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INVESTIGATION INTO THE MECHANICAL PROPERTIES AND METAL CREAKS OF A DIESEL LOCOMOTIVE WHEEL

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Abstract. After JSC 'Lithuanian Railways' (*AB 'Lietuvos geležinkeliai'*) bought new Siemens ER20 CF locomotives produced in Western Europe and brought them into service, some of them have already done about 170–200 thousand km that caused the appearance of indentations of an inadmissible size (the depth is more than 3 mm, the length – 10 mm) the elimination of which turning cutting results in up to 20 mm loss of a wheel. Having grounded off the metal layer of indentation depth, indentation reappears (metal 'flakes off') and needs to be removed by re-turning cutting the wheel. The purpose of the current investigation is to determine whether there is a reason to claim that the cause of wheel surface crumbling could be a chemical composition of the wheel or wheel-to-rail hardness ratio. The carried out investigations have revealed that there is no reason to claim that the cause of wheel surface crumbling could be the chemical composition of the wheel or wheel-to-rail hardness ratio.

Keywords: diesel locomotive, wheel-set, wheel, metal, metal cracks, hardness, chemical composition, wear.

1. Introduction

Locomotives and the track make a complicated mechanical system influenced by a great number of random external and internal factors, e.g. the unevenness of rails or non-uniformly worn-out wheel-set rolling surfaces as well as different rolling radii of one of the wheel-set tyres, variation in track curve radius, dirty or wet rails, interaction of wagons etc. (Bureika 2008; Bureika and Mikaliūnas 2008; Dailydka *et al*. 2008; Lata 2008; Liudvinavičius *et al*. 2009; Lata and Čáp 2010; Djukić *et al*. 2010; Liudvinavičius and Lingaitis 2007; Dukkipati *et al*. 1992; Fang *et al*. 1991). A reliable, safe freight and passenger transportation process is defined by a properly selected mode of rolling stock use, an efficient application of maintenance and repair systems, exact discipline at work and discipline procedures. When using a rolling stock fleet, it is very important to increase reliability and economic efficiency indicators. It depends on rolling stock design, maintenance and repair system, the existing repair depot, the organization of repair works and personnel qualification. It is of prime importance to understand and appropriately apply information technologies allowing to systematize the existing information and to answer the main questions through applying them: what should be the periodicity of planned repairs without the use of additional resources having the preservation of the required technical state of rolling stock, how many spare parts must be available when performing planned and unscheduled repairs at minimum cost, how to improve the reliability of units and assemblies. All these abovementioned factors are directly linked to unscheduled repairs causing a longer downtime of locomotives, additional expenditures on materials, labour inputs and fuel consumption.

After JSC 'Lithuanian Railways' (*AB 'Lietuvos geležinkeliai'*) bought new Siemens ER20 CF locomotives produced in Western Europe and brought them into service, it is critical to track systematic failures occurring during their operation, to record, investigate and eliminate the causes of their appearance, and if necessary, to supplement the system of periodicity and/or the amounts of examinations and overhaul life specified by a manufacturer. The indentations of an inadmissible size (the depth is more than 3 mm, the length – 10 mm) appeared on some ER20 diesel locomotives after they had

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done about 170–200 thousand km. The elimination of indentations by turning cutting results in approximately 20 mm loss of a wheel as indentations can be deep, i.e. having grounded off the metal layer of indentation depth, metal indentations reappear (metal 'flakes off') and are repeatedly removed by re-turning cutting the wheel until they disappear (see Table 1).

Table 1. Sizes of metal cracks in locomotive wheels

Locomotive No	Mileage, km	Wheel*	Indentation dimensions, mm		
			Depth	Width	Length
002	202218	3L	3.0	20	10
003	177489	3R	2.6	50	60
005	172807	4L	3.0	15	15
011	165346	3R	6.0	45	50

* wheel markings are shown in Fig. 1.

Locomotive wheel/rail contact mechanics (metal properties) and dynamics play a great impact on wheel-set rolling surface wearing intensity (Bureika and Mikaliūnas 2002; Rudzinskas *et al.* 2006).

According to instructions on the formation, repair and maintenance of the traction electrical equipment wheel-sets of 1520 mm gauge, indentation may remain untreated until the first roll-out or turning cut in the locomotives and carriages of self-propelled trains when they are no longer than 10.0 mm and no deeper than 3.0 mm (Lingaitis *et al.* 2004, 2005; Mikaliūnas *et al.* 2004).

Having performed a primary visual inspection of wheel-sets with the appeared indentations, an opinion that such situation could be caused by the following reasons is formed:

- metallurgical flaw of a manufacturer (e.g. due to inner cavities in wheel metal) (Povilaitienė 2004; Vaičiūnas *et al.* 2006);
- inappropriate wheel metal (may be ER9 2 cat. wheel metal is excessively soft and its rolling is excessively deep, i.e. it hardens, e.g. in accordance with European standard EN 13262:2004 on cast wheels, hardness in the whole wear area at up to 35 mm depth from the nominal diameter must be over 255HB, however, in accordance with GOST 398-96 (ГОСТ 398-96) 2 cat., the hardness of rims used in old locomotives must be over 269HB at 40 mm depth and in the flange area – up to 321 HB at 16 mm depth);
- inappropriate chassis design (resulting in the operation of a wheel under adverse conditions due to a long locomotive base and uneven distance between wheel-sets in a bogie, suspicion arises due to the appearance of defects only in the middle locomotive wheel-sets: in three instances – in the third and in one instance – in the fourth wheel-set though on different wheels: in three instances – on the left wheels and in one instance – on the right wheel). The wheel layout of ER20 locomotive is shown in Fig. 1.

As the operation of ER20 locomotives demonstrates, minor wheel indentations appear exactly in rolling circumference after approximately 50 000–70 000 km mileage. They are located in one rolling circumference (perimeter) and can have up to 1 mm depth, up to 5 mm width and various lengths. The indentations disappear (roll over) on a further operation of a locomotive.

2. The Object, Purpose and Tasks of Investigation

0065 wheel-set of ER20 locomotive (No 11) was chosen for carrying out investigations. Its rolling surface had multiple visible surface cracks in the whole operating wheel surface as well as in several crumbled areas. ER20 locomotive uses disk brakes, and therefore the rolling surface of wheels is not rubbed off periodically as it happens in the locomotives with brake blocks.

The purpose of the carried out investigation is to identify if the wheels have production flaw and to asses if ER9 wheel metal is excessively soft.

The following investigations must be carried out for the abovementioned purposes: the visual inspection of rim surface, the analysis of wheel metal hardness, a chemical composition analysis of wheel metal, the analysis of wheel production documentation and its comparison with findings on wheel hardness and chemical composition analyses.

3. The Procedure of Investigations

The visual inspection of rim surface defines that a wheel near a reducer is marked with letter A and a wheel further from the reducer – with letter B. Prior to the inspecting wheel rolling surface, every rim is divided into 8 (eight) sectors (see Fig. 2).

Since a wheel is round and has no protruding elements (as a reference base), its division into equal sectors is arbitrary. The division allows defining the relative position of the noticed wheel defects. Having identified

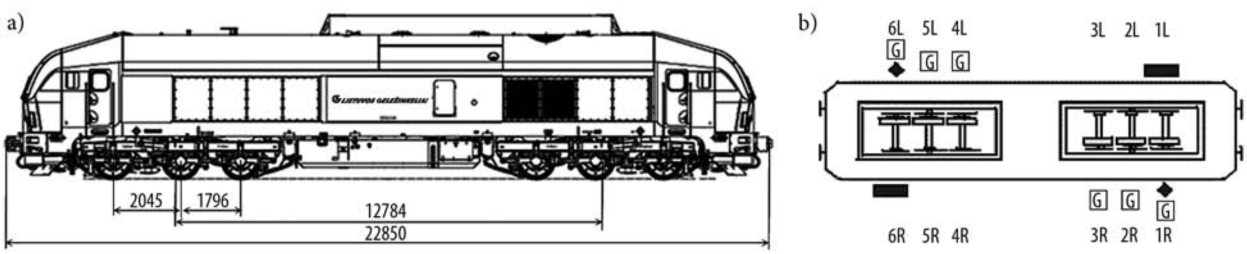


Fig. 1. The wheel layout of ER20 locomotive: a – the construction of ER20 locomotive; b –wheel numeration

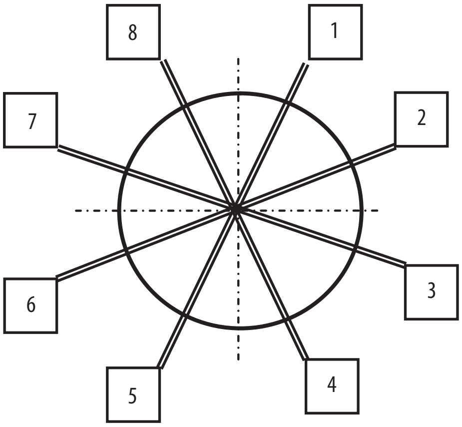


Fig. 2. The diagram of dividing the wheel into sectors

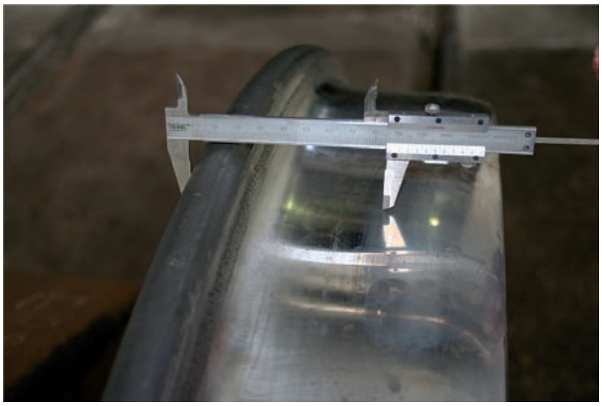


Fig. 3. The layout of the failures of the rolling surface

a defect, its coordinate from the sector start (circumferential distance, in millimetres), defect type (the number according to a standard and its verbal name) and defect dimensions (length and width, in millimetres) are recorded. Most typical defects are photographed. All data are recorded into separate tables (see Table 2).

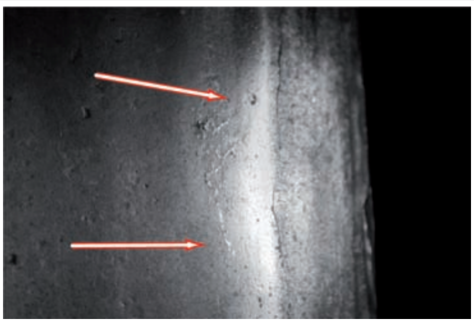
Having carried out an exhaustive inspection, 39 failures of the rolling surface on both wheels were noticed. The absolute majority of wheel rolling surface defects are superficial and not located in the rolling centre (70 mm from the wheel inner surface) but 20–30 mm outward (towards the thin cone part) from it (see Fig. 3).

Only two of the identified 39 failures are on the rolling centre.

The measurements of wheel rolling surface hardness (Brinell hardness) are carried out using DinaMIC hardness tester. The test rolling metal surface of a wheel ground to the flat surface. In order to measure hardness, the wheel rolling surface is divided into 8 (eight) areas (see Fig. 4).

Table 2. A record form of the visual defects of the wheel rolling surface

Defect coordinate (from the measurement sector start), mm	Defect type (note, if necessary)	Defect dimensions, mm
Rim B (not near a reducer)		
1–2 measurement sectors		
0	103 (radial cracks)	40x40



260	103 (radial cracks), 101 (longitudinal cracks)	40x40

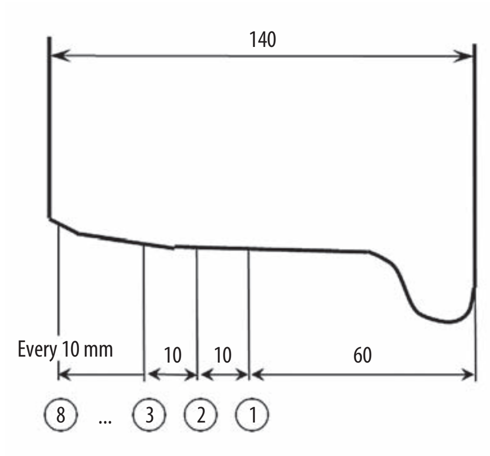


Fig. 4. Areas of surface hardness measurement (1, 2, 3, …, 8 – hardness measurement areas)

The distance between the first area and the inner wheel edge is 60 mm, the second area – 70 mm etc. The surface is divided into areas for measurement convenience, measurement results are presented according to the distance from the inner wheel edge. 5 hardness measurements have been carried out in each area at identical intervals and their arithmetic mean value is presented for the report. The generalized measurement results are displayed in Fig. 5.

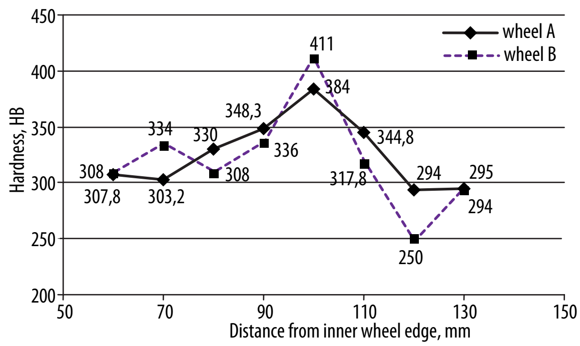


Fig. 5. Measurement results for the hardness of the rim rolling surface

According to the technical certificates of diesel locomotives, the hardness of their wheel surface fluctuate from 279 to 292 HB (complies with EN13262:2004 requirements). According to GOST 398-96 (ГОСТ 398-96), hardness must be 269–275 HB depending on a steel grade. The analysis of Fig. 5 shows that the maximum surface hardness of the tested wheel (411 and 384 HB) is not in the rolling centre (its distance from the inner wheel edge makes 70 mm) but 30 mm further. The elevated hardness area is at approximately 90 to 110 mm distance from the inner wheel edge. It corresponds to the appearance area for the majority of cracks. Therefore, it can be suggested that cracks causing crumbling appeared due to deforming metal hardening.

The diagram of lateral hardness measurement for a wheel is shown in Fig. 6.

The hardness of the lateral wheel surface is measured in 8 areas. The measurement results are presented in Figs 7 and 8.

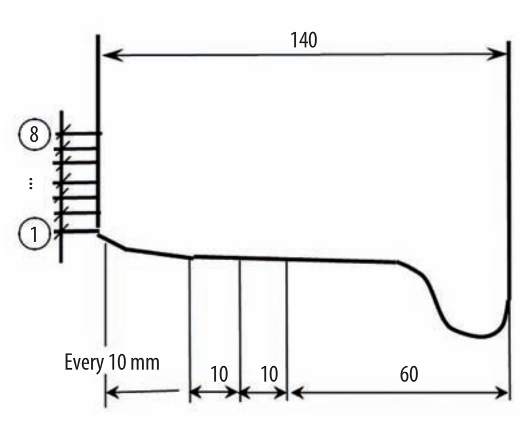


Fig. 6. The diagram of hardness measurement for the lateral wheel surface (1, ..., 8 – hardness measurement areas)

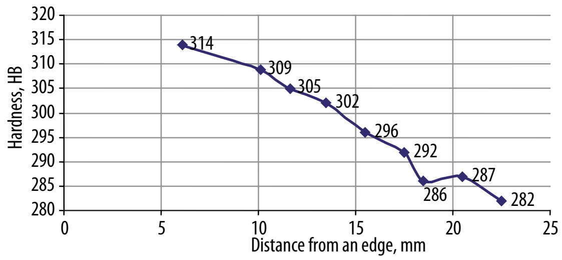


Fig. 7. Hardness distribution in the driving surface of the wheel (left)

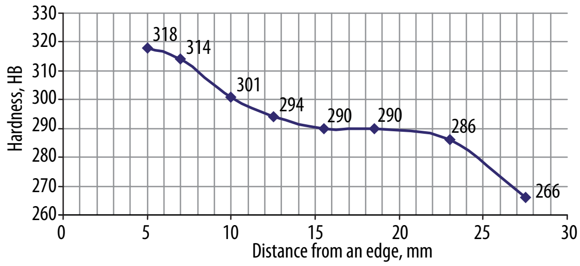


Fig. 8. Hardness distribution in the driving surface of the wheel (right)

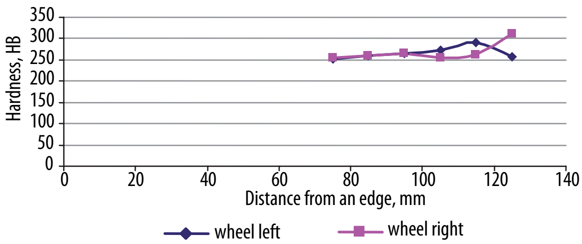


Fig. 9. Hardness distribution in the rolling surface of the wheels

By comparing two diagrams of lateral wheel hardness, we can notice that even though they are different, they also have a common feature: edge hardness decreases in a direction away from the wheel rolling surface. The mean value of hardness decrease under the rolling surface (at 5 to 25 mm depth) equals to 1.5 HB/mm. However, hardness is nowhere lower than 255 HB which means that during production, hardness requirement complied with EN 13262:2004.

Having grounded off the rolling surface of a wheel, hardness was measured once again. Hardness distribution (after grinding off) in the rolling surface of the wheel is shown in Fig. 9.

Hardness distribution in the wheel rolling surface (starting from the rolling centre – 70 mm and moving outward the wheel) is almost uniform, however, in the area where metal hardness and cracks (20–32 mm from the rolling centre) were present prior to grinding off, hardness increase in up to 50 HB is noticed after grinding off as well.

4. The Analysis of the Results of Investigation into Wheel Metal Hardness

Metal hardness governed by documentation is compared in Table 3.

According to a copy of technical certificates, it is apparent that the wheel metal hardness of Siemens ER 20 diesel locomotives fluctuates from 280 to 292 HB (complies with EN 13262:2004 requirements – to be no less than 255 HB) and for 2 wheels of the wheel-set being investigated, it makes 286 and 284 HB. According to GOST 398-96 (ГОСТ 398-96), hardness must not be less than 269 and 275 HB depending on a steel grade. GOST 398-96 (ГОСТ 398-96) and EN 13262:2004 standards govern only the lower limit of wheel metal hardness. The wheel formally complies with the requirements of both standards. Therefore, there is no reason for the assumption that the wheel can be incompatible with rails produced in accordance with GOST (ГОСТ) standards (in terms of metal hardness).

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Table 3. Wheel metal hardness governing by documentation

Technical certificate	GOST 398-96 (ГОСТ 398-96)	EN 13262:2004	Rail hardness, at the rail top
286 and 284 HB	no less than 269–275 HB	no less than 255 HB	up to 401 HB

diesel locomotives fluctuates from 280 to 292 HB (complies with EN 13262:2004 requirements – to be no less than 255 HB) and for 2 wheels of the wheel-set being investigated, it makes 286 and 284 HB. According to GOST 398-96 (ГОСТ 398-96), hardness must not be less than 269 and 275 HB depending on a steel grade. GOST 398-96 (ГОСТ 398-96) and EN 13262:2004 standards govern only the lower limit of wheel metal hardness. The wheel formally complies with the requirements of both standards. Therefore, there is no reason for the assumption that the wheel can be incompatible with rails produced in accordance with GOST (ГОСТ) standards (in terms of metal hardness).

5. Results and Examination of the Chemical Analysis of Wheel Metal

The results of the chemical composition analysis of the wheel rolling surface along with the requirements of the standards and data of technical certificates are presented in Table 4.

Due attention should be given to the fact that while the amount of carbon in steel increases by 0.1%, strength increases by 70–100 MPa and hardness – by approximately 20 HB. However, cold fragility limit for steel also increases by approximately twenty degrees.

Values of mechanical properties for carbon steel depend not only on the amount of carbon in steel but also on the state of steel and above all on cooling steel brought to the austenitic structure. In this case, tensile strength limit increases only to eutectic concentration (0.8). The main plasticity indicators include specific elongation and compression strain. Initially, they increase faster, whereas in the carbonaceous environment, they slow down.

Silicon is an active deoxidizer. However, by increasing strength it also increases the yield point.

Manganese is the main deoxidizer and desulfurizer. By taking sulphur from ferric sulphide distributed around granules as a low-melting-point film, it removes a part of sulphur with slag and sulphur remaining as MnS is arranged as individual inserts, and therefore removes the heating fragility phenomenon. By melting, ferrite manganese enhances the strength of ferrite with almost no effect on the other mechanical properties of steel.

Chromium is an active steel ferritizer. It can form chromium carbides arranged around metal granules, and therefore increase metal strength.

Having carried out a chemical analysis of wheels and having compared the obtained results against data on a technical certificate and the chemical composition of wheels produced in accordance with GOST 398-96 (ГОСТ 398-96), it was found that the chemical composition of wheels fully complied with the imposed requirements.

6. Conclusions

1. Having carried out the visual inspection of the wheel rolling surface, it was found that the defects of the wheel rolling surface were uniformly distributed along the whole perimeter of the wheel.
2. The absolute majority of wheel rolling surface defects are not located in the rolling centre (70 mm from the wheel inner surface) but 20–30 mm outward from it. Only two of the identified 39 failures are in the rolling centre.
3. Failures resulting in crumbling the wheel surface form a failure chain of three areas the total length of which equals to approximately 240 mm.
4. The visual examination of locomotive wheels allows advancing a preliminary version that crumbling the wheel surface could start due to metal deformation. The cracks appeared near and expanded to the rolling centre as well as cracks which expanded to the rolling centre were dense enough to weaken metal in the rolling centre.
5. Prior to turning cutting, the maximum hardness of the rolling surface of wheels under investigation was 411 and 384 HB respectively while according to technical certificates, the hardness of their wheel surface fluctuates from 280 to 300 HB.

Table 4. Norms and results of the chemical composition analysis of wheel metal in comparison with standards

Document	Chemical elements										
	C	Si	Mn	P	S	Cu	Al	Cr	Mo	Ni	V
EN 13262:2004	up to 0.6	up to 0.4	up to 0.8	up to 0.02	up to 0.015	up to 0.3	–	up to 0.3	up to 0.08	up to 0.3	up to 0.06
GOST 398-96 (ГОСТ 398-96)	0.60–0.65	0.22–0.45	0.6–0.9	up to 0.035	up to 0.04	–	–	–	–	–	up to 0.15
Data of technical certificates	0.57	0.3	0.68	0.011	0.01	0.02	0.02	0.17	0.03	0.1	0.001
Actual data	**0.61**	**0.26**	**0.68**	**0.029**	**0.004**	**0.02**	**0.016**	**0.15**	**0.02**	**0.1**	**0.01**

6. The maximum surface hardness of the wheel under investigation is not on the rolling centre but 30 mm further. The elevated hardness area corresponds to the appearance area for the majority of cracks.
7. Hardness decreases deepening away from the rolling surface of a non-turning cut wheel. At 5 to 25 mm depth, hardness decrease equals to an average of approximately 1.5 HB/mm.
8. In wheel metal, hardness is nowhere lower than 255 HB which means that during the process of production, hardness requirement complied with EN13262:2004.
9. Having carried out investigations, it has been found that there is no reason to claim that the cause of wheel surface crumbling could be the chemical composition of the wheel or wheel-to-rail hardness ratio.

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