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Experimental Stress Analysis

IMPROVING OF FATIGUE PROPERTIES OF RAILWAY AXLES

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Abstrakt: One of the most economical types of transport is railway transport. In recent years were put into operation a lot of new high speed lines and vehicles. For new produced railway vehicles there are used railway axles made from steel grades EA1N and EA4T in accordance with European standard EN 13261, eventually stronger steels. These steels are carbon and low alloy types steels with good fatigue properties. Out of consideration for high demands in service we are searching new ways for further improving of the axle properties. One of the possibilities is surface rolling, eventually hardening of surface layers by metal spraying or special heat treatment. Resulting properties are approved by tests of axles in full scale on special testing machines. In this contribution are shown some results of this works.

1. Demands of standards

Every new design of railway axles is designed and calculated in accordance with EN 13103, event. EN 13104 and than proved on fatigue properties by fatigue tests. Basic mechanical properties of material of the axle shall be in correspondence with demands of EN 13261 given below in the table 1.

***Table 1**: Basic mechanical properties of steel grades for axles in accordance with EN 13261*

Standard EN	Re [MPa]	Rm [MPa]	A [%]	KU5 [J] along	KU5 [J] crosswise
EA1N	Min.320	550 - 650	Min 22	Min,30	Min.20
EA4T	Min. 420	650 - 800	Min. 18	Min.40	Min.25

Fatigue strength of material is evaluated on the specimen with diameter of 10 mm, and on the basis of fatigue strength of smooth specimen and specimen with notch is determined notch coefficient and this coefficient shall be smaller than prescribed value of criterion. Results of test on small specimen serve for verification of notch sensitivity of steel to notch effect. Than are approved fatigue properties of the axles on the full scale tests made in accordance with EN 13261 and EN13260.

***Table 2:** Fatigue strength of small test pieces with diameter 10 mm*

Steel grade	RfL [MPa]	RfE [MPa]	q = RfL/RfE	Fatigue strength on the free surface [MPa]	Fatigue strength on the seat surface [MPa]
EA1N	≥250	≥170	≤1,47	200	120
EA4T	≥350	≥215	≤1,63	240	144

Where is: RfL ... Fatigue strength in rotation bending on smooth surface.
RfE ... Fatigue strength in rotation bending on notched small test piece.
Depth of notch shall be 0,1 mm, with angle of 30°and tip radius R0,04 mm.
q ... notch sensitivity.

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2. Hardening of the surface with aim of improving of fatigue properties

2.1 Roller burnishing

For deep roller burnishing of low carbon steels are used machines with pressure rolls that are forced to the surface of the machine part (Hegenscheidt, Masturn).

For low carbon steels as for instance EA1N for axles of freight wagons are reached marked depth and high degree of hardening. In last years this type of surface hardening was often used for locomotive axles and axles in accordance with standards GOST and AAR. Disadvantage of this procedure are problems with roller burnishing of fillet radii.

2.2. Hardening with ball

For hardening of surfaces the low alloyed steel axles there is used special apparatus with ball produced by firma ECOROL that is mounted on the universal lathe type SUI63. This device contains from holder with ball, holder is clamped into tool holder of the turning-lathe and portable compressor. Axle is clamped in lathe centres and is turned with help of catch driver. During hardening process the ball is pressed to the surface, lubricated and simultaneously cooled by emulsion from compressor.

Conditions of hardening by ball:

Speed ca. 100 m/min (in accordance with range of machine revolutions)
Revolutions of the axle for Ø150 ÷ Ø 200mm …... 180 ot/min
for Ø 200 and higher … 140 ot/min
Press ……………………… 225 - 250 bar

Advantage of surface hardening with using ball is possibility oh hardening of filet radii, that is commonly distinguished by concentration of stresses.

There are created compressive stresses on the surface, and these stresses have positive influence on fatigue strength of the railway axle.

Device for surface hardening is relatively small, essential and easy for use. This device can be additionally mounted on universal turning lathe and is relatively easy.

2.3. Gains from hardening and rolling of surface

Gains from hardening and rolling of surface are followed:

1. Smoothing of the surface and over rolling of small crack on the surface.
2. Increase of surface hardness. Steel grade A1N could be hardened about 24% (for instance for roller burnishing of steel grade OsV in accordance with Russian standard.
3. Creating of press residual stresses in surface layer.

3. Methods of inspection of hardened surface

Results of roller burnishing or surface hardening by ball can be approved by measuring of surface Ra in μm, of higher hardness v ΔHV or residual stresses σres in MPa.

Very often is for measuring of hardness used method in accordance with Vickers, when diamond pyramid is pressed against surface with the aid of microscope measuring of average length from both diagonals [7].

In the last years is also used bounce dynamic method for measurement of hardness. Dynamic method is based on difference of kinematic energy of ball shot against the surface of measured material and bounced ball [9]. We use device DYNAMIC from company Krautkrämer.

For measuring of residual stresses is mostly used drilling strain gauge method. Disadvantage of this method is persistent damage of the measured surface and this is a reason why this method can not be used for axles in a service.

From this reason there are recently tested new non destructive methods. In our company we have new device for measuring of residual stresses based on the principle of measurement of eddy currents. The device WIROTEST 301 can measure surface hardness and stress in metallic parts. In recent time we tested this device on parts from steel A1N.

New method should enable to measure hardness on the surface of all produced axles and perhaps will be also possible to check gradient of hardness from the surface to the depth. With the same device shall be evaluated also residual stress on the surface.

Measuring device was developed by Instytut mechanikiy precyzyjnej (IMP) in Warsaw and works on the principle of measuring of lost of eddy currents. Eddy currents are created by electromagnetic induction. When in this electromagnetic field came another magnetic metal than there is induced some electric current in this metal. Eddy currents are inducer currents fluent on circular track. Eddy currents produced own magnetic field that acts together with magnetic field of magnetic coil. Eddy currents are influence by electrical conductivity and magnetic permeability of metals. Because these properties are dependent on heat treatment and degree of plastic forming is possible they use for measuring of hardness and stresses.

Device WIROTEST 301 consisting of device itself and measuring probe. Device itself contains high frequency source with measuring frequency 9,5 kHz and measuring part with own memory. On the front face there is digital display showing instant measured values. There are different measuring probes for measuring of hardness and residual stress. Design of probe is also influenced by form of measured area. Transmission and evaluation of measured data is with the aid of programme MS Excel Wiroterminal.xls. Measuring of hardness and residual stresses on the surface is comparative measurement. For qualitative evaluation there is necessary to do calibration on specially prepared measurement standards. There are used measurement standards that were calibrated with the aid of RTG diffraction method. With change of frequency can be changed depth of eddy current penetration, and by this way can be measured stress in four steps as function of distance to the surface to depth 2,3 mm. After testing of this measuring device this non destructive tested device will be used on the production line.

Table 3: *Example of measured values on hardened surface on the axles from steel grade A1N.*

Place	Force [kN]	Measuring probe	Numer of measure ments	WIROTEST data						Change of stress and hardness
				1	2	3	4	5	∅	
Not hardened	0	SN/02/026	5	-7	4	1	-5	-4	-2,2	100 %
C	6	SN/02/026	5	38	38	38	38	37	37,8	
B	10	SN/02/026	5	59	57	56	54	53	55,8	
Not hardened	0	SNC/07/007	5	9	9	9	8	8	8,6	
C	6	SNC/07/007	5	34	35	34	33	33	33,8	
B	10	SNC/07/007	5	46	46	48	56	45	48,2	

Remark: Not hardened (for calibration)
SN/02/026 … Measuring probe for stress measuring
SNC/07/007 … Measuring probe for measuring of hardness

4. Verification of hardened surface layer

Contribution of roller burnishing is first of all creation of compressive residual stresses. These residual stresses can be measured by drilling method with strain gauges.

During this test of roller burnished surface was found that:

1. Residual stresses were always compressive.
2. Values of residual stresses on the shaft where the surface was not rolled were in the interval from σ_R = 65 to 89 MPa and σ_T = 57 to 77 MPa. On the hardened surfaces were residua stresses always markedly higher; for instance with Ecoroll device could be obtained residua stresses 4,8 times higher.
3. Residual stresses in the fillet radii from shaft to seat in distance 2 mm from surface was always markedly higher (from 5 to 6,5 time) than in the central area of the axle.

As regards A1N steel grade, the hardness may be by up to 32% (e.g. when roller burnishing of axles made of OsV material in accordance with GOST Standard or roller burnishing of locomotive axles.). In this case the deep of rolled material was till 10 mm.

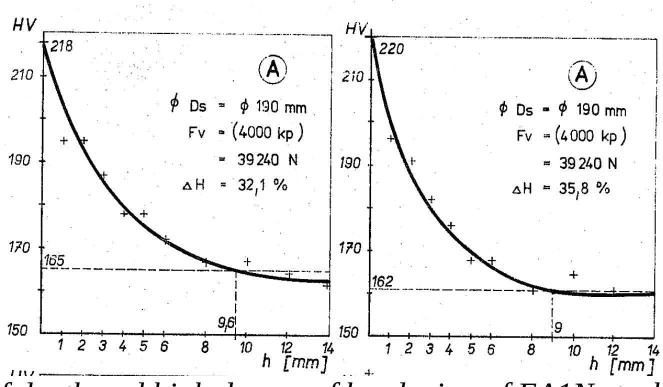

Figure 7: *Example of depth and high degree of hardening of EA1N steel type*

In the case of low alloyed steel EA4T was surface hardening made with special tool with ball that was mounted on the universal turning lathe. Relative speed of the ball to the surface of the axle was approximately 100 m/min. and with great deal is depending on the range of revolutions of used turning lathe. Press of the hydraulic oil that press the ball against hardening surface used to be in range of 225 - 250 bar. Revolutions of rotating axle used to be approximately 180 rpm for axle with diameter to 200 mm.

Identification of favourable pressure stress on the axle surface after a roller burnishing operation is currently carried out by the strain gauge router-cutting method, and/or by using X-ray method. By drilling a hole in the part surface layer a change of internal forces in the vicinity of this hole takes place and results in deformations, which may be measured by strain gauges. The measurement of test axles was carried out by the router-cutting method, i.e. by measurement of released deformations after drilling circular holes in the strain gauge rosette centre 0°- 45°- 90°. The pitch of these rosettes is 13 mm. Strain gauge rosettes were glued in the measuring points of the seat and transition centres, and/or axle body. Their grills „1“ to which angle „α“ of the direction of main residual stresses is related to were orientated in the tangential direction and grills “3” perpendicular to them then in the direction of the axle longitudinal axis.

The identified residual stresses of all the axles were always of the pressure nature.

Table 4: *Comparison of hardened values fro steel grade A4T*

Numer of the axle	Values of residua stresses in depth 1,969 - 2 mm under surface in [MPa]									
	Wheel seat		Transition Part		Journal seat		Seat of the wheel gear		Shift	
	σ_R	σ_T	σ_R	σ_T	σ_R	σ_T	σ_R	σ_T	σ_R	σ_T
128	-453	-441	-138	-111	-	-	-489	-350	-89	-73
135	-427	-321	-127	-76	-	-	-400	-320	-83	-77
119	-	-	-318	-261	-373	-312	-420	-295	-65	-57

Example of measurement of stresses in transition part between seat and axle shaft.

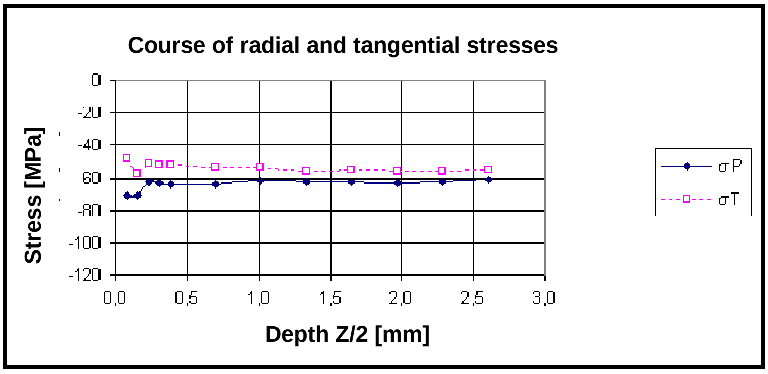

Figure 8: *Example of the measured stress course in the filet radii from Shift to the wheel seat of the axle*

The increased steel hardness was checked in the areas of the surface hardening. Hardness according to Vickers was measured in Vickers – Wolpert hardness meter by a diamond pyramid designed with a peak angle of 136° at a load of 294.2 N (30kg) in accordance with EN ISO 6507-1 Standard Specifications. The nearest in-print toward the surface was located at a depth of 1 mm and the other one at a distance of approx. 2 mm. The line of in-prints on segment No. 1 was located in the place of transition to the hub seat. An example of the hardness curve in the transition to the seat hub is shown in Fig.

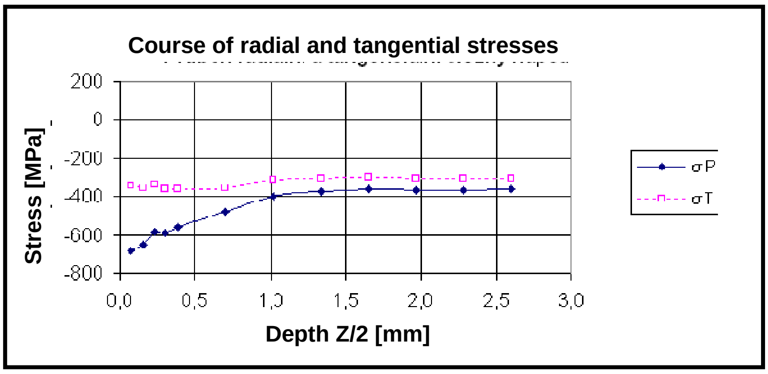

Figure 9: *Example of the stress course on the roller bearing seat*

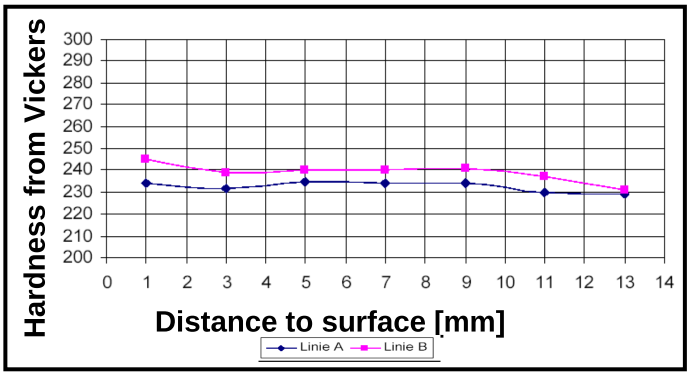

Figure 10: *Example of the hardness course on the wheel seat*

Basic steel surface hardness ranged from 230 to 240 HV. No significant increase of hardness was identified by means of the applied method at deeper layer under the surface. For example on the dust guard seat was course of hardness nearly the same.

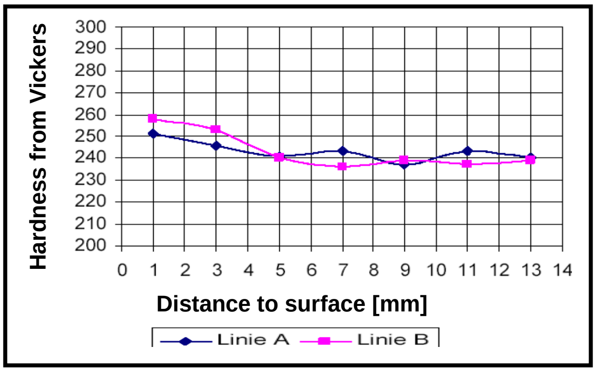

Figure 11: *Example of the hardness course in the fillet*

Increase of the surface hardness by the given procedure in case of EA4T material is noticeable approximately to a depth around 1 mm. Increase of the surface hardness was substantiated by the hardness measurement method by means of ball rebound.

5. Test results

There were two series of axles with roller burnished transitions and molybdenum treated seats [3], [4], [5] tested. The tested axles are marked in the following way: AX x,y , where "x" means a test series (the first and second series with the roller burnished free surface) and "y" means the first, second and third axles in the series in question.

In the first series of tests the axles withstood the stress values σD without any failure as follows:

Table 5: *First series of tested axles*

	σD	σDkrit	**N Number of cycles till failure when stress level is σDkrit**
AX 1.1	285	326	**4760434**
AX 1.2	285	326	**1459833**
AX 1.3	281	321	**3150733**
AVG 1	284	324	**--**

In the second series of tests the axles withstood the stress values σD without any disturbance as follows:

Table 6: *Second series of tested axles*

	σD	σD_{krit}	**N Number of cycles till failure when stress level is σD_{krit}**
AX 2.1	311	349	**1800000**
AX 22	247	275	**7300000**
AX 23	300	329	**3000000**
AVG 2	286	318	**--**

Average values under which the axle was not damaged were for the first test series σ_{AVG1}=284,1 MPa; and for the second test series σ_{AVG2} = 286 MPa.

These values represent an increase of the fatigue limit of the roller burnished surface in when compared with a value of 240 MPa required by the European Standard Specifications by 18.5% , and/or 19.2%.

The fatigue limit in accordance with EN Standard Specifications was verified in respect of the axle with the not roller burnished surface. The seat and axle body diameters were 205 mm and 165 mm, respectively, with a ratio of mean values of 1.242. The axle withstood a load of 240 MPa without damage, and at a load 312 MPa the crack in the transition from the axle body to the wheel seat originated after 514554 cycles.

It is however necessary to point out that in view of the price and the time demands of the tests they are carried out with the minimum possible number of test levels and that we would obtain a more exact result in case of a bigger number of test levels. These tests were made before introduce of producing of the axles for locomotives type 478.

These results of tests of the axles with surface hardened by roller burnishing are not different from earlier results. For instance Mr. Linhart [1] showed results of tests from rolled burnished bars with diameter 16 mm. These test were made before introducing of production of the axles for locomotives type 478, when rolling burnishing help with problem of small cracks on the axle seat.

Table 7: *Benefits of rolled burnished surface*

Used technical procedure	Fatigue limit	Increase of strength compared with basic fatigue limit
Grinding	395 MPa	100%
Roller Burnishing	463 MPa	117%
Roller burnishing and grinding ca 0,5 mm	485 MPa	123%

6. Evaluation

Full scale tests of the axles performed in various test laboratories shows comparable results. There was proved, that with hardening of surface either by roller burnishing or by molybdenum layer can be enhanced fatigue limit and life time of large machine part.

There was proved that in axles made from steel grade A4T with roller burnished surface till stress value Sig = 284,1 MPa in the critical area initiated no cracks and after enhanced value of stress till *value* Sig = 317,6 MPa initiated cracks in transition part from shaft to seat.

Contribution of hardened surface by rolling burnishing on steel grade A4T from fatigue point of view is minimally 18,5%.

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