Influence of operation on tram wheels and rails surface layer condition

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Trams have become a constant in the landscape of many European metropolises in recent decades. The aim of presented research was to evaluate material changes in the surface layer of Siemens Combino, Konstal 105Na, Modernus Beta and Duewag GT tram wheels and rails as a consequence of wheel and rail exploitation in Poznan agglomeration. Microscopic study and hardness measurement were performed. The surface layer of tram wheel was highly deformed, particularly on the top of the wheel flange and under the rolling surface. In the tram wheel so-called overhangs on the top of the wheel flange and on the outer part of the rolling surface were found. Plastic deformation caused an increase of hardness in comparison to the core material. Hardness increase in case of the top of the wheel flange (even 60%) was bigger than in case of the rolling surface (up to 30%). It was also found that the longer approximate total mileage of the wheel was, the higher hardness increase of the surface layer was. ‘White layer’ as a result of presence of higher temperature during exploitation caused by friction was observed. Hard (even 2.5-times harder than the core material) and brittle layer can cause cracks. In case of Modernus Beta and Konstal 105Na wheels in the part from their frontal side decarbonization was noticed. It was stated that decarbonization is also present in the new wheel. It means that it is a defect of PST type wheel production. An area with so low hardness (below 100 HV0.1) could cause faster deformation and wear of whole wheel. A deformation in the surface layer were also revealed in rails. It was observed even in the coating area generated by welding — slip lines in austenite and martensite phase presence. Some recommendations for better wheel exploitation for Poznan Public Transport Company were also determined.

Key words: tram wheel, surface layer, plastic deformation.

1. INTRODUCTION

Tramway are a common city transportation of special performance and functionality. To increase tram transport effectiveness and safety, better understanding of wheel–rail contact wear is required. The most severe wear of wheel is observed on the running gear, especially on the rolling surface.

Problems regarding the durability of the of the wheel–rail contact are associated with many different forms of wear caused by the surface contact friction and fatigue. In literature, models for calculating the wear of wheel–rail contact could be found [1]. It should be underlined that, not only rolling friction in wheel–rail contact is present, but mixed: rolling-slip (sometimes, in the case of rail curves, wheel flanges are exposed to almost pure sliding friction [2, 3]).

In case of wheel–rail interaction rolling contact fatigue (RCF) wear can occur [4]. Fatigue wear in this friction pair can proceed as spalling or shelling.

Slides in curves, speeding up, braking etc. can cause heating of the surface layer above austenitizing temperature in a very short time (e.g. a few seconds) which leads to the formation of martensite. Then, further movement of the tram and cyclic loading of the wheel cause spalling. For instance, those slips at the wheel–rail contact are considered to be the common reason of faster wheel wear of diesel multiple units in district of Wielkopolska [5]. Heating (due to friction) above austenitizing temperature is a reason of so-called ‘white layers’ formation. Mostly, the phenomenon of the white layers creation takes place in the cutting hard steels. White layers could arise as a consequence of dynamic processes affecting intensive deformation and the related with them thermal effects [6, 7]. Because of their high hardness and brittleness they can favour spalling wear. Such layers were observed in the case of rail [6, 8] and also in case of tram wheels of Solaris Tramino after 146 000 km of approximate total mileage [9]. The problem of the surface layer hardening was observed in case of train wheels in which cracks were originated by the existence of MnS in the highly deformed surface layer [10]. Delamination caused by MnS was also observed in rails [11]. Flattened MnS inclusions and severe delamination were observed as well in case of tram wheels [9]. Rolling surface observations during those research revealed also effects of shelling processes (but in early stage of growth). Shelling processes takes place when the rolling surface layer is heated to a temperature of above 300°C for longer time. Stresses caused by wheel–rail contact could cause small thermal cracks. Those cracks can propagate into the substrate by pressing of solids or liquid, for instance. Such cracks could also appear under the rolling surface and as a result of cyclic loading, developed to the surface.

The research presented in authors’ previous paper [9] revealed also high deformation of investigated tram wheel surface layer, particularly on the top of the wheel flange, and in the vicinity of outside angle of rolling profile. This deformation caused 70% hardness increase in comparison to the hardness of the core material. The thickness of hardening was less than 0.1 mm (according to information in literature [5, 12] thickness of such layer is from a few hundredths of a millimeter to 0.5 mm).

The purpose of presented research was to estimate of material changes in the surface layer in wheels of trams after operation in different conditions and in the surface layer of rails in Poznan agglomeration. It is also expected to define some suggestions for improving wheel exploitation by Poznan Public Transport Company (MPK Poznan).

2. METHODS

Objects of presented studies were wheels and some selected sections of two types of rail. All wheels, except the new one were excluded for further exploitation. Investigated wheels were produced of P70 steel and the rail was made of 180S and 60R2 steels. The chemical composition according to standards of those steels is presented in Table 1.
Wheels came from the second axle of the first bogie (the driven bogie) of the tram. They were dismantled from following trams: Siemens Combino, Konstal 105Na, Moderus Beta and Duewag GT. Details of investigated wheels (as approximate total mileage, number of reprofiling and approximate average axle load of each wheel set in the bogie) are presented in the Figure 1. All of them operating in Poznan Public Transport Company.

To assess the surface layer condition, Vickers hardness tester, a light and scanning electron microscope, and 3D profilographometer were applied. Fluorescent spectrometer was also used.

3. RESULTS AND DISCUSSION

The microstructure of the core material of investigated wheels and rails is presented in the Figure 2. In all cases a pearlite was a dominate phase. In case of parts of rail, coated area by welding was also noted. Dendritic microstructure made of austenite phase of the coated area is presented in the Figure 3.

The analysis of chemical composition revealed that investigated steel of the wheels and rails were characterized by lowered carbon amount. The amount of this element in wheels steel was less than 0.65% and was lower than limit of the standard for P70 steel — Table 1. Hence, it was in range for P60 steel. It is worthy emphasizing that P70 is preferred for tram wheels because of its better properties in comparison to P60 steel. The chemical composition is presented in Table 2.

<table>
<thead>
<tr>
<th>Steel Type</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P max</th>
<th>S max</th>
<th>P + S max</th>
<th>Standard No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siemens Combino</td>
<td>0.637</td>
<td>0.896</td>
<td>0.305</td>
<td>0.010</td>
<td>0.011</td>
<td>0.019</td>
<td>PN-K-92016</td>
</tr>
<tr>
<td>Konstal 105Na</td>
<td>0.626</td>
<td>0.885</td>
<td>0.347</td>
<td>0.016</td>
<td>0.008</td>
<td>0.055</td>
<td>PN-92/1-93440</td>
</tr>
<tr>
<td>Moderus Beta</td>
<td>0.622</td>
<td>0.902</td>
<td>0.351</td>
<td>0.015</td>
<td>0.007</td>
<td>0.055</td>
<td>EN-13674-1/2003</td>
</tr>
<tr>
<td>Duewag GT</td>
<td>0.64</td>
<td>0.775</td>
<td>0.305</td>
<td>0.032</td>
<td>0.017</td>
<td>0.284</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. The chemical composition of investigated steels (*) – amount beyond of the range of the accreditation of measurement device

0.75 0.95 0.4 0.04 0.04 0.07 PN-K-92016
1.15 0.4 max 0.04 0.04 0.06 PN-92/1-93440
1.15 0.4 max 0.04 0.04 0.06 EN-13674-1/2003

The new one

<table>
<thead>
<tr>
<th>Tram and rail type</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
</tr>
</thead>
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<tr>
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<td>0.896</td>
<td>0.305</td>
<td>0.010</td>
<td>0.011</td>
<td>0.019</td>
<td>0.032</td>
<td>0.002</td>
</tr>
<tr>
<td>Konstal 105Na</td>
<td>0.626</td>
<td>0.885</td>
<td>0.347</td>
<td>0.016</td>
<td>0.008</td>
<td>0.055</td>
<td>0.03</td>
<td>0.007</td>
</tr>
<tr>
<td>Moderus Beta</td>
<td>0.622</td>
<td>0.902</td>
<td>0.351</td>
<td>0.015</td>
<td>0.007</td>
<td>0.055</td>
<td>0.029</td>
<td>0.006</td>
</tr>
<tr>
<td>Duewag GT</td>
<td>0.64</td>
<td>0.775</td>
<td>0.305</td>
<td>0.032</td>
<td>0.017</td>
<td>0.284</td>
<td>0.148</td>
<td>0.049</td>
</tr>
<tr>
<td>The new one</td>
<td>0.621</td>
<td>0.884</td>
<td>0.291</td>
<td>0.014</td>
<td>0.011</td>
<td>0.124</td>
<td>0.072</td>
<td>0.014</td>
</tr>
<tr>
<td>The rail 180S</td>
<td>0.517</td>
<td>1.13</td>
<td>0.24</td>
<td>0.028</td>
<td>0.02</td>
<td>0.018</td>
<td>0.023</td>
<td>0.001</td>
</tr>
<tr>
<td>The rail 60R2</td>
<td>0.458</td>
<td>1.01</td>
<td>0.253</td>
<td>0.019</td>
<td>0.017</td>
<td>0.021</td>
<td>0.022</td>
<td>0.001</td>
</tr>
</tbody>
</table>
The hardness of the core material of investigated wheels was in the range of 290-360 HV10 while the hardness of the rail was 220 HV10 (180S) and 280 HV10 (60R2). Thus, it could be stated that initial relation of wheel/rail hardness condition (which is: $HV_{\text{wheel}}/HV_{\text{rail}} = 1.2$) has been met in most cases for rail made of 180S steel (Fig. 4).

In case of parts of rail which were coated, the hardness was even twice higher (approx. 450 HV10) than hardness of the core material. The HV0.1 hardness profile on the cross-section form the surface to the core material is presented in Figure 5.

Macroscopic observation of the surface revealed that wear effects indicated about frequent sliding or rolling-sliding motion of all investigated wheels. The most damaged part of the wheel was its rolling surface and the top of the wheel flange (Fig. 6).

Wheel flange is also sometimes in contact with the rail, for example during crossing the intersecting of rails. The rolling contact fatigue wear was revealed by presence of losses in the surface in form of shells created mainly by shelling mechanism. It was observed that surface on the top of the wheel flange was more worn than the rolling surface. A tram wheel runs on the frog through the entry platform, then instead of the wheel tread, wheel rolls at the wheel flange. Turnouts represent trouble spots in tram track sections [13]. 3D isometric views of the wheel flange is presented in Figure 7.

Overhangs due to sever plastic strains near the outside of the rolling profile and on the wheel flange were detected (Fig. 8). In these parts the strongest deformation was noticed. Similar deformation was found in case of rails (Fig. 9).

In the area of overhangs microstructure was especially deformed. This microstructure was characterized by flattened grains and delamination (Fig. 10) initiated very often by flatted phases of MnS.

Severe plastic deformation was observed in the surface layer under the top of the wheel flange (Fig. 11) and under rolling surface of the wheel (Fig. 12a) as well as under rolling surface of the rail (Fig. 12b). It should be mentioned that even in part of the rail which was coated by welding, effects of plastic deformation could be noticed (Fig. 13). Near the surface a huge amount of slip lines in austenite were visible. Moreover, as a result of severe plastic deformation martensite needles formed. Austenite changes into martensite as a consequence of mechanical loading. The energy needed for the martensite transformation can be delivered by the process of plastic deformation. Austenite change in the martensitic phase (known as phase transformation plasticity or transformation induced plasticity) occurs when applied stress or a deformation. For example such process takes place in TRIP steels.

The consequence of huge plastic deformation in the surface layer of wheel was hardness increase. Examples of hardness distribution on the cross-section from the surface to the core material is presented in the Figure 14 for wheels and in the Figure 15 for the rail. Hardened layer did not exceed 0.1 mm in case of wheels and rails.

The average hardness measured on the rolling surface of the wheel and rail as well as on the flange surface of the wheel was higher than in the core material (Fig. 16). Hardness increase in case of the top of the flange was bigger (even 60%) than in case of the rolling surface (up to 30%). The explanation of this higher hardness increase could be in the method of reprofiling. Reprofiling, excluding renewing of the profile of the wheel (renewing is the main...
Fig. 8. Area of severe deformed surface layer with overhang on the top of the wheel flange dismantled of Konstal 105Na tram; SEM

Rys. 8. Obszar silnego odkształcenia plastycznego w postaci nawisu w pobliżu wierzchołka obręza koła zdemontowanego z tramwaju Konstal 105Na; SEM

Fig. 9. The overhang formed in dismantled rail

Rys. 9. Nawis powstały w zdemontowanej szynie

Fig. 10. Microstructure in overhangs area in wheel dismantled of Konstal 105Na (a–d) and Duewag GT (e) tram

Rys. 10. Mikrostruktura w obszarze nawisów w kołach zdemontowanych z tramwaju Konstal 105Na (a–d) i Duewag GT (e)
Fig. 10. The microstructure in overhangs area in wheel dismantled of Konstal 105Na (a-d) and Duewag GT (e) tram

Rys. 10. Mikrostruktura w obszarze nawisów w kołach zdemontowanych z tramwaju Konstal 105N (a-d) i Duewag GT (e)

Fig. 11. Microstructure in the layer of the top of the flange of the wheels dismantled of Solaris Combino (a) Moderus Beta (b) tram

Rys. 11. Mikrostruktura w warstwie przy wierzchołku obrzeża koła zdemontowanego z tramwaju Solaris Combino (a) i Moderus Beta (b)

Fig. 12. Microstructure in the layer under the rolling surfaces the wheel dismantled from Moderus Beta tram (a) and under the rolling surface of the rail (b)

Rys. 12. Mikrostruktura w warstwie pod powierzchnią toczną koła zdemontowanego z tramwaju Moderus Beta (a) i pod powierzchnią toczną szyny (b)

Fig. 13. Microstructure of coated area in the rail near the rolling surface

Rys. 13. Mikrostruktura obszaru pokrycia w szynie w pobliżu powierzchni tocznej

Fig. 14. The hardness profile on the cross-section form the surface to the core material for wheel dismantled of Duewag GT and Siemens Combino tram

Rys. 14. Profil twardości na przekroju poprzecznym od powierzchni do materiału rdzenia kół zdemontowanych z tramwajów Duewag GT i Siemens Combino

Fig. 15. The hardness profile on the cross-section form the surface to the core material of the rail

Rys. 15. Profil twardości na przekroju poprzecznym od powierzchni do materiału rdzenia szyny

Fig. 16. The average hardness of the rolling surface of the wheel and the rail and on the top surface of the wheel flange

Rys. 16. Średnia twardość powierzchni tocznej kół i szyn oraz powierzchni wierzchołka obrzeża koła
The purpose of this procedure (by removing of some thickness of the surface layer which is deformed (after a period of exploitation) also allows to achieve some kind of revitalization of the surface layer microstructure. It is possible, that the thickness of removed surface layer is different in the part of the rolling surface of the wheel and in the wheel flange profile. It is probably larger in case of the rolling surface part of the wheel then in case of the wheel flange. Consequently, some deformed material remains after reprofiling in the surface layer particularly in the wheel flange.

The dependence between hardness increase of the wheel surface layer and approximate total mileage was found (Fig. 17). The longer of total mileage was, the higher hardness of the surface layer was.

Microhardness measurements close to the surface on the cross-section of the wheel allowed to notice a presence of very hard small areas. The value of the hardness of nearly 900 HV0.1 was detected for example on the wheel flange and over 700 HV0.1 in the rolling surface of wheel dismantled of Moderus Beta tram. It proves the existence of high temperature during exploitation as a result of friction between wheel and rail. Microstructure observation revealed presence of very fine-grained microstructure poorly etched with nital. Such microstructure is typical for so called white layers (Fig. 18). White layer was also noticed in tram wheel investigated during research discussed in authors’ previous paper [9]. Such layer were also observed in railways’ rails [6, 8]. Hard (even 2.5-times harder than the core material) and brittle layer can cause crack initiations and as a consequence more intensive wear of wheel.

In case of wheel dismantled of Konstal 105Na and Moderus Beta tram, in the surface layer of the face of the wheel (the frontal side) decarbonization was observed (Fig. 19). It was noticed also for the new wheel. Thus, it means that this was a production of PST wheel type effect, not a result of exploitation. Ferrite instead of pearlite microstructure was observed in this area, which was characterized by hardness of approx. 100 HV0.1. Hardness profile on the cross-section from the surface to the core material is presented in the Figure 20. Such soft microstructure could favour faster wear resulting from more intensive plastic deformation and delamination in this part of the wheel. Plastic deformation of ferrite grains under the overhang in the part of the face of the wheel is presented in the Figure 21.
5. CONCLUSIONS

In the surface layer of tram wheels dismantled of trams operating in Poznan agglomeration has been noticed:
- severe plastic deformation, like strongly flattened grains or presence of large overhangs near the outside of the rolling profile and the wheel flange profile,
- hardness increase in comparison to the hardness of the core material (hardness increase in case of the top of the edge was bigger — even 60%, than in case of the rolling surface — up to 30%),
- delamination (especially in the part of the top of the wheel flange profile), which could help to crack initiation and, as a result, more intensive wear,
- ‘white layer’ (with hardness nearly 900 HV0.1) as a consequence of temperature increase caused by friction during exploitation could help to crack initiation and more intensive spalling wear,
- decarbonization in the part from the frontal side of the wheel (but only in those from Moderus Beta, Konstal 105Na and in the new one, which means that it is a production, not exploitation defect), which could favour faster wear resulting from more intensive plastic deformation and delamination in this part of the wheel.

The influence of approximate total mileage of the wheel on the hardness changes of the surface layer in the wheel surface layer was found: the longer approximate total mileage of the wheel was, the higher hardness increase of surface layer was. Probably some deformed material stays after reprofiling process in the surface layer.

Moreover, it was revealed that all investigated wheels (and both of tested rails) were characterized by lower carbon content. It was below 0.65% which is the lower limit of P70 steel.

In the surface layer under rolling surface of rails plastic deformation was noticed like in case of wheels (in coated area by welding some effects of deformation was also found — huge amount of slip lines in austenite grains and martensite needles crated due to transformation induced plasticity phenomenon).

A tramway do not attain as high velocities as trains, but the need to enter curves with very small radii causes the wheel and rail profile must be especially carefully crafted to avoid derailment. Some recommendations for better wheel exploitation for Poznan Public Transport Company were determined.

Before setting up of a new wheel, hardness on the rolling surface, wheel flange and on the face of the wheel should be checked. Some randomly selected wheels should be allot for chemical composition analysis of the steel to compare it with the appropriate standard.

Reprofiling process of the wheel needs modernization (possibly the larger thickness of the surface layer should be removed each time). It is desired to check the hardness after each reprofiling.

In the order to delay wear of railway parts, it is also crucial to perform the research aiming the solutions in the scope of application of new profiles of those parts, their surface treatments or special materials [14].

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REFERENCES


Wpływ eksploatacji na stan warstwy wierzchniej kół i szyn tramwajowych

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Słowa kluczowe: koła tramwajowe, warstwa wierzchnia, odkształcenie plastyczne.

1. CEL PRACY

Celem badań było określenie zmian, jakie zaszły w warstwie wierzchniej wybranych kół tramwajowych oraz szyn aglomeracji poznańskiej wynikające z ich eksploatacji. Lepsze zrozumienie zjawiska zachodzących na styku koła z szyną powinno przyczynić się do zwiększenia bezpieczeństwa transportu tramwajowego, a także do zmniejszenia kosztów obsługi.

2. MATERIAŁ I METODYKA BADAN

Obiektem badań było jedno nowe oraz cztery zużyte koła tramwajowe zdemontowane po różnym czasie eksploatacji (rys. 1) z pojażdżów: Siemens Combino, Konstal 105Na, Moderus Beta i Duewag GT taboru Miejskiego Przedsiębiorstwa Komunikacyjnego (MPK) w Poznaniu wykonane ze stali P70 oraz dwa fragmenty szyn ze stali 180S i 60R2.

Badania strukturalne przeprowadzono za pomocą mikroskopu świetlnego oraz elektronowego skanującego. Do wyznaczenia składu chemicznego zastosowano spektrometr jarzeniowy. Twardość warstwy wierzchniej określono sposobem Vickersa pod obciążeniem 10 N i 0,1 N.

3. WYNIKI I ICH Dyskusja

Materiał rżnięty kół, jak i szyn charakteryzował się mikrostrukturą, w której dominowała faza perlityczna (rys. 2). Twardość w przypadku kół wynosiła 290-360 HV10, a szyn 220 HV10 dla 180S i 280 HV10 dla 60R2. Oznacza to, że warunek wyjściowy relacji twardości obręczy do twardości szyny (ok. 1,2) był spełniony w większości par w przypadku szyny ze stali 180S (rys. 4). Skład chemiczny był prawidłowy poza mniejszą zawartością węgla (powstałych w wyniku przemiany transformation induced spallingu). W przypadku kół posiadających od tramwajów Moderus Beta i Konstal 105Na obserwowano odwzorowanie występujące w części płaszczyzny czołowej skutkujące prawie czysto ferrytyczną mikrostrukturą (rys. 19, 21) i zmniejszeniu twardości poniżej 100 HV1,0 (rys. 20). Zjawisko to było zauważane również w nowym kole, co oznacza, że jest to wada w produkcji obręczy typu PST, a nie skutek ich eksploatacji. Występowanie tak miękkiego obszaru może przyspieszać odkładanie warstwy oraz przyczyniać się do zwiększonego zużycia.

Znaczne odkształcenie plastyczne w postaci silnego zgniotu skutkowało zwiększeniem twardości warstwy wierzchniej nawet o 60% w przypadku wierzchołka obręczy i o ok. 30% w przypadku powierzchni tocznej koła (rys. 16). Stwierdzono również, że im większy był przebieg kół, tym większa była twardość warstwy wierzchniej (rys. 17) wynikająca od zgniotu (powstającego podczas kontaktu koła z szyną), którego skutki prawdopodobnie nie były całkowicie likwidowane podczas przeprowadzonej przez użytkownika operacji.

Badania twardości na przekroju poprzecznym wykazały, że ocenianie warstwy wierzchniej koła tramwajowego nie przekraczało 0,1 mm (rys. 14). W widłach (w szczególności w obszarze wierzchołka obręczy) zaobserwowano również delaminację i powstawałe „navisów” w pobliżu wierzchołka obręża i przy zewnętrznej części powierzchni tocznej kół (rys. 8) oraz szyn (9).

Silny zgniot skutkował zwiększeniem twardości warstwy wierzchniej nawet o 60% w przypadku wierzchołka obręża i o ok. 30% w przypadku powierzchni tocznej koła (rys. 16). Stwierdzono również, że im większy był przebieg kół, tym większa była twardość warstwy wierzchniej (rys. 17) wynikająca od zgniotu (powstającego podczas kontaktu koła z szyną), którego skutki prawdopodobnie nie były całkowicie likwidowane podczas przeprowadzonej przez użytkownika operacji.

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