EVALUATION OF IN-SERVICE BEHAVIOUR OF DIFFERENT TYPES OF ULTRA-HARD RAILS

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ABSTRACT

The phenomena related to the maintenance in efficiency of the railway infrastructure are subject to continuous studies and investigations as the related actions have an important role from both a security and an economic point of view.

In the present work an activity of inspection and monitoring of the tracks of a main railway line characterized by low radius curves is shown, in order to find a correlation between measurements of rail gauge face wear obtained automatically and a set of parameters including the PK, the curve radius, the gauge, the application of ultra-hard rails (obtained with naturally cooled alloy steel or with thermally treated railhead), the use of trackside lubricators, the data of traffic (cant excess or deficiency), any other critical points in the track or layout geometry.

The attention is focused on wear rate of ultra-hard rails, whose value has a direct implication on maintenance costs and scheduling and, in some instances, is also related to safety. Maintenance implications are depicted, including grinding strategies in order to reduce to a minimum the effect of RCF damages (head checking) that were evident in some sections where these rails were installed.

INTRODUCTION

The useful life of rails in curved track mainly depends on the wear deriving from the contact occurring between wheel flange and high rail, while low rails may be affected by corrugation phenomena that lie outside the scope of this paper.

In order to reduce costs and to better manage maintenance operations, the tendency to use ultra-hard rails led to many applications that were only partly successful. The Hatfield accident (UK, 17 Oct 2000), where head-hardened rails broke in service leading to a high speed derailment with four casualties, raised the question of the best conditions for the applications of such rails and opened a debate on how to avoid as much as possible the consequences of a phenomenon, the so-called Rolling Contact Fatigue (RCF), that was almost neglected in the past.

This papers describes the outcomes of an activity performed by RFI (Rete Ferroviaria Italiana, the Italian infrastructure owner) on some sections of the picturesque main line Genova-La Spezia, in the North-West of Italy, that has curves with radius in the range 300 to 600 m and a maximum train speed in the order of 100 km/h. Following current RFI regulations, rail wear measured on the railhead as the distance between the new and the worn profiles at 45° has a safety limit of 15 mm. Some sections of the line under investigation require a rail change every 9 months, and the related costs are clearly very high.

RFI decided in 2000 to plan the installation of ultra-hard rails in some curves with radius lower than 600 m in order to evaluate the in-service behaviour of two types of steel (R320Cr and R350HT).

The present work included a thorough survey of all the sections where ultra-hard rails are installed and the analysis of the data collected by RFI measuring trains (named *Talete* and *Archimede*). As a comparison, some sections with the standard hard steel grade R260 (corresponding to the UIC 900A steel grade) were considered.

One of the great concerns about the use of hard rails is the potentially increased wear rate of wheels. Textbooks and practical experience suggest that the maximum wear is got when the contact pair is made of the same material; changing the structure or the hardness of one of the elements of the pair leads to a reduction of the *global* wear that is shared between the harder and the softer element, with a reduction of *both* the wear rates.

Nevertheless, abnormal wheel flange wear is often noticed and reported after re-railing with new rails, no matter the rail steel grade. This is simply due to the “bed-in” of the rail profile that is suddenly inserted in a context where worn rails are used to work with worn wheels. The abnormal wear in fact disappears after a few weeks or months, when profile coupling lead to a better distribution of mutual loads. Clearly, harder rails take a longer time to wear (that’s the main reason for their use!), suggesting some different strategies to prevent or to mitigate the problem.

TRACK GEOMETRY CHARACTERISTICS

The line considered was built at the beginning of the 20th Century in a particularly difficult area, as it can be easily observed by looking a map. The 40 km-long section studied is between Genova Brignole and Rapallo, along a magnificent portion of the Mediterranean Sea coast that is famous for the extremely favourable climate that allows extensive flower cultivations. Rocks, promontories and gulfs inspired poets, but from the civil engineering point of view the line was a real nightmare, being a sequel of tunnels, bridges and numerous stations that relieved local populations from centuries of isolation. Track is characterized by a infinite number of curves, the longest straight track being concentrated in a stretch of 3 km close to Santa Margherita Ligure. No slope is present, as the line altitude remains practically unchanged, some meters above see level.

Trains in Italy are numbered with odd numbers for trains running from the North to the South and from the West to the East; as a consequence, in the following the “odd track” will be the one from Genova to Rapallo and the “even track” the one in the opposite direction.

TRAFFIC DETAILS

The considered line has a mixed traffic load whose composition remained practically unchanged since 2000. The main train operating company, Trenitalia SpA which belongs to the same holding (FS SpA, Ferrovie dello Stato) of RFI SpA, renamed some typology of trains but, as mentioned, it did not bring to a substantial variation of the traffic mix.

The traffic for the last three years (2004 to 2006) is shown in Table 1, where an approximate figure of 1000 trains / month per direction can be observed. It can be retained that the traffic is uniform and that any variation of rail wear rate can not be ascribed to its variations.

RAIL STEEL GRADES CONSIDERED

European railways nowadays use normally for rails the steel grade R260 (CEN, 2003). It corresponds to the formerly called “hard rails UIC 900A” (UIC, 2005), whose ultimate tensile stress is around 900 MPa. This steel, which is harder than the previously used steel grade “UIC 700”, was gradually adopted by the former

FS starting from the early ‘80s and it was since increasingly used until it became the Italian standard rail steel grade in 1991.At the same time, the profile used was standardized to the 60E1 profile (CEN, 2003) that corresponds to the UIC 60 profile (UIC, 2005).

RFI launched in 2000 a test installation in some sections of the Genova – La Spezia line of what are colloquially known as “head hardened rails”. Clearly, this designation is strictly valid only for rails whose increased performances against wear are obtained by a specific railhead cooling after rolling, while it has no sense for rails that get their “naturally hard” properties by the usual normalization in the cooling bed. Throughout the rest of the paper the rails under test will be therefore called “ultra-hard rails”.
As already mentioned, two types of ultra-hard rails were tested:

- the R320Cr steel grade, manufactured by Lucchini (chromium-alloyed steel naturally cooled, with an ultimate tensile stress of approximately 1100 MPa);
- the R350HT steel grade, manufactured by Voest Alpine Schienen (head hardened carbon-manganese steel with an ultimate tensile stress of approximately 1200 MPa, obtained through a thermal treatment of the surface with a cooling process).

It is important to underline that at the moment of the decision to test these steel they were not normalized yet, as the EN 13671-4 standard (CEN, 2003) was published only during 2003. A summary of the mechanical properties of the steel grades is shown in Table 2, while the reader is referred to the standard for the many other properties.

The application of ultra-hard rails along the line is shown in Table 3. All the curves with ultra-hard rails have radius lower than 600 m and the maximum cant is 160 mm.

Train type following RFI names convention	*2004*	*2005*	*2006*
Diretto			1942
Espresso	1551	1495	1193
Intercity	6019	5705	5724
Interregionale	3685	3490	1180
Merci rapido speciale	1118	1095	1033
Regionale	8563	8722	9182
Treni combinati	1826	2286	2531
Treni combinati speciali	1068	1096	988
Others	3445	3764	3232
TOTAL	*23830*	*23889*	*23773*

Table 1. Number of trains travelled in the years 2004-2006 divided for train typology

Rail steel grade	Brinell hardness HBW [MPa]	K_{Ic} (MPa $m^{1/2}$) Min single value	K_{Ic} (MPa $m^{1/2}$) Min mean	ΔK= 10 MPa $m^{1/2}$	ΔK= 13.5 MPa $m^{1/2}$	*Rm* min. [MPa]	Min. elong. *A* %
R260 (UIC900 A)	260÷300	26	29	17 m/Gc	55 m/Gc	880	10
R320Cr (1100)	320÷360	24	26	---	---	1080	9
R350HT (HSH/1200)	350÷390	30	32	17 m/Gc	55 m/Gc	1175	9

Table 2: Mechanical properties of rail steel grades (from (CEN, 2003))

No.	RFI Curve number	Rail steel	Curve Radius [m]	Cant [mm]	Right Rail PK start	Right Rail PK end	L [m]	No.	RFI Curve number	Rail steel	Curve Radius [m]	Cant [mm]	Right Rail PK start	Right Rail PK end	L [m]
1RE	34	R260	508	120	12.091	12.444	353	1RO	34	R260	508	120	12.091	12.444	353
1LE	34	R260	508	120	12.091	12.444	353	1LO	34	R260	508	120	12.091	12.444	353
2RE	43	R320Cr	391	140	14.176	14.500	324	2RO	35	R350HT	380	160	12.460	12.760	300
2LE	44	R320Cr	374÷479	130	14.528	14.909	381	2LO	37	R320Cr	429÷382	160	12.838	13.018	180
3RE	45	R320Cr	479	90	14.852	15.010	158	3RO	37	R320Cr	429÷382	160	12.838	13.018	180
3LE	44	R320Cr	479	90	14.783	14.909	126	3LO	43	R320Cr	391	140	14.190	14.500	310
4RE	47	R320Cr	403		15.230	15.430	200	4RO	44	R320Cr	374	130	14.515	14.887	372
4LE	46	R350HT	403	140	15.100	15.364	264	4LO	45	R320Cr	519	90	14.906	15.050	144
5RE	48÷49	R320Cr	498÷497	100	15.616	15.635	19	5RO	46	R320Cr	403	140	15.150	15.402	252
5LE	47	R320Cr	403		15.430	15.857	427	5LO	48	R320Cr	392	120	15.676	16.631	955
6RE	48÷49	R320Cr	498÷497	100	15.675	16.320	645	6RO	49	R350HT	356	130	16.358	16.880	522
6LE	53÷54	R350HT	433	110	18.020	18.615	595	6LO	50	R320Cr	397	120	16.910	17.090	180
7RE	53÷54	R350HT	387	120	18.130	18.346	216	7RO	53	R350HT	433	110	18.050	18.410	360
7LE	56	R350HT	398÷437÷402	120÷110÷120	19.487	20.261	774	7LO	56	R350HT	437	110	19.904	20.300	396
8RE	56	R350HT	398÷437÷402	120÷110÷120	19.487	20.261	774	8RO	55	R350HT	424	110	18.635	19.030	395
8LE	57	R350HT	467÷491÷509	130÷120	20.550	21.040	490	8LO	58	R350HT	380	120	21.235	21.450	215
9RE	65÷66	R320Cr	452÷382	130÷160	28.395	28.895	500	9RO	59	R350HT	629	70	21.756	21.925	169
9LE	58÷59	R350HT	487÷419÷353	120÷140÷120	21.446	21.662	216	9LO	66	R320Cr	410	130	28.350	28.860	510
10LE	64	R320Cr	421÷529 ÷433÷450	120÷80 ÷140÷130	26.782	27.600	818	10LO	66	R320Cr	561÷438 ÷448÷461	110÷140 ÷130÷110	28.884	29.420	536

Table 3: Location of the ultra-hard rails. The assigned number (first column) is used for reference in the following.

RAIL WEAR DATA

Data collected by the automatic measuring coaches that RFI continuously uses to check the status of the Italian railway infrastructure were made available and processed. The *Archimede* measuring train is able to measure every 50 cm numerous parameters related to the track geometry (right and left rail longitudinal level, right and left rail alignment, cant, twist, gauge, track curvature) and to the rails geometry, both on the gauge face (horizontal, vertical and 45° rail wear) and on the field side (plastic flow). An older measuring coach, named *Talete*, with lower capabilities, was used in the past but those data are not considered here for uniformity and simplicity, requiring further processing and calibration.

As an example of the available data, Figure 1 shows some worn profiles compared to new ones. As usual, the rail head gauge corner tends to assume the shape of the wheel flanges contacting it, although more slowly in case of ultra-hard rails. From the entire profiles and their relative position it is possible to derive wear parameters and the track gauge. As an example, Figure 2 shows the 45° rail wear obtained after the processing all the rail profiles in a generic run.

DATA PROCESSING, RESULTS AND RAIL LIFE ESTIMATION

The numerical data, shown in Figure 3 for the both the odd and the even track, were obtained by averaging the 45° wear along the entire ultra-hard rail; this process, applied to data with good numerousness, allows to remove automatically single values, whose effect would have altered the result in case of short measurements.

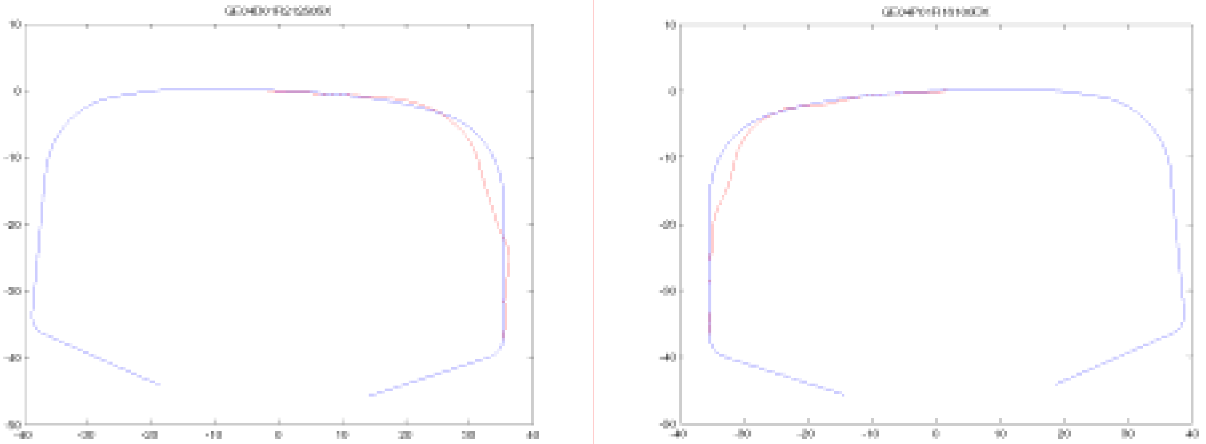

Figure 1: Comparison between reference rail profiles (UIC 60, laid 1:20) and real rail profiles

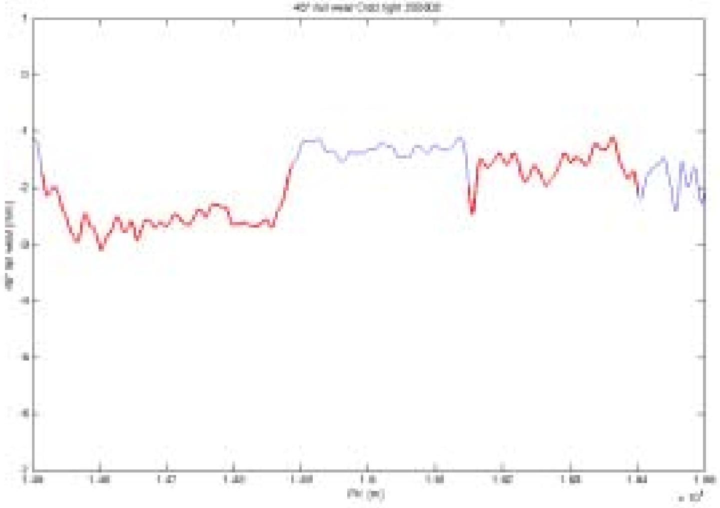

Figure 2: Typical printout of the rail wear at 45° measured by *Archimede* during a test run. Red segments were introduced during post-processing and are related to ultra-hard rails locations.

While some sets give results apparently coherent, some others don't. It can be related to other operations on the track (re-railing, grinding, track renewal) that are not described here and to the intrinsic error in the measuring system that was conceived to work as a safety-related device and therefore sensitive to large deviations from the original profile (let's say in the order of 10 mm or more).

Although a numerical general rule can not be derived from the entire set of data, nevertheless it can be stated that the wear rate is in relatively limited and certainly lower than that observed with R260 rails. As the initial wear rate is different for different rails, a general conclusion on the expected life of ultra-hard rails in service can not be reached. Anyway, it is quite likely that the wear rate will decrease with the adaptation of the rail profile to the average wheel profile. This leads to the conclusion that the estimations presented hereinafter should be considered as absolutely conservative, leading to an expected life that will be certainly lower than that that will be reached in service.

Measuring date	1RO	2RO	3RO	4RO	5RO	6RO	7RO	8RO	9RO
2004-11	-0.3	-0.5	0.2	-0.5	-4.8	-0.6	-0.4	-0.9	-0.5
2005-06	-0.4	-0.9	-0.4	-0.5	-5.0	-1.2	-0.8	-1.3	-0.8
2005-11	-0.6	-0.7	-0.4	-1.2	-6.5	-1.7	-1.4	-1.9	-0.6
2006-02	-1.3	-2.4	-1.3	-2.5	-1.6	-3.0	-2.6	-2.9	-1.9
Average wear [mm/month] 2004-11 2006-02	0.07	0.12	0.10	0.14	-0.21	0.16	0.15	0.13	0.09
Years to rerailing 2004-11 2006-02	16	9	12	8	-6	7	8	9	13

Measuring Date	1LO	2LO	3LO	4LO	5LO	6LO	7LO	8LO	9LO
2004-11	-5.8	-1.1	-0.5	-0.3	-0.3	-0.4	-0.4	-1.5	0.0
2005-06	-1.4	-1.1	-0.8	-0.3	-0.7	-1.1	-1.1	-1.4	-0.8
2005-11	-3.5	-2.6	-2.5	-1.9	-2.3	-2.9	-2.4	-2.9	-2.6
2006-02	-2.2	-1.3	-1.1	-0.4	-1.1	-2.0	-1.4	-1.6	-1.3
Average wear [mm/month] 2004-11 2006-02	-0.34	-0.19	-0.17	-0.09	-0.17	-0.32	-0.15	-0.17	-0.20
Years to rerailing 2004-11 2006-02	-3	-6	-7	-12	-7	-4	-8	-7	-6

Measuring Date	1RE	2RE	3RE	4RE	5RE	6RE	7RE	8RE	9RE
2004-11	-5.4	-0.6	-0.9	0.1	-0.6	-1.0	-0.2	-0.7	-1.3
2005-06	-1.8	-2.3	-2.5	-0.7	-0.6	-3.5	-0.9	-0.7	-7.8
2005-11	-3.1	-4.0	-3.1	-1.8	-2.2	-3.6	-2.6	-1.7	-3.0
2006-02	-5.1	-6.3	-5.8	-3.8	-1.2	-4.8	-3.0	-1.2	-9.2
Average wear [mm/month] 2004-11 2006-02	-0.02	0.38	0.33	0.25	0.04	0.26	0.19	0.03	0.52
Years to rerailing 2004-11 2006-02	-58	3	4	5	31	5	6	35	2

Measuring Date	1LE	2LE	3LE	4LE	5LE	6LE	7LE	8LE	9LE
2004-11	-0.2	-0.4	-0.4	-1.3	-0.1	-0.6	-0.2	-2.3	-1.7
2005-06	-1.0	-1.1	-1.0	-1.8	-0.8	-1.2	-0.9	-2.1	-2.1
2005-11	-0.7	-0.5	-0.4	-1.8	-0.4	-0.9	-0.4	-2.1	-2.3
2006-02	-1.7	-2.3	-2.1	-2.9	-1.8	-2.1	-1.5	-3.2	-3.3
Average wear [mm/month] 2004-11 2006-02	0.10	0.13	0.11	0.10	0.12	0.10	0.09	0.06	0.11
Years to rerailing 2004-11 2006-02	12	9	10	11	10	11	13	19	11

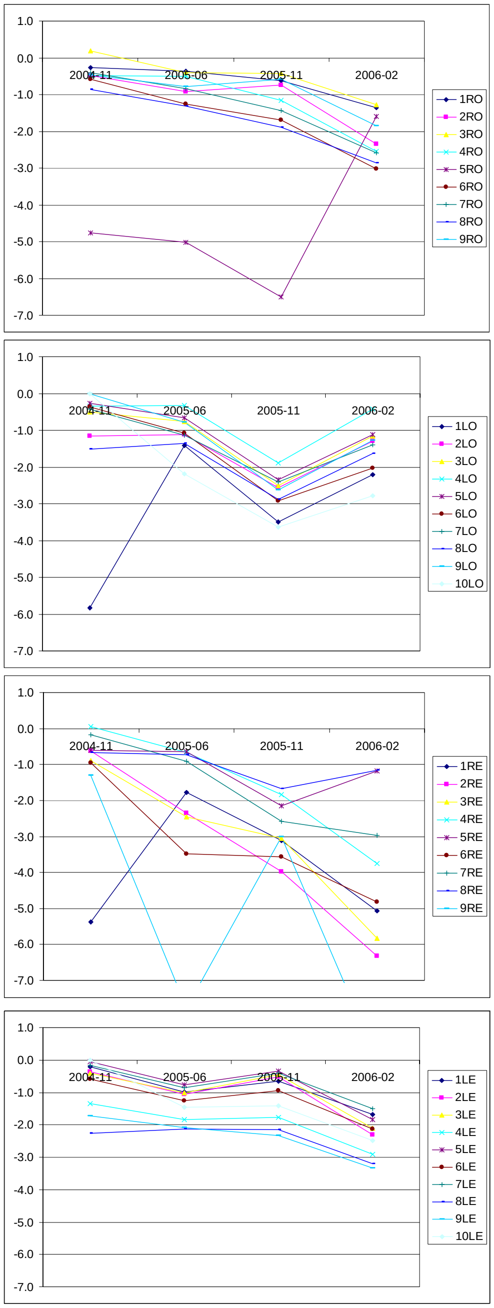

Figure 3. Summary of the 45° wear of all the ultra-hard rails considered for the available measurement from *Archimede* measuring train.

RAILHEAD DEFECTS

It is widely acknowledged that ultra-hard rails are prone to RCF defects if their transverse profile is not properly maintained. One of the more classical defects observed is the so called “head checking”. The term “head check” is used to refer to a type of cracking in rails that occurs particularly on curves. As a result of excessive localised plastic deformation of the rail head, which occurs in response to increasing shear forces and decreasing contact area between the wheel and the rail, small cracks appear in the contact area region.

If the classical antagonist phenomenon, the transverse profile wear, is limited by high hardness, these cracks propagate further deep in the rail head with a rather shallow angle till they reach a bifurcation length. If they

turn up, spalling occurs and small portions of material are removed from the surface, whose appearance becomes particularly bad but with an associated low risk of fracture. If, conversely, the crack turn down, it can lead to a complete rail fracture without any other evident deformation or measurable characteristic.
While the presence of liquid (mainly water) is necessary for the crack to propagate up to a “critical” length, the mechanism the leads a crack to turn up or down is not clarified yet.

During the inspections, the head checking phenomenon was observed in some curves. As an example, Figure 4 shows two defective rails with the relevant parameters. The actions to be taken to better understand the implications of these head checks in terms of safety will be defined in the near future.

Figure 4. Head checks on R350HT ultra-hard rails on curve 49 (R= 356 m, h= 130 mm, left) and on curve 57 (R=491, h=120mm, right)

Table 4 shows the characteristics of the curves where head checks phenomena were observed. In particular the non-compensated accelerations at the maximum line speed are shown. Note that the non-compensated acceleration value is much lower than the maximum allowed (1 m/s^2) for track stability reasons.

Steel grade	Curve n°	Radius [m]	Cant [m]	V max [km/h]	Maximum a_{nc} [m/s^2]	Inspection date
R320Cr	37	382	0.160	95	0.73	30/11/2006
R350HT	49	356	0.130	85	0.68	14/02/2007
R350HT	57	491	0.120	85	0.32	14/02/2007
R350HT	53	433	0.110	85	0.30	13/02/2007
R350HT	59	629	0.070	85	0.41	16/02/2007
R350HT	55	424	0.110	85	0.56	13/02/2007
R350HT	56	437	0.110	85	0.52	12/02/2007

Table 4: Curves with head checks

At a first visual inspection, head checks were observed more frequently in the R350HT rail type than in the R320Cr rail type. If confirmed, this could indicate the fact that the harder the material is the heavier the phenomenon is.

RAIL LUBRICATION

Rail lubrication has a great importance on gauge face wear. At the same time, the presence of lubricant is necessary from the beginning in order to avoid, or to delay at a maximum, the formation of surface cracks due to rolling contact fatigue. Lowering friction forces, reduce the plastic flow of material avoid the accumulation of deformation (ratchetting process) that is responsible for head checks. Once the head checks are formed, rail lubrication can be negative as the fluid can pressurize the crack, especially if the traffic is monodirectional.

A few trackside lubricators are installed along the considered line, but from the analysis of the 45° wear in lubricated rails it emerges that rail lubrication does not lead to a complete reduction of gauge face wear. Furthermore, no trackside lubricators are installed in curves with ultra hard rails. This means that analyses shown above are not affected by the presence of lubricators as their effect is absolutely negligible.

To tackle the high wear rate phenomenon RFI has recently released new specifications defining the requirements of more efficient lubrication systems, adopted with the lubricants, must comply to in order to be able to be used in line (RFI, 2006). These specifications were developed considering the demand to reduce the lubricant dispersion to the minimum on the railway place and also foreseeing some criteria for the choice of the products based on the maximum health for workers and environment.

During the certification phase, equipment and lubricants should prove to be able to satisfy the following criteria:

- reduction of the 45° rail wear;
- effective length of lubrication;
- adhesion of the lubricant to the rails (no drying up, no washing under rainfall, etc.);
- device robustness (resistance to impact, vibrations, environmental conditions, etc.);
- compatibility of the device with the normal track maintenance activities;
- quality of dispensing (lubrication of the rail gauge face and not of the rail crown, no clogging, no random leaks, no dispersion of lubricant on the ballast);
- low influence of environment temperature;
- overall reliability of the device.

It is hoped to report in the near future about the results of the activities currently in progress on several industrial products whose manufacturers decided to supply a full test system including the lubricant.

CONCLUSIONS

The measurements analysed have shown that the ultra-hard rail type R320Cr and R350HT have a 45° wear lower than rail type R260. In curves with radius lower than 600 m, R260 rails were changed every 9÷12 months, while the R320Cr and R350HT rails showed a 45° wear between 3 and 4 mm after two years from installation. It can be forecast that the head hardened rails type have an average duration of 12÷14 years, resulting in evident advantages concerning both the maintenance and the economic aspects.

Rail lubrication remains a critical topic, and RFI has set up a medium-term strategy in order to get properly working and reliable trackside lubrication equipment. The efficiency and efficacy of these systems will be fundamental to allow the achievement of the desired goals in terms of re-railing intervals.

The head checking phenomenon, which is non negligible for the testes rails, will be subject to further investigations in the next months.

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