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DAMAGE TO RAILWAY RAILS CAUSED BY EXPLOITATION

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In modern railway exploitation rails are submitted to a constant increase of speed and loading on the vehicle axles and to constant stress increase in welded railway tracks. Therefore, modern railway rails production technology and exploitation in European Community have require a new philosophy and content for the proposals of new European standards for the manufacturing and delivery of railway rails (series pr EN 13674 and other recommendations). In this paper an overlook over the new requirements mainly given in EN 13674-1/2004, the criteria for the selection of steel grade and the valuation of damages to railway rails caused by exploitation especially on the head of rails are given.

Key words: *railway rails steels, new European standards, selection criteria, damages to railway rails in exploitation*

Oštećenja željezničkih tračnica tijekom eksploatacije. U suvremenim uvjetima eksploatacije željezničke tračnice su izložene kako porastu brzina i osovinskog opterećenja, tako i porastu zaostalih naprezanja od zavarenih kolosijeka. Zato su moderna tehnologija proizvodnje željezničkih tračnica i zahtjevi u okviru Europske unije dali sasvim novi pogled na filozofiju i sadržaj prijedloga novih europskih standarda za proizvodnju i isporuku željezničkih tračnica (serija pr EN 13674 i druge preporuke). U ovom radu dan je pregled novih zahtjeva koji su specificirani uglavnom u novom europskom standardu EN 13674-1/2004, kriteriji izbora čelika i oštećenja željezničkih tračnica u eksploataciji naročito na glavi tračnica.

Ključne riječi: *čelici za željezničke tračnice, novi europski standardi, kriteriji izbora, oštećenja tračnica u eksploataciji*

INTRODUCTION

Railway rails are a very important element of the overall railway track and have the basic role of supporting and guiding railway vehicles and to endure the exploitation life time with an acceptable level of damage.

In modern railway exploitation, rails are exposed to a constant increase of speed and loading on the vehicle axles and to constant stress increase in welded railway tracks. To meet the increased exploitation requirements, new requirements regarding rail steel quality have been set out in standards for manufacture and delivery of railway rails.

Modern railway rails production technology and exploitation in European Community have required a new philosophy and content of proposals for the new European standards for manufacture and delivery railway rails (series pr EN 13674 and other recommendations). An overlook of the new requirements is given in EN 13674-1 for the qualifying criteria and the acceptance tests with a number of new tests such as: fracture toughness, fatigue crack growth rate, fatigue test, residual stress test, microstructure, decarburisation, oxide cleaness, hardness etc. The reference acceptance value used until now is the minimal hardness of the running surface which is the base also for the new designation of rail steel grades.

The full denominations of six new European drafts of standards for railway rails are:

1. EN 13674-1/2004 - Part 1: Flat bottom symmetrical railway rails 46 kg/m and above (Vignole rails);
2. Draft pr EN 13674-2/April 2003 - Part 2: Switch and crossing rails used in conjunction with Vignole railway rails 46 kg/m and above;
3. Draft pr EN 13674-3/April 2003 - Part 3: Check rails;
4. Draft pr EN 13674-4/April 2003 - Part 4: Vignole railway rails from 27 kg/m to < 46 kg/m.

As we have seen the series EN 13674 Railway applications - Track - Rail consists on four parts mentioned above;

I. Vitez, D. Krumes, I. Kladarić, Faculty of Mechanical Engineering University of Osijek, Slavonski Brod, Croatia, M. Oruč, Metallurgical Institute "Kemal Kapetanović", Zenica, Bosnia and Herzegovina

1. Draft pr EN 14587-1/October 2002 - Railway applications - Track - Flash butt welding of rails - Part 1: New 220 and 260 grade rails in a fixed plant. EN 14587 will comprise five parts. First is mentioned above and other parts will be following - Part 2: New 260 Mn and 350 HT grade rails in a fixed plant; Part 3: Welding of rails by mobile welding machines at sites other than a fixed plant; Part 4: Welding of reusable rails and Part 5: Welding in association with crossing construction;
2. CEN/TC 256/SC 1/October 2000 - Railway applications - Track - Aluminothermic welding of rails - Part 1: Approval of welding processes. The second part of this EN will be denominated as - Part 2: Requirements for Approval of Welding Contractors and Operatives. Beside this six drafts of EN for railway rails there are:
   - Recommendations for the use of rail steel grades - draft from International Union of Railways (UIC) as leaflet 721R/2003,
   - Treatment of rail defects - draft UIC as leaflet 725R/ 2005 and
   - Catalogue of Rail defects Code UIC 712R/2002 [1-8].

THE PRESCRIBED PROPERTIES OF STEEL FOR RAILWAY RAILS

The Requirements of the Codex UIC 860V

Technical conditions of manufacture and delivery of railway rails were standardized in Codex UIC 860V of the International Railroad Union, which has been harmonized with the world trends before 20 years.

Table 1. gives a survey of the prescribed values regarding chemical composition and tensile properties for four types of normally hard rail steels [4, 9].

Table 1. **Prescribed chemical composition and tensile properties of rail steels according to UIC 860V**
Tablica 1. **Propisani kemijski sastav i vlačna svojstva čelika za tračnice prema UIC 860V**

Grade of steel	Chemical composition, elements in % of mass						Tensile strength R_m / MPa	Elongation, min A_5 / %
	C	Mn	Si	Cr	P_{max}	S_{min}		
R0700	0,4-0,6	0,8-1,25	0,05-0,35	-	0,05	0,05	680-830	14
R0900 A	0,6-0,8	0,8-1,3	0,1-0,5	-	0,04	0,04	880-1030	10
R0900 B	0,55-0,75	1,3-1,7	0,1-0,5	-	0,04	0,04	880-1030	10
R1100 *	0,6-0,82	0,8-1,3	0,3-0,9	0,8-1,3	(0,025)	0,03	≥ 1080	9

* Other alloy elements such as V or Mo, Nb can be applied according to agreement between manufacturer and the buyer.

The Requirements of new European Norm

The new European Norm EN 13674-1: 2004 - Part 1 covers the flat bottom symmetrical rails having a linear mass 46 kg/m and above. Modern rail production technology and the requirements of high speed railways within the Community have demanded a new philosophy and content of this EN. Whenever possible, this part of EN is performance based, adopts the European Quality System standard EN ISO 9001 and requires the manufacturers to offer the latest verified technology. Two major parts of the proposal EN are: the qualifying tests and the acceptance tests. The qualifying tests introduce a number of performance requirements not prescribed seen in national and international standards (such as fracture toughness K_{Ic}). They also include typical results from relevant acceptance tests. The principle of the acceptance criteria is based on the measured hardness values as base for the designation of new steel grades for railway rails (Table 2.). This steel grades reflect trends in railway usage.

Table 2. **Steel grades hardness range, fracture toughness and other [10]**
Table 2. **Raspon vrijednosti tvrdoća čelika za tračnice, lomna žilavost i drugo [10]**

Steel grade	Hardness range HBW	Fracture toughness K_{Ic} / MPa $m^{1/2}$ Minimum value		Description lines	Branding	R_m min / MPa	Elongation min A_5 / %
		Single	Mean				
200	200-240	30	35	C-Mn		680	14
220	220-260	30	35	C-Mn		770	12
260	260-300	26	29	C-Mn		880	10
260 Mn	260-300	26	29	C-Mn		880	10
320 Cr	320-360	24	26	1 %C		1080	9
350 HT	350-390	30	32	C-Mn low-alloyed HT*		1175	9
350 LHT	350-390	26	29	with HT*		1175	9

HT* - heat treated rail that has undergone accelerated cooling from austenitizing temperature during the metallurgical transformation period.

Two major divisions of the draft proposal EN are: qualifying tests and acceptance tests. The qualifying tests introduce a number of perfomance requirements not previously prescribed in national or international standards (such as fracture toughness K_{Ic}). They also include typical results from relevant acceptance tests. The acceptance tests have been designed to control the characteristics of the rail steel and rail that are of relevance for the production of high quality rails and the demands of the railway user. The principle of the acceptance criteria is based on measured hardness values and not on measured tensile tests which are now part of the qualifying tests. This hardness is the base for the designation of new steel grades for railway rails [10].

Qualifying tests

All qualifying tests shall be undertaken at least once every five years and as a results of any significant production process change for all grades. In addition, the residual stress should be determined on all available grades every two years. The maximum longitudinal residual stress in the foot shall be up to 250 MPa. The residual stress tests are to be performed on 6 samples and the test pieces of 1 m of length should be cut out at least 3 m in from each rail end. For the determination of rail foot surface longitudinal residual stresses electrical strain gauges of the encapsulated type, 3 mm in length with a gauge factor accuracy of better than ± 1 %, are used.

Standard test method for the determination of the plain strain fracture toughness (K_{Ic}) of rails shall be performed in accordance with the requirements of ASTM E399:1991.

The thickness "B" of all test pieces shall be of 25 mm. For any rail head transverse profile the test piece width "W" shall be the maximum achievable of the following dimensions: 40, 45 and 50 mm. A minimum of 5 tests from each sample shall be performed. It is recommended that the chevron notch in ASTM E399 is used to avoid crack front curvature problems. Tests shall be performed at the temperature of –20 ± 2 °C. Test temperature shall be measured using a beadless thermocouplespot welded to the test piece.

The supplier shall only carry out tests on the 60 E1 profile or the heaviest section produced. Prescribed are the following qualifying tests: fracture toughness (with three point bend); fatigue crack growth rate (17 m/Gc by ΔK =10 MPa·m$^{1/2}$ and 55 m/Gc by ΔK=13,5 MPa·m$^{1/2}$ for steel grades 200 and 320 Cr); fatigue test (min. 3 test pieces, the life of each samples shall be greater than 5×10^6 cycles by total strain amplitude ε_{uk} = 0,00135); residual stress in rail foot; variation of centre line running surface hardness of heat treated rails (till ±15 HBW from of the mean result obtained); tensile strength and elongation (calculated using multiple regression analysis); segregation (sulfur prints by ISO 4968); other qualifying requirements.

Acceptance tests

A sequence of laboratory tests is to be performed: chemical composition; microstructure; decarburisation; oxide cleaness (K3 < 10 on minimum of 95 % samples); sulfur prints; hardness (HBW 2,5 mm/1,839 kN, 15 s; max. variation till 30 HBW); tensile test (R_m and A_5 are mostly calculated by the predictive equation, while for 350 HT and 350 LHT are tested on specimens of diameter of 10 mm, L_0 =5 d_0).

Samples for oxide cleanness shall be prepared and assessed in accordance with DIN 50602. For orders less than 5000 tonnes, only one sample with a K3 greater than 10 and less than 20 is allowed. Samples shall be taken from one of the last blooms of the last heat of the sequence but from each sample 2 specimens shall be tested. The following limits shall apply:

Total index:

10 < K3 < 20 for a maximum of 5 % of samples,
K3 < 10 for a minimum of 95 % of samples.

Other acceptance test of rails are: dimension tolerances; gauges (control calibers for height, web and foot thickness, crown profile etc.); inspection requirements/ tolerances for internal quality and surface quality.

Internal quality of rails shall be ultrasonically tested by a continuous process ensuring that on the entire rail length and cross-sectional area are inspected (at least 70 % of the head and at least 60 % of the web). Surface quality includes the checking of all protrusions, hot marks and seams from rolling, wear patterns, hot scratches, slivers etc.; cold marks, surface microstructural damage (martensite or white phase), automatic foot inspection on surface defects (cracks). Rail profiles, dimensions, properties and linear masses shall be in accordance with is prescribed EN. This EN contains 21 different profiles railways rails with linear masses from 46 till 60 kg/m. The profiles have designations: 49 = 49 E1 (previous DIN S 49), and UIC 60 = 60 E1 [10].

CRITERIA FOR THE SELECTION OF THE STEEL GRADE

Increases in railway traffic, greater axleloads, higher speeds and the introduction of new generations of rolling stock have increased the loadings on rails, (especially in curves). Today, in light, of developments in rail manufacture and changing prices for rail steels, most railways opt for steel grades 260 and, to a very limited degree, for 260 Mn (steel grades 900 A and 900 B) as standard equipment for their track. Rails of steel grade 260 and 260 Mn are not exempt of problems that arise in curves with small and very small radii and/or heavy loadings. Compared to rails from inferior steel grades, these lateral and vertical wear problems arise later or in another form (corrugation, head-checking).

The various criteria used to select a steel grade are grouped under the three following headings: local parameters, maintenance methods and economic assessment [11 - 14].

Local parameters influence the development of wear and rolling contact fatigue defects with:

- curve radius (lateral wear, corrugation on the low rail in curves, head-checking, rail contact fatigue defects causing serious problems on curve radii on which trains run at higher speeds),
- tonnage carried (the actual daily or annual mega gross tonnage - mgt in the zone under consideration),
- the impact of falling and rising gradients (of around 20 ‰ and more),
- speed and cant on curves (a wide range of traffic types which are either pulling and pushing and cant contributes to lateral wear on the high rail and to propagation of rolling contact fatigue defects whereas excess cant causes crushing on the low rail),
- axleload (a higher axleload conducive to crushing on the low rail),
- the type of rolling stock (which are harsh on the track may exert substantial forces in curves or high adhesion forces which are conducive to rail damage, smaller wheel radii may also contribute to rail damage).

Rail maintenance methods as lubrication and grinding help combat the wear and rolling contact fatigue phenomena. By applying these methods appropriate way, the maintenance costs can be reduced. Economic assessment must be taken when choosing a steel grade for rails.

RECOMMENDATIONS FOR THE USE OF NORMAL AND HARD STEEL GRADE RAILS

The normal steel grade are rails of 260 or 260 Mn grade steel, while hard steel grade rails are the rails 320 Cr, 350 HT or 350 LHT. Today, the rails from 260 or 350 HT steel grades are by far and away the most used.

The maintenance policy (rail lubrication and grinding) has a substantial impact on the service life of rails, of normal or hard steel. As service life is a key factor in any economic analysis, the maintenance policy must be taken into account when choosing the steel grade for rails.

A key parameter in the selection of rail steel grades is the procurement and maintenance cost of the rails. It is important to consider whether the higher capital costs of 350 HT, 350 LHT and 320 Cr are justified by the longer service life and/or lower maintenance costs.

In small and very small radius curves and/or subject to heavy loadings, many railways achieve a longer (and therefore more cost-effective) service life by laying rails made from steel grades 350 HT, 350 LHT or 320 Cr. The

Table 3. **Rail defect coding system**
Tablica 3. **Sustav označivanja oštećenja tračnice**

1st digit	2nd digit	3rd digit	4th digit
Situation 1. Rail ends 2. Zone away from rail ends	Location 0. Full section 1. Rail head 3. Web 5. Foot	Pattern, nature 1. Transverse 2. Horizontal 3. Longitudinal vertical 4. Corrosion 5. Passing through a hole 6. Not passing through a hole 9. Lap	Additional characteristics and diferentiations
	2. Surface of rail head	0. Wear 1. Surface defects 2. Shelling 3. Crushing 4. Local batter 5. Wheel BURNS 7. Cracking and local subsidence of the running surface	
3. Defects caused by damage to rail	Location 0. Full section	Origin, cause 1. Bruising 2. Faulty machining 3. Permanent deformation	(no 4th digital)
4. Welding and resurfacing defects	Welding method 1. Electric flash-butt welding 2. Thermit welding 3. Electric arc welding 4. Oxyacetylene (autogenous) welding 5. Pressurised gas welding 6. Induction welding 7. Resurfacing 8. Other welding methods	Pattern, nature 1. Transverse 2. Horizontal or shelling	Additional characteristics and diferentiations

corresponding hardness of these rails is obtained either through heat treatment or by the addition of alloying element like chromium, with or without structural change. Timely execution of maintenance measures (grinding and above all lubrication of the rails) has a decisive impact on the service life of rails in curves.

Often, a combination of these two measures (choice of rail steel grade and maintenance) is necessary to achieve a cost-effective service life for rails. Both technical and economic criteria must therefore be considered when making that choice [13].

RAIL DEFECTS

By each railway track maintenance always involve the removal of a number of rails because of cracking or damage resulting from manufacturing defects and/or traffic loads. The monitoring of the behaviour of rails in the track must be connected with computer processing with the aim that users and producers could focus their efforts in improving the quality of the rails and the conditions of their use. The handbook of rail defects includes definitions, recommendations, location and general coding system of defects [14].

For broken, cracked and damaged rails a code is given that may comprise up to four digits. The general coding system for rail defects and the classification of the different types of defects are given in the Table 3.

Typical damages to railway rails caused by exploitation on the head of rails are damages:

1. Defects in rail ends on head (11 /12) and web (13)
   - 111 Progressive transverse cracking (kidney - shaped fatigue crack)
   - 112 Horizontal cracking
   - 113 Longitudinal vertical cracking
   - 121 Surface defects
   - 122 Shelling of running surface
   - 123 Crushing
   - 124 Local batter of running surface
   - 125 Wheel burns
   - 132 Horizontal cracking
     - 1321 at the web - head fillet radius
     - 1322 at the web - foot fillet radius
   - 133 Longitudinal vertical cracking (piping)
   - 134 Corrosion
   - 135 Star - cracking of fishbolt holes
   - 139 Lap

2. Defects away from rail ends on head (21 /22) and on web (23)
   - 211 Progressive transverse cracking (kidney - shaped fatigue crack)
   - 212 Horizontal cracking
   - 213 Longitudinal vertical cracking
   - 220 Wear
   - 221 Surface defects
   - 222 Shelling
     - 2221 Shelling of the running surface
     - 2222 Shelling of the gauge corner
     - 2223 Head checking / Fissuring / Scaling
   - 223 Crushing
   - 224 Local batter of the running surface
   - 225 Wheel burn
   - 227 Squat / Cracking and local depression of the surface
   - 232 Horizontal cracking
   - 233 Longitudinal vertical cracking (piping)
   - 234 Corrosion
   - 235 Cracking around holes other than fishbolt holes
   - 236 Diagonal cracking away from any hole
   - 239 Lap

Characteristics and appearance of damages No. 2223 Head checking

Head checking is a rolling contact fatigue (RCF) phenomenon and it occurs mainly on the high rail in curves with high shear stresses and relatively low wear. It is a growing concern for infrastructure managers and difficult to detect in the early stages. The defect starts directly under the surface ($\approx$ 1/10 mm), grows rapidly and reaches the surface very quickly. Under traffic loads, these cracks may turns downwards with a risk of multiple breakings. It is quite difficult to predict the development of the heed checking and to detect with eddy currents. Preventive rail treatment (grinding, milling, planning it) on stretches with tendency to develop RCF defects is usually recommended to prevent the occurrence of this type of defect [12].

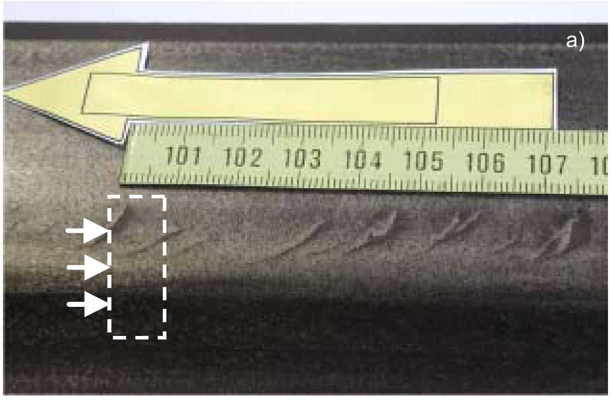
Head checking (HC) takes following shapes (see Figure 1.):

1. Stabilised and regular HC.
2. HC with scaling. Fissures inside railhead progress according to an angle going from 10° to 15°, up to maximum depth that is, in certain instances, several mm. Then they progress parallely to the running surface of the rail and end up meeting again in the gauge corner where they generate the scaling. Laboratory tests showed that it is possible to use eddy currents to assess the depth of the crack.
3. HC that looks like a long fissure. This defect looks like defect No. 227. (squat), but for its location in the gauge corner. If recurring periodically, this defect may result in multiple breaking over several metres and becaming particularly dangerous.

The means of detection are: visual inspection and ultrasonic testing. Recommendations from UIC code are:

- keep rail under inspection,
- withdrawal of the rails showing defects endangering

running safety or quality,
- grinding the rail sometimes make it possible to prevent or delay scaling,
- removal of the broken rail [14, 15].



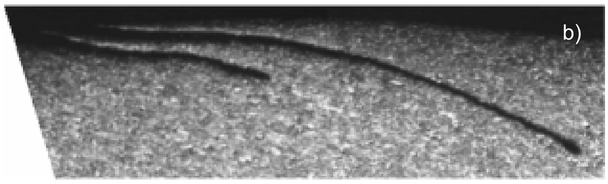


Figure 1. **Appearance of damage "Head checking" [15]: a) appearance in general; b) cross section (× 20)**
Slika 1. **Izgled oštećenja "Head checking" [15]: a) opći izgled; b) poprečni presjek (× 20)**

CONCLUSIONS

Codex UIC 860 V/1986. prescribes four pearlitic steel grades for railways rails with tensile strength 700 till 1100 MPa (see Table 1.), while in EN 13674-1/2004. seven pearlitic steel grades are specified with the hardness between 200 to 390 HBW (see Table 2.).

EN 13674-1 has two mayor divisions: qualifying tests and acceptance tests. The qualifying tests introduce a number of perfomance requirements not previously prescribed in the earlier norm and include also typical results of relevant acceptance tests. The acceptance tests have to control the prescribed properties of the high quality rail steel according to the norm EN ISO 9001 and requires for the manufacturers to offer the latest verified technology. The principal of the acceptance criteria is based on measured hardness values. The new properties of steels for railway rails in qualifying tests are: fracture toughness, fatigue crack growth rate, fatigue test, residual stress in rail foot etc.

UIC Recommendation Leaflet 721 R from 2003 for the use of rail steel grades only refers to steel grades specified in European standard EN 13674-1. Criteria to determine the choice of steel grade are grouped under following 3 headings: local parameters, maintenance methods and economic assessment. Recommendations for the choice of rail steel grades require that both, technical and economical criteria must be considered.

UIC the handbook of Rail defects includes the definitions, recommendations, location and general coding system of defects.

Head checking is a rolling contact fatigue (RCF) phenomenon and it occurs mainly on the high rail in curves with high shear stresses and relatively low wear. RCF is currently one of the major factors limiting the productivity of infrastructure. Squats, shelling and head checks are all forms of RCF, but head checks are prevalent in curves and switches where flange contact towards the gauge corner may results in increased tangential force and slip in a smaller wheel-rail contact area. If not treated correctly, these surface-initiated cracks can lead to complete fracture of the rail.

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