Paper 114

Proceedings of the Second International Conference on Railway Technology: Research, Development and Maintenance, J. Pombo, (Editor),
Civil-Comp Press, Stirlingshire, Scotland.

Naturally Hard Steel Rails: Development and Feedback from Service

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Abstract

Rail life in service can be strongly reduced by both excessive wear and extensive rolling contact fatigue (RCF) damage. Although several solutions exist on the market for premium rails, their use is limited to specific situations where specific needs arise. This work shows the outcomes of the installation of rails manufactured in naturally hard microalloyed steel in two opposite situations, i.e. in the low rail on a metro system (affected by extensive corrugation phenomena) and on the high rail of a conventional mixed-traffic railway (affected by wear and/or RCF damages). Welding procedures are analysed as well, ensuring compatibility with existing rails. Very promising results show that this steel grade could be used everywhere as replacement of the conventional rails made of R260 steel grade.

Keywords: rail, steel grade, wear, rolling contact fatigue, welding, hardness

1 Introduction

Track maintenance is heavily influenced by rail technical life. This can be defined as the overall duration of a rail before replacement, including all the treatments (grinding, reprofiling) that are intended to keep it in service as long as possible.

Apart for exceptional cases that should be treated correspondingly (such as extensive corrosion phenomena or sudden breakings), three types of damage normally limit the rail life:

- longitudinal profile modifications, due to corrugation (a special wavy unevenness of the rail), happening mainly in narrow curves and affecting therefore in an endemic way all metros and most of the conventional railways in mountain territories;

- lateral rail profile modifications, due to wear on the high rail and plastic flow on the low rail, happening as well on narrow curves on almost all railway systems;
- rolling contact fatigue (RCF) damages, mostly happening in mild radius curves (over 700-800 m and up to 1500-2000 m) where wear is less evident and steel is overloaded showing plastic flow, ratchetting, cracks, and so on.

The literature on the subject is extensive (see, for example, the proceedings of the last conference on "Contact Mechanics and Wear or Rail-Wheel Systems" [1]) and the reader is referred to it to deepen the concepts that led to the development of a number of *premium rail steels*.

The concept of a premium steel can be roughly but efficiently summarized in the quest of a steel that is less affected by wear (consider that in some cases the high rail must be changed within one year after lay down) and at the same time is less prone to be damaged by the classical RCF phenomena. About the last point, the famous accident that happened in Hatfield (UK) on 17 October 2000 [2,3] triggered a set of studies aiming at identifying the best "compromise" steel and the corresponding maintenance policies.

A compromise is in fact necessary, as long as to reduce wear a greater hardness is needed although, at the same time, this physical property is, generally speaking, promoting crack propagation and fracture mechanics. The effort of the rail manufacturers went mainly in the direction of finding a hard (or even ultra hard) steel without affecting RCF resistance. It can be said that the tendency of the market is towards the so-called *head hardened rails*, i.e. rails where the pearlitic structure of the steel is optimized (i.e. made finer) by an accurately controlled cooling process of the rail head after rolling. Rails are cooled down either with an on-line or an off-line hardening process [4] which makes the structure very fine, strong and resistant to RCF.

The other possible solution, which is only depicted here, is the possibility of using a *bainitic steel*, i.e. a rail that is massively cooled down with a specific cooling rate in order to get bainitic microstructure instead of pearlitic.

This paper shows the results of a long-lasting activity made with the Italian rail manufacturer Lucchini SpA to develop a microalloyed steel capable to reach the "premium" performances not by a specific thermal treatment but by a specific microstructure obtained after natural cooling on the existing cooling bed.

When designing the steel composition, a choice on the resulting hardness had to be done. Nowadays premium rails with hardness greater than 430 BHN exist, but their use is clearly very specific; a lower hardness was instead looked for, with the aim of finding a rail which could be used both in tangent track, in mild and narrow curves obtaining significant improvement of rail life without forcing the infrastructure owner to manage different steel grades in different locations. The resulting steel grade, internally named *VAR110*, with an average hardness of 330-340 BHN, was therefore tested in the laboratory where also welding processes were optimized.

This paper summarizes the results of application tests on the Naples metro and on a line near Zurich, showing and discussing the results obtained in revenue service. The in-service behaviour of existing R220 and R260 rails is shown as well and compared to *VAR110*, highlighting the advantages of the new steel grade.

2 Low-rail corrugation issues

2.1 Introduction

Although in some cases it may happen also on tangent track, rail corrugation is a phenomenon influencing almost all railways with curve radius in the order of or below 400-500 m. The genesis of corrugation is still unknown, although the *wavelength-fixing mechanism* is well established and accepted within the scientific community.

To limit the appearance (or the reappearance) of corrugation, a number of measures can be taken in practice, from self-steering bogies to the use of friction modifiers to limit the static friction coefficient. The first measure aims at reducing the sliding due to large angle of attacks of the wheelsets in conventional "rigid" bogies, while the second aims at reduction the sliding work (and therefore the removed material) by reducing the coefficient of friction. All the measurements can be applied together, although this can be harder in a conventional railway where the Infrastructure Owner is not coincident with the Railway Undertakings.

The use of harder rails has historically shown that they are a good remedy against roughness appearance and growth. As long as the classical wear approach is used (Archard's law), the amount of removed material is roughly speaking inversely proportional to rail hardness. This is consistent with the engineering experience that harder materials wear less, and harder rails are therefore expected to corrugate less. What is less evident, and this will be discussed in the following paragraphs, is the in-service behaviour of different rail steels, showing some partly unexpected trends.

2.2 Description of the application in Metronapoli

A number of 18 m-long rails were installed in the Naples metro, where all the assets (rolling stock and track) are managed by the operator Metronapoli SpA. The situation in a specific curve of this metro was discussed in detail by one of the authors [5], although corrugation phenomenon appears in almost all curves. The main parameters of the infrastructure are: maximum slope of 55 ‰, minimum curve radius of 208 m, full traction vehicles (all motor wheelsets).

As long as the metro was built in different periods of time, a mixture of track formations exist (ballast, concrete slab, floating slab) and rails of different steel grades are used, namely R220 steel [6] is used in the Northern part of the line (opened until 1995) while R260 steel is used in Southern part of the line (partly still under construction), all with 60E1 section. It was therefore decided to test *VAR110* rails in three different locations, where historical data (in terms of rail corrugation measurements before and after grinding) were available since long time. This was done with the goal of testing the rails in different service situations (traction, braking, track formation, curve radius) where corrugation recursively appears (see Figure 1 for some examples).

Figure 1: Rail corrugation appearance in a curve with floating slab track on Naples metro.

After the permission to run the tests was obtained by the competent safety authority (Ministry of Transportation) on the basis of the results of the laboratory tests phase, some rails were installed on the line. It is important to say that, beyond the obvious homogeneous *VAR110*/*VAR110* joint, both the flash butt and the aluminothermic welding processes of the *VAR110* steel grade were developed only for the use of an R260 steel grade as the parent rail, all according to European standards [7,8]. This forced, in one of the sites were an R220 rail was used, to introduce some short R260 bars between R220 and *VAR110* rails.

Only six bars, 18 m long for handling reasons, were available for testing. The following list shows the stations in between the rails were installed on low rails together with the installation and grinding date:

- Site 1) Medaglie D'Oro - Montedonzelli (Northbound – 18.5/11.10.2010);
- Site 2) Quattro Giornate - Vanvitelli (Northbound – 19.5/12.10.2010);
- Site 3) Materdei - Museo (Southbound – 20.5/20.10.2010).

Although the measurements after grinding will be mainly considered here, also some information will be given on *as rolled* rail roughness in order to highlight the requirements of preventative grinding on roughness growth. Hardness measurements were performed with the bouncing hardness meter *Equotip*, rail corrugation measurements were performed with *CAT* (*Corrugation Analysis Trolley*), transverse profiles were measured with *MiniProf*. As-rolled and just ground rails hardness measurement is difficult (the *Equotip* head is very small) and also the measurement of roughness has a lower accuracy due to the unevenness of the surface (oxides or grinding stones marks).

2.3 Corrugation growth

In order to give the reader an idea of the measurements and processing done on the data collected in Naples, only the results of Site 2 (the one described in [5]) are shown in some detail, while the Tables and Figures in the following will summarize the situation for all the three sites.

After *VAR110* rails lay down, the situation was as described in Figure 2. All the features described in [5] can be found, showing how the track exhibits the same behaviour year after year. New rails are pretty rough in the wavelength range of interest (30-100 mm). Figure 3 shows that initial rail roughness (rails *as rolled*) is in the order of ±20 μm in this wavelength range, but the overall spectrum is extended well beyond this range. As rail grinding was postponed for service reasons, it is interesting to observe how rail roughness grew slightly 145 days after *VAR110* rails lay down without showing any periodicity (roughness remained a “broadband” process).

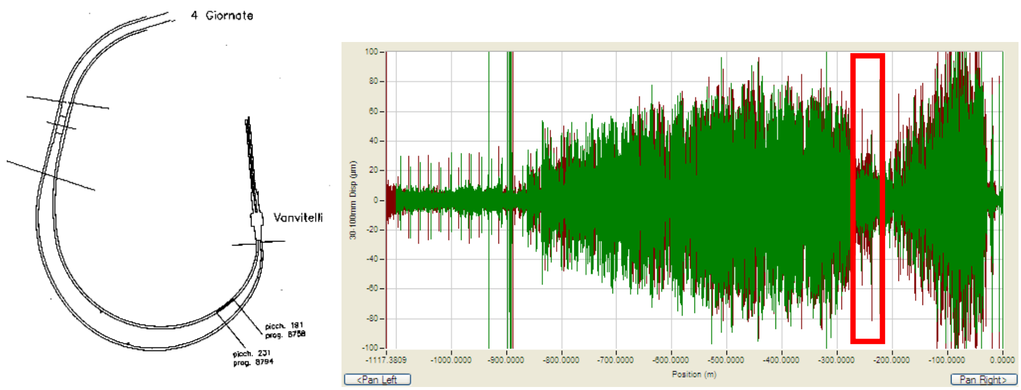


Figure 2: Left: track geometry in Site 2 (Metronapoli). Right: low rail roughness 66 days (green) and 145 days (red) after *VAR110* bars lay down. Peak-to-peak amplitudes greater than 200 μm can be observed in the 30-100 mm wavelength range in the existing R260 rails. *VAR110* bars are indicated in the red box.

Grinding was therefore performed by traditional tangential stone grinding train. The resulting roughness RMS was uniformly below 4 μm as requested by the grinding specifications in force at that time [9]. After barely 90 days the situation went back almost to the one before grinding (20 to 45 µm block RMS) except for the *VAR110* region where roughness remained consistently below 5 µm RMS (Figure 4).

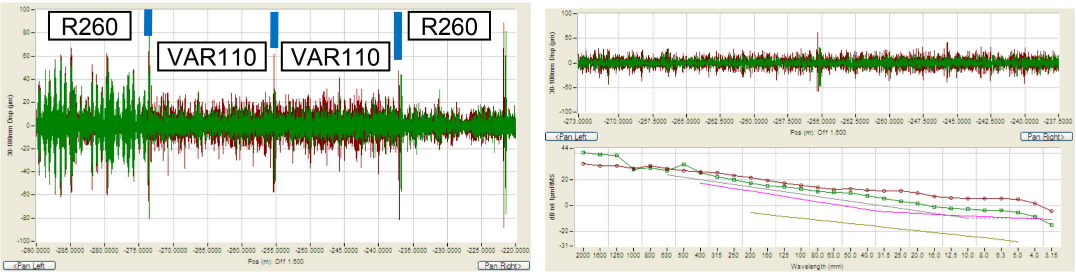


Figure 3: Left: close up in the region where two 18 m-long *VAR110* bars. Right: rail roughness spectra of *VAR110* bars 66 days (green) and 145 days (red) after lay down.

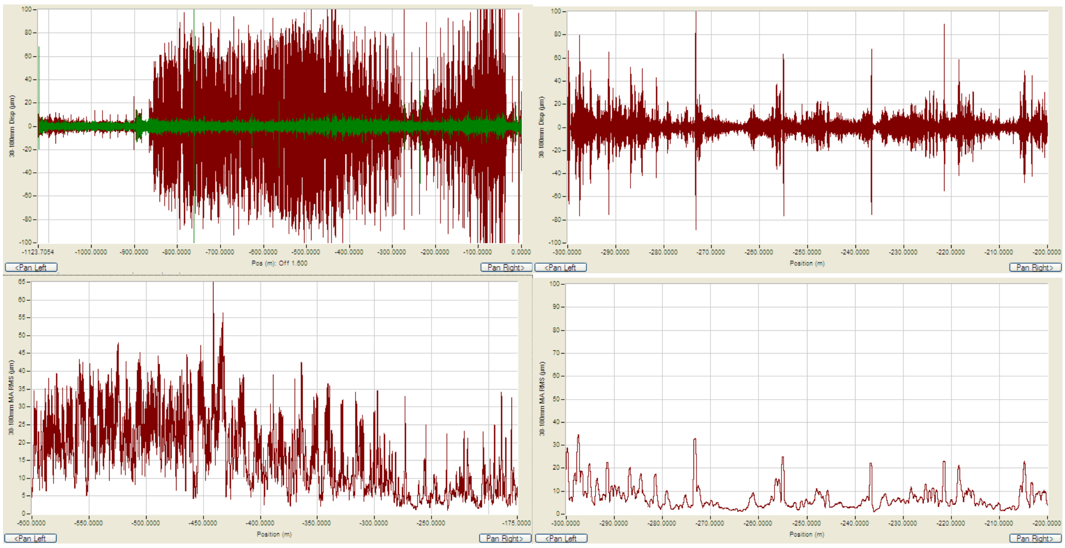


Figure 4: Comparison of rail corrugation 1 day (green) and 90 days (red) after grinding (top left). Close up on the *VAR110* bars (top right). Block RMS values (base = 0.5 m) for the final part of the track (bottom left) and on the *VAR110* rails (bottom right).

A similar behaviour was found in the other sites, confirming that short-term outcomes were all very positive. These results, published elsewhere [10], showed that corrugation after 90 days was still growing; a final check was therefore performed after a further year from the last measurement considered above, showing that corrugation reappeared on all rails, including *VAR110* rails.

Two different criteria were chosen to globally compare the behaviour of *VAR110* rails and pre-existing R220/R260 rails, i.e. the use of exceedence of a threshold (set at 10 μm) and the RMS value of the corrugation in the usual wavelength range 30-100 mm. These criteria were applied to each bar in order to avoid mixing the results. The reduction of rail roughness is clear (Figure 5) for both site 1 and site 2, where it is in the order of 15% to 40% respectively. It must be said that site 2 suffered by a “boundary effect”, i.e. the *VAR110* bars were apparently affected by the preceding R260 rail, whose corrugation “propagates” inside the *VAR110* rail probably for vibrations transmission reasons. A countertendency behaviour is observed for site 3, where corrugation increases faster on *VAR110* rails than on following R260 rails. This was explained by the different residual exceedence roughness after grinding, that in this case was in the order of 13 μm for the first bar and 7 μm for the second bar, while in the other sites was consistently below 2 μm. The authors did not attend the grinding process and therefore no hypotheses on the technological parameters used can be done; in any case roughness growth is slightly slower in this site showing some differences that should be investigated in greater detail.

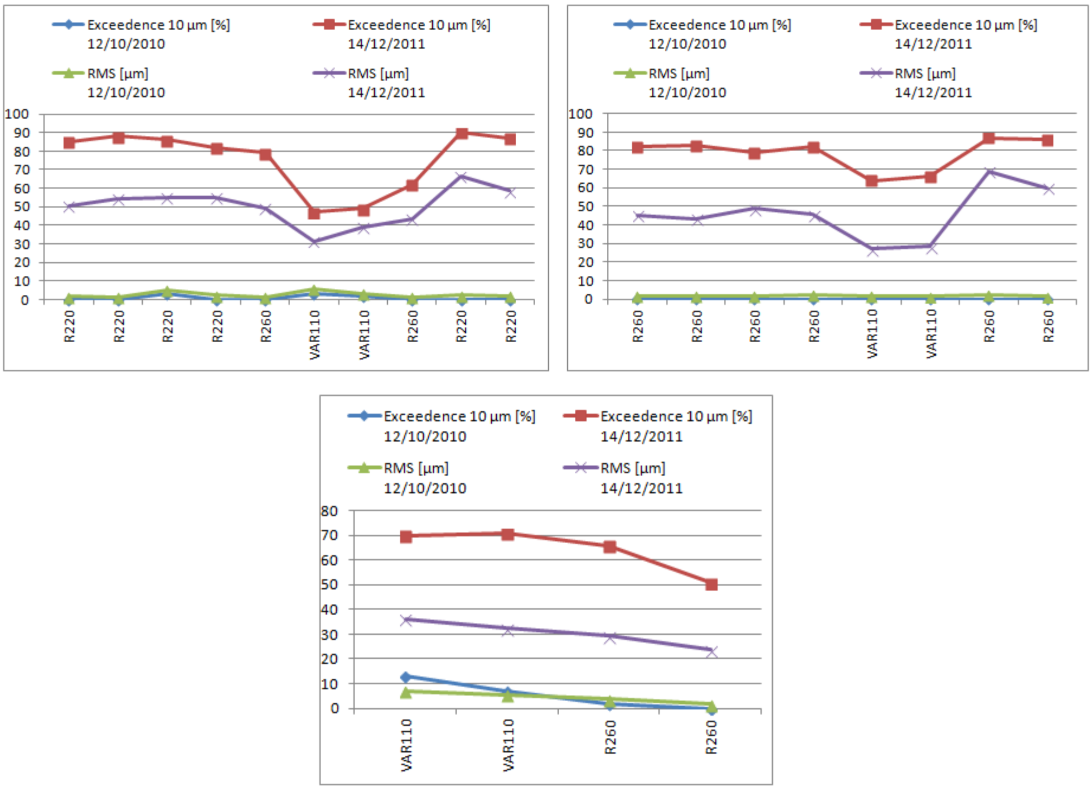


Figure 5: Exceedence of 10 μm threshold and RMS roughness in the 30-100 mm wavelength for site 1 (top left), site 2 (top right) and site 3 (bottom) after grinding (lower curves) and after approximately 14 months (upper curves).

3 High-rail wear and contact fatigue issues

3.1 Introduction

As aforementioned, wear and cracking are competitive phenomena, in the sense that wear is undesirable but “wipes away” growing cracks. Search a more durable rail inevitably passes through the selection of a harder steel with higher risks of potential failures in service of the rails for RCF problems.

History tells that great expectations from “hard” rails often fail due to side effects related to RCF. This was the case of the Hatfield accident, after which no railway administration would accept the installation of rails different from the “conventional” R260 steel grade without extensive tests including checks on railhead damages due to RCF. In order to evaluate the feedback from service in a demanding application, it was decided to plan a test on a conventional railway line (axleload of 22.5 t/axle) with mixed traffic.

3.2 Description of the application in SBB-Zurich Seebach

Tests were made between Zurich Seebach and Regensdorf, where existing head hardened premium rails installed on Swiss railways (SBB) suffered extensive railhead damage as shown in Figure 6. A total of 486 m of *VAR110* rails were install in a reverse curve, including a short tangent section and the corresponding transitions. The minimum curve radius was 439 m, a value that justifies to make recourse to *premium rails* in order to limit as much as possible rail gage face wear. Line speed is 100 km/h and the traffic volume is around 8.5 MGT/year. As a result of the application on only one rail, part of the *VAR110* bars resulted to be installed on the low rail and part on the high rail.

Figure 6: Extensive railhead damage shown by a heat-treated *premium rail* installed on the high rail in a track near Seebach Zurich. These rails were replaced with *VAR110* naturally hard rails.

3.3 Rail wear

The first issue was to check whether the developed steel grade was resistant enough to wear as on-board flange lubrication often proves to be largely insufficient to protect the rail gauge face from rapid wear. Lucchini choice to select an *as-rolled* hardness of around 330-340 BHN had to be verified in comparison with rails manufactured by the competitors where hardness goes well beyond 400 BHN.

A set of railhead transverse profile measurements was planned after installation (10 July 2009), after grinding (16 September 2009) and during periodic visits, with the last measurement performed on 27 April 2012, i.e. more than 2.5 years of service. This time span is often sufficient to observe railhead wear of several mm, reaching in some cases the maximum allowable value that forces to replace the rail. The resulting wear in the SBB test site was observed to be negligible, in some cases below the repeatability of the measurements, made with *MiniProf* (see for example Figure 7). It can be concluded that, at least from the wear point of view, the test was completely satisfactory.

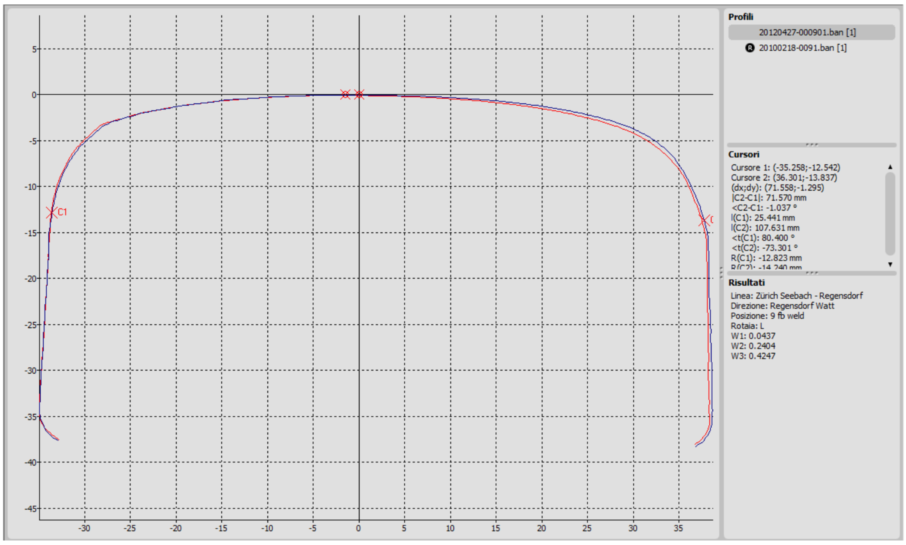


Figure 7: Original (after grinding) and last measured transverse profile of railhead in the SBB curve near Seebach Zurich (R=439 m) after about 34 MGT.

3.4 Rolling Contact Fatigue phenomena

Excluding naked eye observable defects like spalling, shelling, squats, etc., RCF problems starts with small size and features that need to be checked with other NDT methods. The chosen one was the well-known surface check with dye penetrant (PT). Compared to other volume methods (such as UT, Ultrasonic Testing), PT cannot reveal cracks that start inside the material (where the combination of normal and tangential stresses reaches its maximum) but only cracks that appear on the surface.

One of the most popular defects is called “head checks” or “hairline cracks”. With these terms the appearance of fairly parallel fine cracks, oriented with respect to the rail axis with an angle which depends on traction and curving forces, is indicated. These cracks can coalesce leading to detachment of initially small portions of the railhead and eventually lead to the destruction of the railhead shoulder (or “rail gauge corner”) such as already shown in Figure 6. In case there is energy enough, these cracks can “branch”, with the upper branch leading to spalling and the lower branch leading to complete split of the rail. An early detection of head checks is therefore needed in order to suggest further controls, such as the already mentioned one with UT, in case the analyst finds evidences that may rise doubts about the integrity of the rail.

Correct usage of PT requires long application times to allow the dye penetrant to fill the cracks and favourable environmental conditions. Unfortunately application times had to be short and weather was often bad in this particular case, as it was not possible to stop traffic for the long time needed to investigate in detail around 500 m of rail and checks were planned without considering weather conditions. For this reason it resulted not possible to use PT during some rainfall and, in any case, the application time of the dye penetrant was in the order of ten minutes, which is normally considered to be insufficient. All the actors involved in the tests considered, anyway, that the outcomes of the tests performed in Zurich Seebach are reliable enough to decide whether keep the rails in service or not.

Figure 8 shows the worst situation found on the *VAR110* rail 2.5 year after grinding. RCF appeared as approximately 45° inclined hairline cracks. This evidence was discussed in detail with SBB, which observed that “these head checks are very stable and visible only on the ending part of the curve” and concluded “very good behaviour of this *VAR110* rails”.

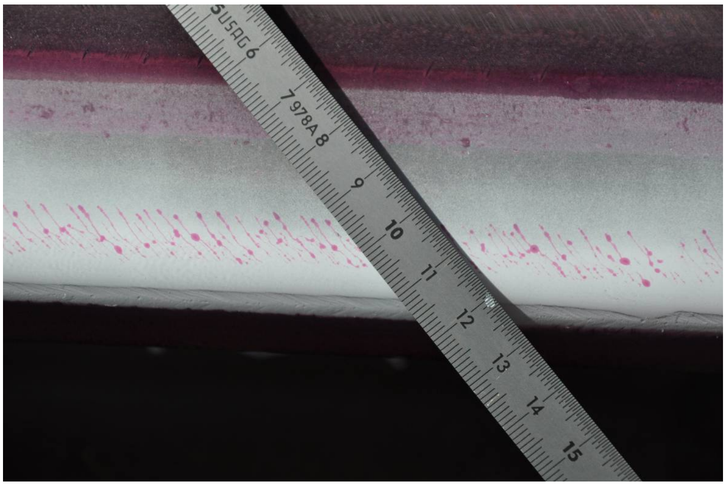


Figure 8: Head checks found on the *VAR110* rail during the last test (27.04.2012). High rail, running direction left to right.

4 As-rolled and in-service rail hardness

4.1 Introduction

Hardness has always been acknowledged as one of the fundamental parameters for rail steel grade selection. While the old UIC regulations were expressed in terms of ultimate tensile stress (for example the UIC 900A rail had an UTS of 900 MPa), the current European and International Standards refer to as-rolled hardness. This is a consequence of the fact that the empirical evidence that hardness expressed with the Brinell scale is approximately the 30% of the UTS expressed in MPa does not hold anymore for head hardened rails, for which the hardness gradient on the railhead is noticeable and volume properties such as UTS obtained from specimens taken from the bulk part of the rail section make less sense.

Although the transition from R220 (ex UIC 700) to R260 (ex UIC 900A) rail was in practice completed in the '80s for main and also for regional lines, it should be said that as-rolled hardness is destined to change dramatically during service due to the well-known mechanism of strain hardening (or work hardening). When a steel component that exhibit a large elongation before rupture (ductile steel) is stressed beyond the yield stress, a plastic deformation occurs and the mechanical properties of the steel increase before the UTS is reached. Work hardening of rails is exacerbated by the high longitudinal forces that arise in narrow curves and that can saturate the available friction limit. In this case wheels slip on the rail removing some railhead material and generating a work hardening of the surface layer of the rail. This phenomenon, coupled to the complex vertical and lateral forces arising from Hertzian contact and large angle of attack, excite a "wavelength fixing mechanism" which is eventually responsible for rail corrugation.

4.2 Rail hardness in Metronapoli

As already discussed, Metronapoli network has a mixture of R220 and R260 rails, laid down in 1992-1995 and in 2001-2002 respectively. During the activities linked to the observation of the behaviour in service of the new *VAR110* steel grade, a large number of hardness measurements were taken in different places on the line (straight track, curves, in the stations, etc.).

The results of these measurements are summarised in Figure 9. Some interesting conclusions can be drawn by looking at these values, where the number in brackets represent the hardness increase compare to the "as rolled" condition:

- R220 rails in Montedonzelli station (straight track) have an average hardness close to 270 BHN (+50 HBN), due to work hardening during braking and acceleration (no grinding was done on these rails);

- R260 rails in Quattro Giornate station (straight track) have an average hardness close to 305 BHN (+45 HBN), for the same reasons (no grinding was done on these rails);

- R220 rails in the Medaglie d'Oro – Montedonzelli curve had an average hardness close to 300 BHN (+80 BHN). Please consider that at the time of the first measurement, the rails were ground 15 months before. After grinding the hardness went back to 274 BHN on a rail while remained identical (300 BHN) on the other rail. This let's suppose a different depth of the hardened layer. In any case, two months after grinding, hardness returned to 295 BHN (+75 BHN), very close to that before grinding. After one more year, average hardness remained practically unchanged (298 BHN, +78 BHN), even if it decreased in one case (from 292 BHN to 281 BHN) and increased in another case (from 300 BHN to 316 BHN). These variations are believed to be linked to corrugation, and in the second case it appears that rail hardness is not saturated yet as it increased by further 16 BHN;

- R260 rails in the three curves where *VAR110* rails were installed, had the following initial values before grinding:
  - site 1: close to 292 BHN (+32 BHN)
  - site 2: close to 352 BHN (+65 BHN)
  - site 3: close to 320 BHN (+60 BHN)

  These values, only marginally affected by grinding, were substantially confirmed two months after this trackwork operation, as follows:
  - site 1: close to 295 BHN (+35 BHN)
  - site 2: close to 317 BHN (+57 BHN)
  - site 3: close to 326 BHN (+66 BHN)

  After one more year, the final average value reached was 328 BHN, i.e. +18 BHN w.r.t. the previous value. In one section, the hardness reached 350 BHN, a value very high for a rail with a nominal hardness of 260 BHN (+90 BHN). Also in this case further hardening appears possible.

- *VAR110* rails in the three curves where they were installed, had very similar initial values:
  - site 1: close to 325 BHN (-5 BHN)
  - site 2: close to 330 BHN (0 BHN)
  - site 3: close to 337 BHN (+7 BHN)

  Three months after grinding hardness values were:
  - site 1: close to 327 BHN (-3 BHN)
  - site 2: close to 334 BHN (+4 BHN)
  - site 3: close to 348 BHN (+18 BHN)

  After one more year, the final average value reached was 346 BHN (+10 BHN w.r.t. the previous value), barely +16 BHN compared to the original "as rolled" hardness. Also in this case further hardening appears possible.

The situation is summarised in Figure 10, showing how all the rail installed in the curves are affected by work hardening, even if in different proportion (R220= +78 BHN, R260= +68 BHN, VAR110= +16 BHN).

	FIRST MEAS.	SECOND MEAS.	AFTER GRINDING							
R220 rails in a station (expected hardness: 220 HBN)	13/07/2010	11/10/2010								
Montedonzelli	269 ± 21	269 ± 8								
R260 rails in a station (expected hardness: 260 HB)	13/07/2010	11/10/2010								
Quattro Giornate	301 ± 15	312 ± 20								
R220 rail in a curve with corrugation (expected hardness: 220 HB)	13/07/2010	11/10/2010	12/10/2010	21/10/2010	28/10/2010	08/11/2010	02/12/2010	10/01/2011	14/12/2011	Final average
Medaglie D'Oro-Montedonzelli (lato Montedonzelli)	296 ± 8	274 ± 11	280 ± 14	288 ± 7	289 ± 4	276 ± 9	287 ± 6	292 ± 4	281 ± 4	298
Medaglie D'Oro-Montedonzelli (lato Medaglie d'oro)	302 ± 14	300 ± 16	297 ± 10	283 ± 7	282 ± 3	286 ± 8	295 ± 6	300 ± 5	316 ± 3	
Average Brinell hardness values of R220 rails	299	287	288	286	286	281	291	296	298	
R260 rail in a curve with corrugation (expected hardness: 260 HB)	13/07/2010	11/10/2010	12/10/2010	21/10/2010	28/10/2010	08/11/2010	02/12/2010	10/01/2011	14/12/2011	Final average
Medaglie D'Oro-Montedonzelli (18 m bar on Montedonzelli side)	292 ± 24	286 ± 25	264 ± 8	294 ± 7	304 ± 3	292 ± 4	289 ± 5	297 ± 5	312 ± 5	328
Medaglie D'Oro-Montedonzelli (9 m bar on Medaglie d'Oro side)	292 ± 9	277 ± 19	270 ± 12	293 ± 6	302 ± 5	300 ± 4	290 ± 4	293 ± 4	313 ± 7	
Quattro Giornate - Vanvitelli (Vanvitelli side)	323 ± 7	330 ± 20				315 ± 9	326 ± 7	318 ± 7	322 ± 11	
Quattro Giornate - Vanvitelli (Quattro Giornate side)	329 ± 13	322 ± 15				299 ± 4	321 ± 7	316 ± 3	334 ± 6	
Materdei-Museo (Materdei side)	325 ± 5	315 ± 25				321 ± 6	323 ± 6	330 ± 5	350 ± 5	
Materdei-Museo (Museo side)	317 ± 22	330 ± 14				343 ± 6	310 ± 3	322 ± 9	337 ± 8	
Average Brinell hardness values of R260 rails	313	310	267	293	303	311	310	313	328	
VAR110 rails in curves with corrugation (expected hardness: 330 H	13/07/2010	11/10/2010	12/10/2010	21/10/2010	28/10/2010	08/11/2010	02/12/2010	10/01/2011	14/12/2011	Final average
Medaglie D'Oro-Montedonzelli (Montedonzelli side)	327 ± 29	328 ± 18	307 ± 11	323 ± 7	339 ± 8	326 ± 5	324 ± 5	319 ± 5	349 ± 7	346
Medaglie D'Oro-Montedonzelli (Medaglie d'oro side)	323 ± 5	328 ± 16	320 ± 17	327 ± 6	330 ± 11	340 ± 6	335 ± 9	335 ± 5	333 ± 8	
Quattro Giornate - Vanvitelli (Vanvitelli side)	335 ± 7	337 ± 20				336 ± 9	340 ± 7	338 ± 7	343 ± 11	
Quattro Giornate - Vanvitelli (Quattro Giornate side)	323 ± 14	328 ± 15				320 ± 8	327 ± 5	330 ± 6	340 ± 7	
Materdei-Museo (Materdei side)	337 ± 25	355 ± 11				327 ± 5	335 ± 4	348 ± 5	357 ± 12	
Materdei-Museo (Museo side)	337 ± 15	355 ± 18				327 ± 3	335 ± 5	348 ± 6	357 ± 9	
Average Brinell hardness values of VAR110 rails	330	339	314	325	334	329	333	336	346	

Figure 9: Rail hardness measured in Metronapoli network.

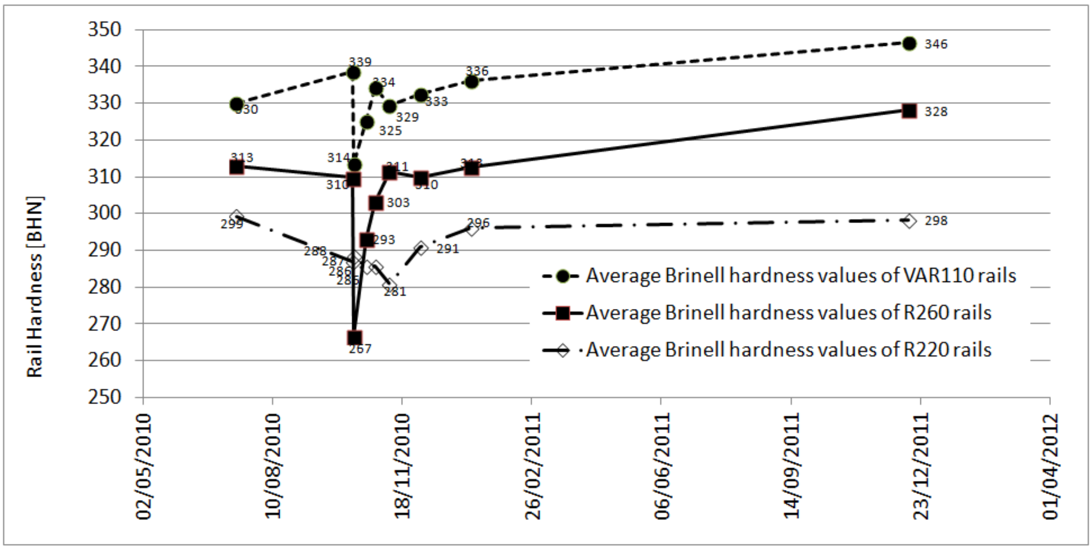


Figure 10: Rail hardness measured in Metronapoli network plotted vs. time.

4.3 Rail hardness in Switzerland

The tests in Switzerland showed a rather constant hardness of *VAR110* bars. This parameter was constantly monitored over the test campaign, but for clarity only the results obtained after the last check are shown in Figure 11 after 34 MGT traffic. It can be observed that rail hardness is rather constant, and that the average is exactly the original "as rolled" expected hardness. In this case it can be said that rolling forces did not induce any work-hardening of the railhead. Although not detailed here, the reader can easily check that there is no relationship between the hardness and any of the other track parameters (cant, radius, low or high rail). The relatively high and constant hardness value is responsible for the very low wear already discussed.

Rail #	km	Rail length [m]	Curve radius [m]	Cant (superlevation) [mm]	Low or high rail	Average twist [mm/m]	Speed of trains [km/h]	Non-compensated acceleration [a_{nc}]	Hardness measurements on the rails (10 samples in the same area on the running band)										Average rail hardness [HBN]	
1	27.743	35	-1306	-50	Low	-0.8	100	0.26	335	335	335	335	335	335	337	335	382	340	**340**	
2	27.778	36	-1412	-47	Low	1.0	100	0.24	331	331	324	328	328	332	327	328	330	336	**330**	
3	27.814	36	-200384	-1	Low	1.6	100	0.00	340	335	335	332	328	330	327	326	331	328	**331**	
4	27.850	36	1207	55	High	1.6	100	0.28	324	326	324	328	328	326	326	326	327	327	**326**	
5	27.886	35	593	112	High	1.6	100	0.57	326	331	330	340	332	330	327	330	327	327	**330**	
6	27.921	36	454	145	High	0.3	100	0.75	328	322	320	320	320	322	330	323	327	327	**324**	**Global average**
7	27.957	36	439	150	High	0.0	100	0.78	340	332	331	335	337	328	331	331	327	326	**332**	**330 ± 8**
8	27.993	36	439	150	High	0.0	100	0.78	335	336	335	336	327	327	328	335	332	330	**332**	
9	28.029	36	439	150	High	0.0	100	0.78	341	343	348	348	348	343	350	344	343	340	**345**	
10	28.065	36	439	150	High	0.0	100	0.78	331	324	324	326	319	319	327	320	326	323	**324**	
11	28.101	36	439	150	High	0.0	100	0.78	340	339	340	337	332	328	337	332	333	339	**336**	
12	28.137	35	439	150	High	0.0	100	0.78	327	322	333	326	332	330	328	330	326	324	**328**	
13	28.172	35	508	130	High	-1.2	100	0.67	331	330	336	333	327	328	328	331	333	326	**330**	
14	28.198	18	685	96	High	-1.4	100	0.50	322	317	315	317	323	319	319	315	320	318	**319**	

Figure 11: Rail hardness measured near Zurich Seebach after 34 MGT traffic. The yellow line indicates the straight track in between the two curves of the "S" shaped track.

5 Weld hardness and straightness profiles

5.1 Introduction

The welding process is responsible for modifications in the railhead profile. Although there are in practice only two welding processes, namely the aluminothermic (AW, [7]) and the flash butt (FBW, [8]) processes, the modifications in the rail microstructure are quite noticeable.

It is quite common that the AW process is more sensitive to metallurgical change. This technique requires that the rails that have to be welded are separated by approximately 25-30 mm and in this volume a welding portion is melt thanks to a exothermic reaction and cast in a refractory mould. The nearby areas that are not melt, known as HAZ (*heat affected zones*) suffer by the greatest hardness modifications, despite welding post-treatments (with propane burners and/or muffles).

As a result, and even if the weld is accurately ground, after a short time a differential wear (or simply a different settling of the railhead due to different mechanical properties) is almost always shown. This unevenness of the geometry of the running band induces noise, vibrations and, more important, high stresses in the weld that is, by far, the most fragile component of the rail.

When developing the *VAR110* steel grade, the greatest attention was placed to optimise the welding parameters with some quite ambitious goals:

- AW had to be possible by using the same portions used for R260 rails, working on post-treatment to guarantee the maximum uniformity of hardness profile;
- post-treatments of AW joints had to be limited at the minimum such that they do not constitute an obstacle or a limitation for in-service repair or lay-down welds;
- FBW parameters followed a similar rationale, checking the feasibility of best hardness profiles with existing welding machines.

The welding processes were developed at Swiss Railways, Elektrothermit GmbH and CSM (*Centro Sviluppo Materiali*) laboratory fulfilling all the requirements.

5.2 Welds hardness in Metronapoli

One of the three sites, i.e. site 1, had all of the three types of possible AW of interest in this works, namely a R220/R260 weld, a R260/*VAR110* weld and a homogeneous *VAR110*/*VAR110* weld. These welds were monitored by measuring 11 points, 20 mm apart centred on the weld axis, in order to highlight changes in rail hardness especially in the HAZs and/or affecting the parent material or the portion itself.

Figure 12 shows the profiles of the three welds monitored over the measuring campaign, with a particular emphasis to the values measured during the last campaign (14.12.2011). It can be seen that the hardness profile is very irregular for the R200/R260 case (where HAZ hardness is and remains much lower than that of the parent rail – remind that the weld is in the low rail of a narrow curve where corrugation regularly appears), while it is more regular for the R260/*VAR110* heterogeneous joint.

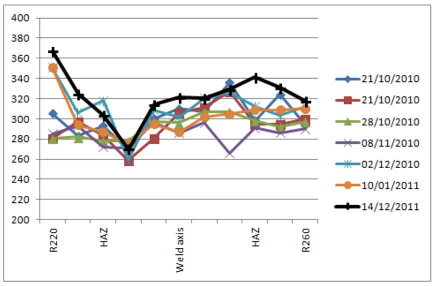
It is particularly interesting to observe that hardness is quite constant for the homogeneous *VAR110*/*VAR110* rail, where the last measurement has an average value of 346 BHN (incidentally equal to that of the average hardness of all *VAR110* installed rails) and a standard deviation of barely 9 BHN. In this case the work hardening has improved the profile by increasing the hardness of HAZs until a practically constant hardness profiles is reached.

5.3 Welds hardness in Zurich Seebach

Fifteen welds were present in the Zurich Seebach installation, most of them were “homogeneous” AW and FBW made on *VAR110*/*VAR110* rails (2 to 14) while weld number 1 and number 15 were AW “heterogeneous” (weld 1= R260/*VAR110*, weld 15=*VAR110*/head hardened rail). Figure 13 and Figure 14 show the hardness valued measured at the end of the measurement campaign, after approximately 34 MGT, in a set of points identical to the one used in Metronapoli. It can be observed that hardness is exceptionally constant and close to the parent material one; moreover, the deviations from the average value are limited to 10÷15 BHN. What’s more important, hardness profiles do not exhibit the typical behaviour where hardness reaches a minimum in correspondence of the HAZs.

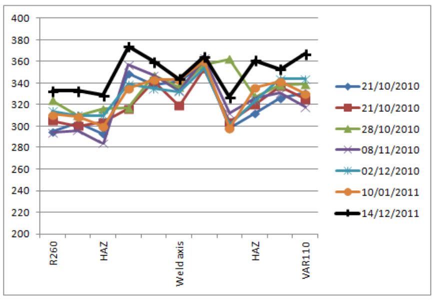
R220/R260 weld Montedonzelli side

		21/10/2010	21/10/2010	28/10/2010	08/11/2010	02/12/2010	10/01/2011	14/12/2011
R220	1	305	281	281	285	351	351	367
	2	283	297	282	293	306	294	325
HAZ	3	293	283	278	272	318	287	304
	4	269	259	278	271	260	275	270
	5	300	281	297	296	309	295	314
Weld axis	6	310	306	296	286	302	287	321
	7	307	311	307	296	320	302	320
	8	336	327	307	266	326	305	329
HAZ	9	298	295	298	291	312	309	341
	10	324	295	292	286	303	309	331
R260	11	294	300	297	290	312	310	318
Average hardness		**302**	**294**	**292**	**285**	**311**	**302**	**322**
Std. dev.		**18**	**18**	**11**	**10**	**22**	**20**	**24**



R260/VAR110 weld Montedonzelli side

		21/10/2010	21/10/2010	28/10/2010	08/11/2010	02/12/2010	10/01/2011	14/12/2011
R260	1	295	305	324	294	314	311	333
	2	303	300	310	296	310	309	333
HAZ	3	293	304	316	284	310	300	329
	4	349	316	317	357	339	335	374
	5	338	342	347	347	335	343	360
Weld axis	6	342	319	336	333	332	343	344
	7	358	353	357	363	354	360	365
	8	298	304	362	312	302	298	327
HAZ	9	312	320	327	326	324	336	361
	10	326	337	338	331	344	342	353
VAR110	11	331	325	339	318	344	330	367
Average hardness		**322**	**320**	**334**	**324**	**328**	**328**	**350**
Std. dev.		**23**	**17**	**17**	**26**	**17**	**20**	**17**



VAR110/VAR110 weld

		21/10/2010	21/10/2010	28/10/2010	08/11/2010	02/12/2010	10/01/2011	14/12/2011
VAR110	1	333	327	331	343	332	358	347
	2	337	337	325	330	331	333	343
HAZ	3	332	336	323	302	312	335	344
	4	351	349	348	347	343	317	366
	5	339	332	344	285	348	344	344
Weld axis	6	317	326	329	319	335	324	336
	7	348	342	341	333	342	352	349
	8	347	324	365	352	363	352	356
HAZ	9	306	306	314	313	311	280	346
	10	338	320	336	332	325	337	339
VAR110	11	337	337	347	336	338	331	335
Average hardness		**335**	**331**	**337**	**327**	**335**	**333**	**346**
Std. dev.		**13**	**12**	**14**	**20**	**15**	**22**	**9**

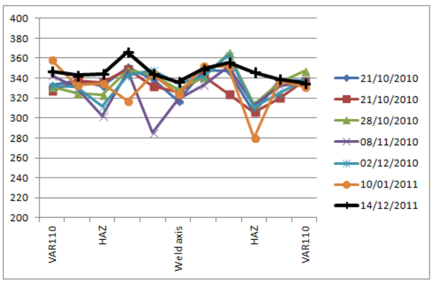


Figure 12: Hardness of AW joints in Metronapoli.

Weld	km	Curve radius [m]	Cant (superelevation) [mm]	Low or high rail	Speed of trains [km/h]	Non-compensated acceleration [a_{nc}]	Point 01 (-100 mm from weld axis)	Point 02 (-80 mm from weld axis)	Point 03 (-60 mm from weld axis)	Point 04 (-40 mm from weld axis)	Point 05 (-20 mm from weld axis)	Point 06 (on weld axis)	Point 07 (+20 mm from weld axis)	Point 08 (+40 mm from weld axis)	Point 09 (+60 mm from weld axis)	Point 10 (+80 mm from weld axis)	Point 11 (+100 mm from weld axis)
Distance form weld axis							-100	-80	-60	-40	-20	0	20	40	60	80	100
W1A	27.725	-1882	-36	Low	100	0.17	305	305	267	331	332	320	332	326	314	348	357
W2F	27.760	-1000	-64	Low	100	0.35	351	352	344	344	320	315	330	340	340	337	335
W3F	27.796	-2402	-29	Low	100	0.13	326	327	332	326	323	298	314	341	347	352	347
W4A	27.832	2461	27	High	100	0.14	333	330	313	295	359	339	320	332	336	336	336
W5F	27.868	800	83	High	100	0.42	326	328	330	327	308	289	304	324	328	323	327
W6F	27.903	471	140	High	100	0.72	336	337	333	333	333	312	303	332	328	339	331
W7A	27.939	439	150	High	100	0.78	324	326	322	297	314	327	327	300	312	340	341
W8F	27.975	439	150	High	100	0.78	340	343	339	346	331	302	313	335	328	333	336
W9F	28.011	439	150	High	100	0.78	341	336	337	335	335	299	315	346	347	354	347
W10A	28.047	439	150	High	100	0.78	346	344	343	320	315	332	328	318	328	327	327
W11F	28.083	439	150	High	100	0.78	327	327	327	328	319	288	328	358	343	347	358
W12F	28.119	439	150	High	100	0.78	347	336	333	330	330	297	318	337	333	336	335
W13A	28.154	439	150	High	100	0.78	352	347	341	287	339	328	326	339	292	331	328
W14F	28.189	602	109	High	100	0.57	313	310	302	310	279	318	319	365	352	350	348
W15A	28.207	794	83	High	100	0.43											
Average values on welds							**333**	**332**	**329**	**327**	**327**	**320**	**325**	**333**	**332**	**335**	**340**
Standard deviation							**11**	**10**	**16**	**15**	**14**	**15**	**10**	**12**	**15**	**9**	**10**

Figure 13: Welds hardness in Zurich Seebach. The last letter in the weld name indicated the welding process (A=AW, F=FBW).

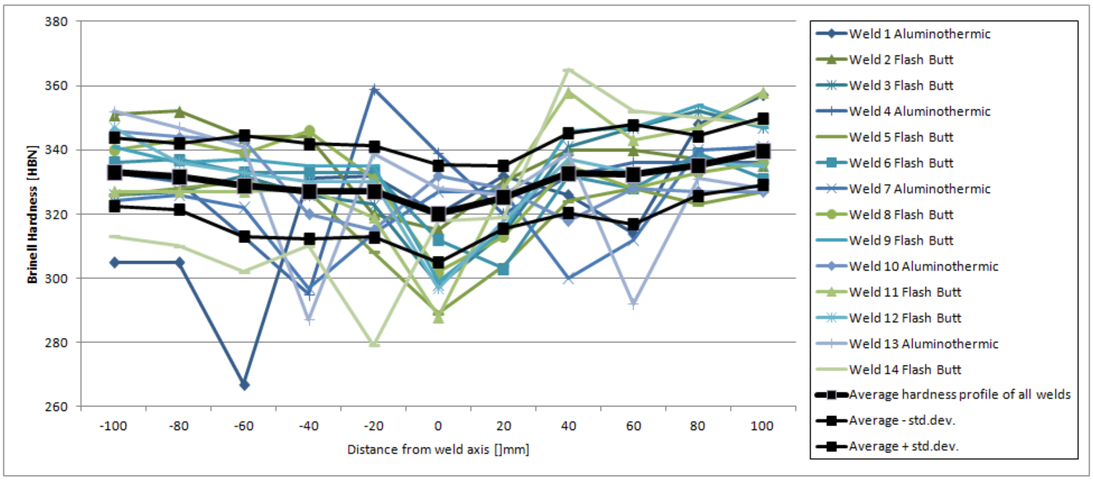


Figure 14: Hardness profile for all welds in Zurich Seebach.

5.4 Welds straightness in Zurich Seebach

As long as train speed and axleload in Naples are rather limited (around 60 km/h and 12 t/axle respectively), longitudinal weld profile is not much important. This can't be said for Zurich Seebach installation, where both train speed and axleload are much higher (100 km/h and 22.5 t/axle). That's why measuring straightness of welds was considered to be important.

It is worth to remind that weld straightness results not only from weld preparation but also from welding process management in terms of post-treatment. Table 1 shows the straightness at the end of the test campaign (after 34 MGT). The values of deviation from perfect straightness are encouraging, showing that neither the welding process nor the rail lay down highlighted any kind of criticality.

Weld	Straightness deviation [mm]
W1A	-0.30
W2F	0.20
W3F	0.10
W4A	-0.25
W5F	-0.07
W6F	-0.10
W7A	-0.30
W8F	0.30
W9F	0.15
W10A	-0.35
W11F	-0.08
W12F	0.25
W13A	-0.40
W14F	0.20

Table 1: Straightness deviation for welds in Zurich Seebach

6 Conclusions

A new steel grade developed by the company Lucchini SpA, named *VAR110*, was tested in some demanding applications, including a metro where corrugation extensively appears and a conventional rail where wear and rolling contact fatigue are a major issue.

All the aspects of the application of a new steel grade were considered. Once the compatibility of the new steel grade with the existing infrastructure in terms of weldability was ensured, all typical properties that are requested to a *premium rail*, i.e. resistance to wear, corrugation, RCF damages were verified in the laboratory and with very demanding field tests.

Particularly promising results were discussed and criticised. The main goal of the rail manufacturer, which is the development of a harder steel rail which may constitute a valid alternative to the traditional R260 rails not only in some critical areas but as a replacement for standard rails seems to have been brilliantly achieved as *VAR110* rails last for longer, have less RCF problems, corrugate less and result in very good welded joints.

The test sites described in the paper are going to be monitored again in the future, as long as the railway and metro administrations involved decided to keep the rails in service; what's more, other even more demanding sites are going to be opened together with the first supplies of *VAR110* rails to some selected infrastructure owners.

At the moment, Lucchini SpA is proposing the *VAR110* rail to be included in the revision process of the European Standard EN 13764-1 with the name "R330".

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