381. EVALUATION OF THE STRENGTH ANISOTROPY FOR RAILWAY WHEELS

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Abstract. The results of experimental investigation of railway wheel failures and strength anisotropy due to rolling contact fatigue are presented. The results indicate that plasticity acts to concentrate regions of intense hardening near the edges of contact. The determination of overall mechanical properties of small-scale volumes frequently relies on the indentation technique. Strength characteristics of the wheel material were investigated by dynamic indentation method and portable dynamic indentation tester was used for hardness measurements. It was found that some characteristic force values of the instrumented hardness test are very well correlated to tensile strength.

Keywords: wheel-rail, contact, hardness, strength.

Introduction

Life assessment of railway wheels needs to study different factors that are typical to these components [1]. It is a well-known fact that the yield strength cannot be the only measure to quantify the fatigue strength of wheel material since increased brittleness and material defects may reduce the fatigue strength [2]. The material will also experience strain hardening and at the same time single constants such as hardness or yield limit will be shown to characterize the fatigue behavior sufficiently well [3]. After a finite number of load cycles, when plastic strains are initiated, a purely elastic response is achieved. This phenomenon is known as the *shakedown limit* [4]. If this limit does not occur, additional plastic strain is accumulated, material exceed ductility and will rupture. Wheel – rail contact pressures beneath the shakedown limit are expected to be "safe", i.e. the stress cycle will be ultimately elastic, resulting in a very long fatigue life. Above the shakedown limit there will be plastic flow leading relatively quickly to failure. In practice, there are other factors such as wheel flats, surface roughness, friction, etc., which can lead to failures even when the wheel – rail contact pressure is nominally below the shakedown limit. Performance of rails and wheels generally is determined by some or all of the following parameters:

- resistance to wear;
- resistance to fatigue;
- optimization of contact geometry for stability and noise reduction.

Among these, wear and fatigue play a major role, particularly because of the large contact stress and spalling observed in the wheel rail top contact (Fig. 1). The former creates debris and change in wheel – rail profile. The latter produces cracks that may develop into collapsible failure. Hence, to gain parameters that are relevant for modeling mechanical contact problems, including high degrees of strains, indentation experiments appear particularly suitable. Some methods for the determination of yield strength and ultimate strength of materials that are based on indentation measurements with various indenters have been developed in past years [5]. Anisotropy of the wheel material is discussed and test results are presented to quantify these effects.

Background

To minimize damage on train and track, the wheels have to be tested in a set of experiments, which define their reliability and economics [6]. Wheels have to be machined or replaced as soon as possible to get rid of all transformed volumes and cracks. Wheel replacement and tuning induce large costs and it is therefore crucial to find solutions to the problem. Several steps can define this cycle of testing. Ones of the most important are maintenance and strength testing [7]. They define wear intensity of separate joints and parts, their wheel dynamics, the possibility of repairing, accessibility, etc. Characteristic reasons of gradual alteration of technical state are wear, fatigue, materials aging, surfaces obstacles, etc [8].

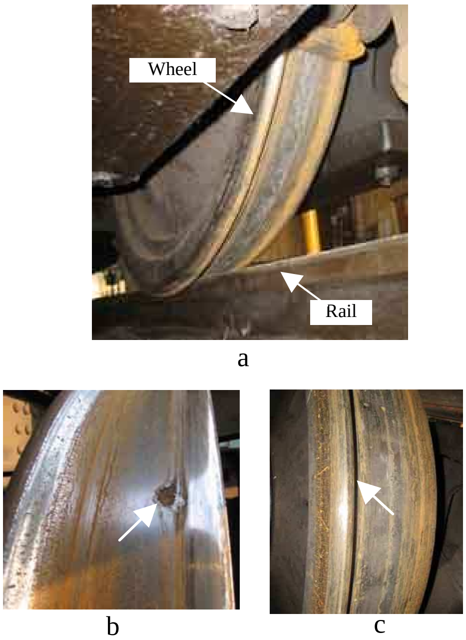

Fig. 1. Surface damage due to surface initiated fatigue: a – railway-wheel contact; b – surface damage of wheel tread resulting from surface-induced cracks; c – damage in rim

Normally, after industrial heat treatment wheel materials are anisotropic, microstructural gradients occur and strength test samples data shows a strong dependence on the local microstructure and cannot be quantitatively compared to specimens of homogenous medium carbon steels. This fact is of great importance because mechanical characteristics of thereby obtained material are later used in a fatigue design [9]. Yield strength is the main parameter for the characterization of plastic behavior. It determines, together with the fracture toughness and critical tensile strength the load carrying capacity of materials. For massive samples, it can be obtained from tensile or compressive tests, but for small volumes a standard measurement method does not exist and it is very difficult to obtain accurate values. Indentation test is one of the most popular techniques to measure the mechanical properties of small volume of materials due its simplicity. The analysis of indentation results, however, is very ambiguous because of the complex indentation stress field beneath the indenter, so that it has usually been used in comparing materials properties qualitatively. Since indentation hardness takes necessarily into account only monotonic components of strain hardening (corresponding to around 8 % Brinell tests), this may explain why it is not more significant than yield limit.

The most characteristic reason of technical state change of mechanical parts of the rails is wearing. Nowadays the most widely used wheel in Lithuania and Russia are rolled wheels [10]. The weight of such wheel is 385 kg. The diameter of currently used wheels in carriages is 950 mm, the diameter of the wheel that were manufactured in the past is 1050 mm. Rolled wheels are manufactured from carbon steel, with 0.52 – 0.63 % of carbon. Hardness is not lower than 248 HB units. Impact toughness is not less than 0.2 MJ/m^2.

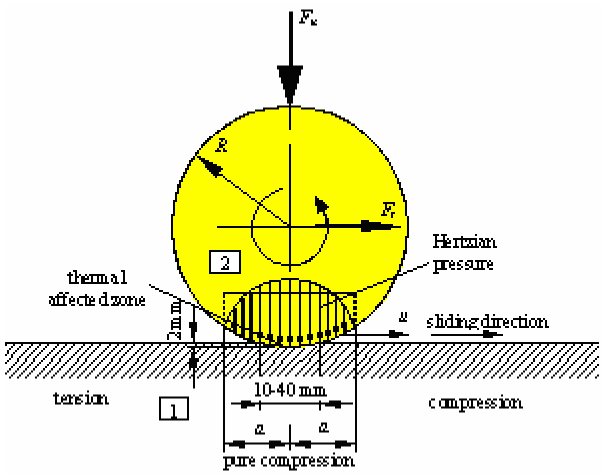

Fig. 2. Elastic strain in rolling wheel – railway contact; typical width of the wheel flats is 10 – 40 mm. The material that is sheared off during the slide often piles up just behind the contact area, but usually it halls off during subsequent rolling

Yield of ductile metals is usually taken to be governed by either Tresca maximum shear stress criterion or von Misses strain energy criterion [11]. In uniaxial tension principal stresses are $\sigma_1 = \sigma_y$ and $\sigma_2 = \sigma_3 = 0$. Critical maximum shear stress is equal to $\sigma_y / 2$. Tresca criterion thus suggests that in pure shear the material will yield at a shear yield stress whose magnitude τ_{max} is given by $\tau_{max} = \sigma_y / 2$. On the other hand, von Misses strain energy criterion depends on the value of the expression $(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2$. In pure shear the von Misses condition predicts τ_{max} and σ_y are related by $6\tau_{max}^2 = 2\sigma_y^2$: it follows that $\tau_{max} = \sigma_y / 3$. Although careful experiments on metallic specimens tend to support von Misses criterion, the difference in predictions of the two is not large and in practice it is often considered quite acceptable to use whichever criterion leads to greater algebraic simplicity.

Wheels have key importance for safety of the vehicle and special care is needed in order to ensure their strength. The development of the vehicle industry has strongly influenced the loading level, material mechanical properties selection and manufacturing processes of wheels

[12]. An element of the railway (Fig. 2) originally undeformed undergoes shear at points before moving into a region of pure compression. As it emerges from the strain zone there is an element or reverse shear, until it remains its original shape.

The shear stress produced on the contact area of the wheel and rail is:

$$\tau_{max} = \left(\frac{F_{din}}{R} \right)^{1/2} \quad (1)$$

where F_{din} is dynamic wheel – rail load, R is radius of the wheel. From the viewpoint of stresses caused in rails, reduction of the diameters of the vehicle wheels is unfavorable because with the reduction of the wheel diameter contact stress between the wheel and the rail increases. In order to counterbalance this harmful effect, rails of higher tensile strength are used, which in turn might have a stronger tendency to be brittle. Rail steel tends to be brittle also with decreasing temperature. This embrittlement takes places in case of considered rail steels at relatively high (10% to – 20° C or even higher) rail temperature. Also the effect of manganese content of rails on their tensile strength is remarkable, because due to the increased vehicle load if is recommendable to increase the tensile strength of the rails.

In the case of 2D wheel-rail contact the condition of plane strain deformation ensures that the stress component σ_y is the intermediate principal stress. Applying Tresca criterion thus involves equating the maximum principal shear stress to τ_{max} or $\sigma_y / 2$, hence, critical value of the peak pressure p_0 is given by $p_0 = 3.3\tau_{max} = 1.67\sigma_y$. The corresponding value of the mean pressure p_m is $p_m = \frac{\pi}{4} p_0 \cong 2.6\tau_{max} = 1.3\sigma_y$, even when some yielding has taken place, the scale of the changes of shape must be small. This is because initial yield has occurred beneath the surface, so that the plastic zone is still totally surrounded by a region in which stresses and strains are still elastic. From [13] one can see that hardness H calculated from the size of the remaining indentation after unloading agrees reasonably well with the Tabor's criterion:

$$H = (3 - 3.3)\sigma_y \quad (2)$$

(that is strictly valid for softer materials which upon the indentation, respond in a classical rigid - plastic manner). This proportionality factor is somewhat smaller than that of 4 estimated on the basis of analysis of the measured indentation curves [6]. The reason of this difference as found for hard materials is related to an error of the strain at the corrected indentation depth when elastic part of the indentation is relatively large.

The mechanical state control (inspection) of railway rails and axles, performed by indenting a conical indenter without disassembling the rails, was for the first time employed by a Russian engineer P. Kubasov in approximately 1903.

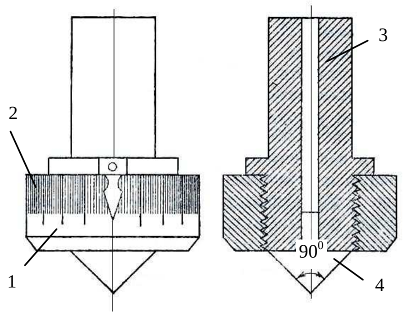

Fig. 3. Kubasov indenter to check the carriages' quality by hardness method application: 1 – nut; 2 – grade; 3 – frame; 4 – conical indenter $(2\theta = 90^{\circ})$

In Fig. 3 conical Kubasov indenter is shown. It consists of threaded nut 1, which external surface consists of approximate 200 even sections. When twisting a nut in the frame 2, it is possible to change conic indentation depth, when indenting the indenter up to the nut's back surface.

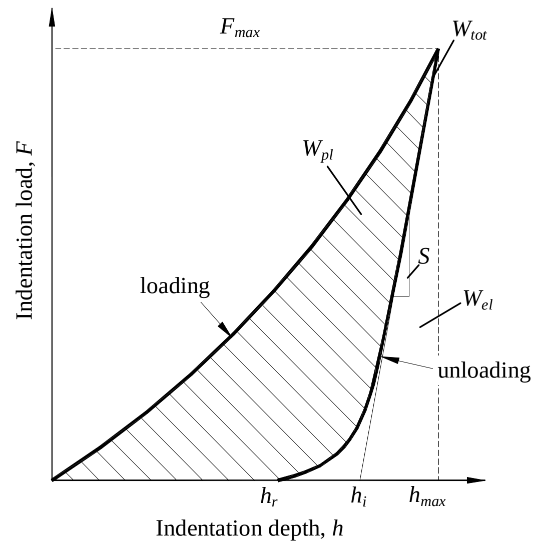

Fig. 4. Schematic representation of indentation load – depth curve of elastic – plastic materials (S - stiffness, F_{max} - maximum load, h_{max} - maximum depth, h_i - interrupt depth, h_r - residual depth)

The hardness unit needs certain indenting force, when indenting the indenter up to a definite depth. In recent years the methods of indentation work assess indentation data with the use of the energy dissipated or work done during the indentation [14]. In case of measuring the indentation load – depth (F – h) curve instead of the residual imprint, hardness is usually defined as the mean contact pressure under the indenter, so that the contact depth h_c corresponding to the projected area A

must be derived from the $F - h$ curve (Fig. 4). The area under the loading curve gives the total work W_{tot} done during indentation, while elastic contribution, W_{el}, is given by the area under unloading curve. Thus, plastic work is the difference between these, $W_{pl} = W_{tot} - W_{el}$. This work of indentation method equates the conventional hardness, to the plastic work divided by the volume of the indent

$$\frac{\text{load}\, F}{\text{plastic area}\, A_{pl}} = \frac{\text{plastic work}\, W_{pl}}{\text{plastic volume}\, V_{pl}} \quad (3)$$

In general, it was found [15] that for sharp (cone, pyramid) indentation of an elastic – plastic material the loading response is governed by $F = C h^n$, where C is constant, h is penetration depth and $n \approx 2$. Thus we get:

$$W_{tot} = \int_0^{h_{max}} C h^2\, dh = \frac{C h_{max}^3}{3} = \frac{F_{max}\, h_{max}}{3} \quad (4)$$

Alternatively, by taking the hardness to be based on plastic strain done, then the work done should be the work:

$$H = \frac{k F_{max}^3}{9 W_p^2} \quad (5)$$

where F_{max} is the maximum indentation load and k is a constant equal to 0.04…0.06 for sharp indenters. In all cases the H_{area} and H_{volume} values are very similar.

When taking into consideration that the rail wear is radically defined by rail steel hardness, which was found out more later, this rail quality control method apparently becomes a perfect object for future investigation.

Specific cases in wheel –railway contact

The formation of wheel flats in wearing and shearing, transformed volumes have been treated in the literature [16]. However, there are still many problems to be explained. The wheel/rail slide is a very complicated process. The maximum available friction force in every point of the thermal affected zone (Fig. 5) is proportional to the loading component perpendicular to the surface and friction coefficient according to basic solid mechanics. If shear stress in the wheel/rail surface layer is high, plastic strain occurs under the surfaces. Taking into account the factors treated above, the most important parameters that influence material transformation during wheel – railway skidding are hardness and residual stresses [17,18]. Many important properties, such as wear resistance adhesion, are related to those two parameters. Wheel surface that appears smooth on macro-scale will show roughness on micro-scale. When wheel/rail surfaces are pressed together, only the largest asperities will initially be in contact and at higher pressures will take a larger portion of the load than the surrounding material. Fatigue crack initiation as well as propagation of small cracks is mainly promoted by shear stresses [19-22]. Once a millimeter-size crack has been developed, its propagation is usually driven by tension. In rolling contact loading, however, tensile stresses of any significant magnitude do not occur. Thus, a rolling contact fatigue crack is normally propagated by shear stresses throughout its entire fatigue life. From elastic – plastic indentation analysis is clear, that the largest shear stress occurs some 3-5 mm below the surface. It could thus be expected that a surface-initiated crack will be confined to the surface zone of high shear stress. In a later stage, the cracks will deviate into a circumferential direction. The most basic parts of a wheel are the rim, disc and hub of the wheel (Fig. 6). The most difficult are the wheel rim operating conditions, especially the part which rolls on the rail. During common inspection of the wheels, the objects under observation and checking is the correspondence of the wheels elements dimensions to predefined norms; wheels are inspected by defect scope; wheels are checked, the middle part of the axis and braking plates are inspected by magnetic defect scope.

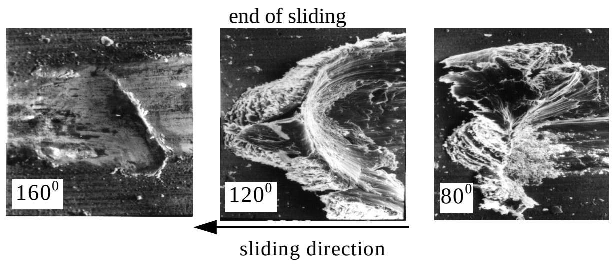

Fig. 5. Scanning electron micrographs of scratch test failures for wheel steel with different contact geometry 2Θ=160, 120 and 90 degrees. Also apparent are the subsurface deformation and fracture associated with the indentation scratch process

Comprehensive axle inspection is performed:

- during forming and maintenance, while the elements of the axle are repaired;
- when the impressions and stamps of the last comprehensive inspection on the end of axle neck are unreadable and unclear;
- when allowable micro-cracks, non-metallic gaskets and other defects according the defined norms are removed;
- after train disaster and accidents, checking of axles of all the damaged carriage.

All damages of axles and their elements are classified according two-digits decimal system, for example 10, 11, 20, 21, 30, 31, etc. For damages distribution according the types and location of appearance, the classification is accepted, according which damages of continuous rolled wheels, can be:

- wearing;
- defects of rolling surfaces;
- cracks and fractures.

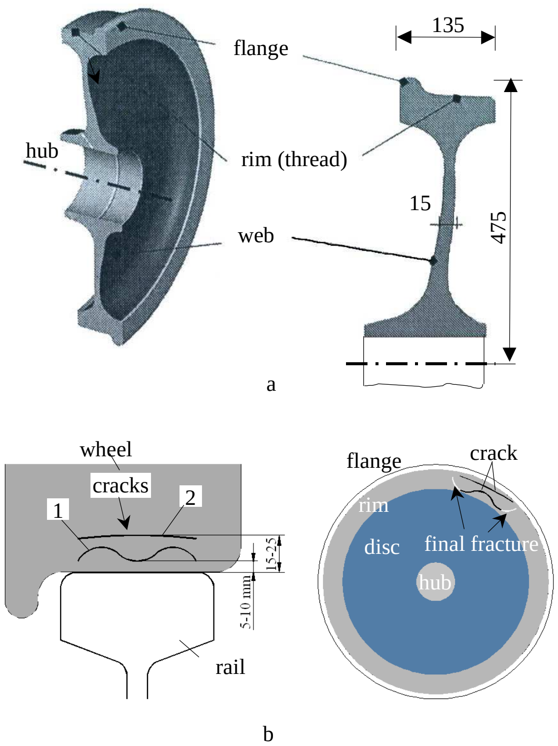

Fig. 6. Main geometry characteristics of the wheel (a) and place and depth of possible fatigue cracks initiation (b) [1]

Crack appearance is defined by mechanical properties of material – ratio p/τ_y, here p is wheel pressure onto a rail; τ_y - shear yield strength, MPa. The more τ_y increases, the more material damage propagation decreases. The approximate material value τ_y can be defined from the measured hardness:

$$\tau_y \approx 10HV/6 \tag{6}$$

here HV is hardness according Vickers (in case when steel hardness is not greater than $480\,HB$, than $HV \approx HB$). The centre of fatigue flow is situated under the running surface of the wheel by 1/3 of the railhead depth, i.e. to 11 to 24 mm from the running surface, above the rail web. Cold hardening of steel on the running surface is significant and up to the depth of 11 mm. Hydrostatic pressure exists which gradually changes into tension and reaches its maximum value at 5 to 11 mm. The relation of hardness and wear is based on the first phase of indenter stamping correspondence with stamping process of abrasive grain. Testing has shown that relative resistance to wear ε for annealed steels is directly proportional to their hardness H, defined before testing:

$$\varepsilon = b\ H \tag{7}$$

here b is proportionality coefficient for structural and some tooling carbon and high-carbon steels. For steels, tested after hardening and annealing:

$$\varepsilon = \varepsilon_0 + b\left(H - H_0\right) \tag{8}$$

here ε_0 is relative resistance to wear in annealed state, b is coefficient, depending on the steel microstructure, H_0 is steel hardness in annealed state. A rail wheel typically has a wear life of about 240.000 km, which for a standard fright wheel is about 8×10^7 loading cycles. Some of these cycles ratchet the wheel steel until the metal reaches its ductility limit.

Materials and experimental investigations

In order to analyze the amount of anisotropy, test samples were taken from several locations and in several directions of the wheels. Mechanical characteristics of steels that are used for manufacturing of carriages and axles must be as follows: ultimate strength $\sigma_{ut} = 500 - 550$ MPa, yield strength $\sigma_{yt} = 400$ MPa, relative elongation $\delta \approx 20\%$, endurance $\sigma_{-1} = 210 - 230$ MPa, hardness according Brinell $HB = 250$. The steel must not contain more than 0.03 % of phosphorus and sulphur. Hardness alteration in an axle depth $(30 \pm 1\ \text{mm})$ must not exceed $20\,HB$ units. For steel mechanical properties ($\sigma_y, \sigma_u, \sigma_f$) definition, tension type testing is used currently. However for testing performing it is necessary to have comprehensive, expensive tension device and large-sized specimens manufactured for specific testing. Moreover, it is impossible to perform testing without dismantling constructions in operation. Railway steel belongs to special application structural steels with exclusive technological or operational properties. Wheels (and rails) steel must be strong and resistant to wear. It must have 0.40 – 0.80 % of carbon, must be high-carbon with manganese (0.6 – 1.4 %).

Table 1. The main chemical composition (%), yield strength, ultimate tensile strength and hardness of the rail and wheel materials

Material	Rail (GOST 24182-80)	Wheel (GOST 10791-89)
C	0.69	0.491
S	0.045	0.039
P	0.035	0.039
Si	0.35	0.502
Mn	0.95	0.920
Cr	0.25	0.308
Ni	0.29	0.302
$\sigma_{0.2}$, MPa	720	412
$\sigma_{u,t}$, MPa	1100	660
HV (Vickers)	370	260
HB (Brinell)	363	250

A batch of continuously casted wheels was received from Radvilishkis carriage depot, SC “Lithuanian railway” (GOST 10791-89, grade 2, 9036 – 88, TY 0943 –

156 – 01124328). The wheels were supplied from metallurgical factory NTMK/Ferro Транс Treid from Russia, Nizhnij Tagil and were turned locally. They are supplied to all SE SC "Lithuanian railway" axles maintenance depots. Before a wheel flange was turned, mechanical state of the received wheels was checked precisely, with defining mechanical properties of the metal, by the application of non-destructive testing of mechanical properties. The most characteristic reasons for gradual change of technical state of axle are wearing, part fatigue, materials aging, surface pollution, etc. For frictionless rolling/sliding wheel-rail contact shakedown limit is four times the shear yield stress of the rail material [9]. Shakedown in repeated loading is the process whereby plastic strain in the first cycles of load leads to a steady cyclic state which lies within the elastic limit. The maximum load for which shakedown occurs is called the shakedown limit. In rail-wheel contact there are two processes that can contribute to this phenomenon. Firstly, protective residual stresses, and secondly, strain hardening of the material can raise its elastic limit. The properties of a typical rail material used in Lithuania and Europe countries are given in Table 1. The shear yield stress (τ_{max}) can be estimated from the yield stress ($\sigma_{0.2}$), given in Table 1, using von Misses criterion: $\tau_{max} = \sigma_{0.2} / 3 = 277\,\text{MPa}$.

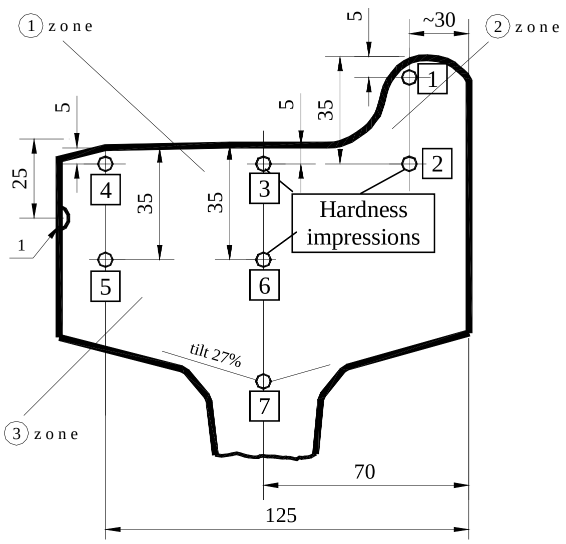

Fig. 7. Location on the wheel rim cross-section circumferential hardness tests

Rail steel hardness, for repeated contact can be made from the hardness value in Table 1, since hardness testing results in plastic strain of about 0.8%; $\sigma_{0.2} = H / 3$ and therefore $\tau_{max} = 519\text{MPa}$. For this material, taking the latter value of shear yield stress, the shakedown limit ($p_s = 4\tau_{max}$ for frictionless sliding) is 2077 MPa. Von Misses yield conditions are more representative of engineering materials then Treska. Although the slip-line field theory can be applied to both types of yield condition, Tresca is generally selected as it leads to a simpler equation that can be solved analytically. However, von Misses yield can give up to 15.5% $\left(2\sqrt{3}\right)$ higher limit load value than Tresca [11], which would lead to $c = 3.285$ in equation (2). All metallic engineering materials display elastic-plastic strain hardening behavior that is quite different from rigid-plastic non-hardening materials. There exists a strong empiric relationship between hardness value according Brinell (*HB*), hardness value according Vickers (*HV*) and ultimate (strength) values in tension diagram, which can be expressed by this formula:

$$\sigma_i = k\,HB \tag{9}$$

here *k* is proportionality ratio (0.2 < *k* < 0.38).

A relation between strength and hardness value according Brinell, in low carbon steel original state and after short time of operation, is expressed as:

when *HB* = 100 – 175 $\sigma_u = 0.34\,HB$,

when *HB* = > 175 $\sigma_u = 0.36\,HB$.

For relative yield strength estimation the following formula can be applied:

$$\sigma_{0.2} = 0.545\,HB - 48 \tag{10}$$

For low stamping forces application, when evaluating mechanical state, during defining hardness value according Vickers *HV*5 (stamping force *F* = 5 kG), steel relation formulas are:

$$\sigma_u = 7.5\sqrt{\frac{HV5}{3}} \qquad \sigma_{0.2} = 0.25\,HV5 \tag{11}$$

For the evaluation of mechanical state of carriage continuous by casted axles (in order to define the strength and plasticity characteristics), the available non-destructive methods, based on both static and dynamic hardness measurements, are widely applied [17-22].

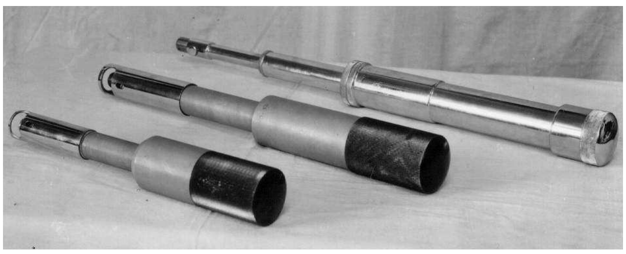

Fig. 8. Dynamic indentation devices, designed in Kaunas University of Technology, for non-destructive evaluation of structures

Together with static indentation methods, dynamic hardness measuring tools are widely employed in practice. For practical application of dynamic indentation method, in Kaunas University of Technology hardness measuring tools of original design were developed (Fig. 8). They are distinguished by small size, they do not require special fastening and may be operated in production conditions without disassembling the construction. To receive dynamic indentation, a spring system mechanism is used. When an indentation diameter *d* (mm) has been measured by a carry microscope, it is possible to receive metal hardness value according Brinell (*HB*), further – another strength characteristics. The indentation impression diameter was measured by a carry Brinell microscope, by two perpendicular arrows and the arithmetical average value was estimated. The hardness is estimated from the table, when calculated analytically, or according to the constructed dependence curve.

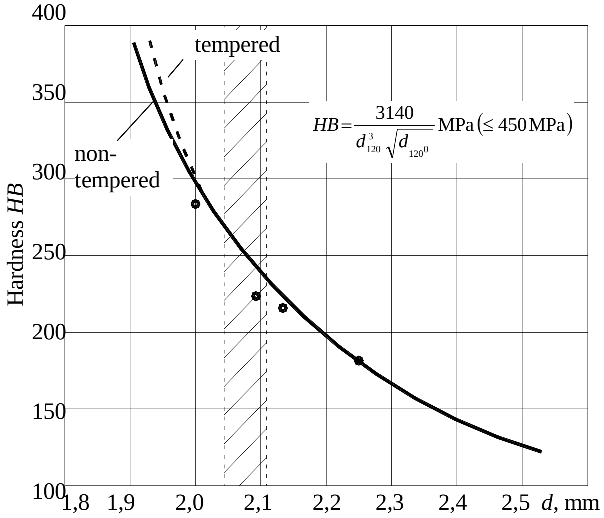

Fig. 9. Dependence curve defining strength limits based on indentation impression diameter, obtained according to the performed dynamic indentation when indenting conical indenter $2\theta = 120^\circ$

Hardness measuring tools help to research both small and big metal volumes, to perform testing in hardly accessible locations of the construction, to research local areas of welding seals.

Results and discussion

The results of the hardness measurement are listed in Tables 2 and 3. In the case under analysis we can test the specimens with hardness not greater than $HB\,450$.

Table 2. Results of hardness testing in cross-section of the wheel (Fig. 7)

Position	***1***	***2***	***3***	***4***	***5***	***6***	***7***
Hardness *HV*10	270	272	267	264	269	268	261

The deviation in hardness magnitudes is about 8 %. The hardness decreases somewhat with depth below wheel tread, probably due to the rim chilling, surface hardening during manufacture and work hardening during operational loading. Further, material in the flange is harder than material in the wheel tread. In general, plasticity characteristics is a relative elongation in tension expressed as:

$$\delta = \alpha \left(d / D, tan\,\theta \right)^{\beta} \tag{12}$$

here α and β are material constants, depending on material strengthening coefficient n. D is roll diameter, θ is half-angle of the conical by the apex. In practice $\alpha = 0.2$ and $\beta \cong 2$ or $\beta = (2n-3)/(n-1)$ [10] are assumed. Between δ and H^{120°, the hardness value in indenting a conical $2\theta = 120^\circ$

$$\delta_t = 0.299 - 6.05 \cdot 10^{-4}\, H^{120^\circ} \tag{13}$$

Table 3. Research results of mechanical characteristics of carriage wheel metals

No.	Wheel code	Hardness impression diameter d^*_{vid}, mm	*HB*	σ_{ut}, MPa	Remarks
1	131097	2.07	260	598	σ_{ut} = 0.23HB
2	131273	2.008	270	621	
3	128606	2.01	265	609.5	
4	52014	2.08	252	579.6	
5	52936	2.04	258	593.4	
6	181161	2.08	252	579.6	
7	131116	2.07	260	598	
8	128876	2.05	253	581.9	
9	52070	2.155	240	552	
10	52950	2.01	265	609.5	
11	52950(def)	2.13	245	563.5	25x25 mm
12	52950(def)	2.02	264	607.2	In the limits of defects

*****Diameter *d* value of the indentation impressions in each zone was estimated as the average value of 5 indentation impressions values.

This formula was used to make a data table and dependence curve (Table 2, Fig. 9.) for a set of steels. Combining data given in Table 2 and the hardness values in Fig. 7, it can be found that specimens with high compressive stresses do not possess higher hardness. All these observations suggest that residual stress is not necessarily correlated with the hardness determined by indentation on wheel track. Residual compressive stresses at the wheel surface due to manufacturing and operational loading may tend to suppress shallow fatigue crack initiation. Estimating methodology of relative elongation (δ) is mechanical characteristics of axle elements – strength and yield $(\sigma_{ut}, \sigma_{yt})$ and plasticity characteristics – is based on real tension diagrams $\sigma_u^{'}(\delta)$ and recovered hardness diagram $H(d/D, tan\theta)$ similarities, which are approximated according exponential functions:

$$\sigma_u^{'} = b\,\delta^{m} \qquad (14)$$

$$H = B\left(d / D, tan\,\theta\right)^{n-2} \qquad (15)$$

here $\sigma_u^{'}$ is real stresses in tension diagram, $H\left(HB, HV\right)$ is hardness units (stresses) in hardness diagram, b is given materials constants, δ is a relative elongation, m and n is strengthening ratios in tension and compression.

Table 4. The relationship between hardness value H^{120° and relative elongation in tension

No	Hardness value, H^{120^0}, MPa	Elongation, δ, %	No	H^{120^0}, MPa	δ, %
1	157 (1570)	20.3	6	229 (2290)	13.2
2	180 (1800)	21.2	7	270 (2700)	12.4
3	189 (1890)	18.2	8	297 (2970)	9.6
4	197 (1970)	18.6	9	318 (3180)	10.8
5	203 (2030)	17.6	10	340 (3400)	11.7

The experiments have demonstrated that for axle and rail miscellaneous structural steels, in case of greater original hardness, the absolute ant relative increase reduces under cyclical increasing shakedown and this is a result of the increase of absolute and relative hardness.

The greatest hardness increase, which appears under cyclical shakedown, does not depend on the type of the structure, and is the same for both grade structures with equal hardness, and flat grade structures. The enlarged hardness increase in beinitic structures can be explained by the strength due to plastic strain combination with the strength, which is a result of remaining austenite transfer into martensite. Hardness variation within the limits 330 – 410 HB has not influenced the resistance to impact yield

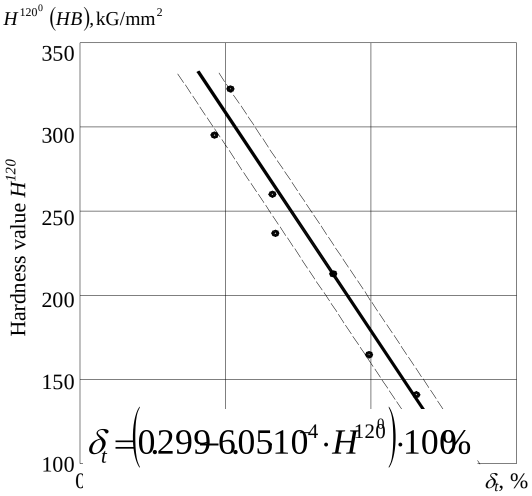

Fig. 10. The link between hardness value, when indenting conical indenter $2\theta = 120^\circ$, H^{120° and relative elongation δ_t, in tension

(brittleness), however for lower hardness $\left(< 330\,HB\right)$, it was slightly higher. This problem is presently under further study and the results will be published in the near future.

Conclusions

1. The material of railway wheels has been tested and anisotropic properties have been studied. The results indicate that anisotropy, in terms of position of the test specimens, exists. Material strength is of importance, but it is unclear which material parameters correlate to the resistance against subsurface cracks.

2. The deviation in hardness magnitudes is about 8 %. Hardness decreases somewhat with the depth below wheel tread, probably due to the rim chilling, surface hardening during manufacture and work hardening during operational loading. Further, material in the flange is harder than material in the wheel tread.

3. To define wheels mechanical characteristics, a dynamic indentation method was used, which allows to define strengths σ_{ut} and σ_{yt} and plasticity δ characteristics within ± 8 % tolerance limits. The strength of a certain volume of wheel material is dependent on its position in the wheel.

4. In the absence of fatigue test results, hardness tests provide a sensitive measure of anisotropy. It may also lead to the direct dependence between hardness and fatigue tests.

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