” wear and the amount of metal removed by grinding. Economic input data is the costs of individual maintenance interventions and financial data, such as the rates of interest and inflation. The LCC for the two rail grade alternatives can then be easily calculated.

For tight curves, where rail life governed by wear, LCC quantification considers primarily the life extension (factors of 2 or greater as mentioned previously) between rail renewals.

When RCF damage is the life-limiting factor, the comparison starts by sketching the total service life of the two alternatives considering all required maintenance activities and the limit for area loss of the rail head. This will be reached by adding the “natural” wear and the material removal by grinding. The grinding requirements are defined by the different needs of the new steel grades for removal of any RCF defects and the basic needs for profile control.

High strength rail steels contribute to a longer rail life in two ways:

- With better resistance to RCF damage they require less frequent grinding
- smaller changes of the rail head profile (as-rolled or as-ground target profile) due to higher resistance to wear and plastic flow

Particularly the latter property supports a stable rail-wheel contact that reduces the contact forces, provided that the proper rail head profile was ground at first.

Since it was not possible to obtain sufficient data at the time of writing this paper for a heavy haul condition based LCC analysis, an example analysis with data collected from DB for a mixed traffic operation, i.e. freight and passenger traffic on the same track, is presented here.

The life cycle as shown in Fig. 11 considers rail replacements due to wear and grinding of the different rail types studied. During the planned lifetime of 40 years, the softest rail R260 must be replaced twice, while all other head hardened rail steels will easily achieve a much longer rail service life. During that time, numerous grindings can be skipped due to the better RCF resistance of all head hardened rail steels, reducing the total costs by more than 50 %.

3. Conclusion

The LCC optimized solution concept presented in this paper entails the combined use of high strength premium rail steels with min. 400 BHN hardness, advanced FB and AT welding techniques for reliable joint welds with improved track performance as well as optimized rail maintenance strategies (grinding in particular) that are adjusted to the specific track and loading conditions, and also the improved performance pattern of these products.
Track performance evaluation programs proved that with premium rail grades, multiple rail service life times can be realized in comparison to softer steel grades. This contributes to the reduction of maintenance costs, too, because these steels require less grinding to manage RCF and maintain the required profile. Considering the importance of weld quality in preventing defects and premature failure, the performance of welds has been improved significantly by the presented FB and AT welding techniques for these high strength rail steels.

Rail grinding is a major contributor to material loss in the rail head. High strength rail steels bear the potential for a possible elongation of grinding cycles. This supports the increase of track availability and the reduction of down-time costs and maintenance costs respectively. However, it is only at the beginning that these elongated cycles are put into practice.

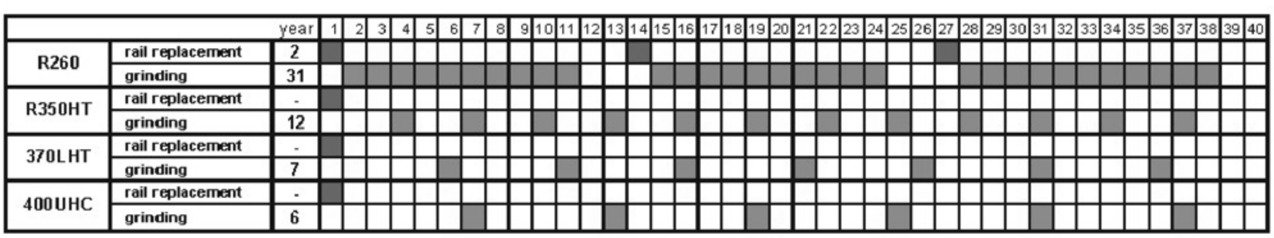

Figure 11: Life cycles corresponding to the track test results at DB presented in chapter 2.

Often grinding was not implemented in many cases due to costs and lack of knowledge. Logistical circumstances such as time windows for grinding and machine availability often play a dominant role for the effectiveness of the grinding strategy. Common projects between railroads, rail-machining companies and voestalpine Schienen aiming on the development of optimized rail machining procedures i.e. machining cycles perfectly adjusted to the rail grade strategy applied have been started.

Nevertheless, with the use of premium rail steels in conjunction with advanced welding procedures, less maintenance is needed. A perfect match of an optimized rail-grade strategy, which shall be based on specific loading conditions and damage pattern, together with optimized welding and last but not least maintenance procedures will increase reliability of track components (R), track availability (A) and improve maintainability (M) and safety (S) – RAMS [15]. Concurrently overall LCC can be reduced.

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