A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 56 2011 Issue 3
DOI: 10.2478/v10172-011-0078-9

J. KRAWCZYK*, M. WITASZEK**, K. WITASZEK**

TRIBOLOGICAL PROPERTIES OF TYRE STEEL IN ROLLING-SLIDING CONTACT AGAINST BAINITIC RAIL STEEL

WŁAŚCIWOŚCI TRIBOLOGICZNE STALI OBRĘCZOWEJ PRZY WSPÓŁPRACY TOCZNO-ŚLIZGOWEJ Z BAINITYCZNĄ STALĄ SZYNOWĄ

Recently a development of new rail steels takes place. Steels with bainitic microstructure are considered to be alternative for pearlitic ones, because they exhibit high strength and good toughness. Also their wear behaviour can outperform the other microstructures in some conditions. Nevertheless no or little attention is devoted to study how the use of bainitic rail steels influences wear processes of wheels. This article is an attempt to file this gap. The influence of slippage and rotational speed on wear behaviour of a B6 tyre steel mated with the first polish bainitic rail steel, in rolling-sliding, high-pressure, friction conditions was studied. For this study laboratory friction and wear tests were carried out on an Amsler apparatus. The effect of slippage and rotational speed on mass loss and coefficient of friction was determined. To study wear mechanisms optical microscopic observations were carried out. The dependence between test parameters and thickness of plastically deformed layer as well as fracture length and depth was assessed.
Keywords: tyre steel, wear, coefficent of friction, wear mechanisms

Obecnie ma miejsce rozwój nowych stali szynowych. Stale o strukturze bainitycznej są uważane za materiały alternatywne wobec tradycyjnych stali perlitycznych, ponieważ wykazują wysoką wytrzymałość i odporność na pękanie. Również pod względem odporności na zużycie stale bainityczne mogą przewyższać stale o innych mikrostrukturach. W badaniach nad takimi stalami niewiele uwagi poświęca się wpływowi ich zastosowania na zużywanie kół kolejowych. Niniejsza praca stanowi próbę wypełnienia tej luki. Określono w niej wpływ poślizgu i prędkości ruchu obrotowego na zużycie próbek ze stali obręczowej gatunku B6, w styku z pierwszą, polską, bainityczną stalą szynową, przy wysokim nacisku w warunkach suchego tarcia tocznego z poślizgiem. W tym celu przeprowadzono badania tribologiczne na stanowisku Amslera. Ich wynikami było zużycie wagowe i współczynnik tarcia dla różnych poślizgów i prędkości obrotowych współpracujących elementów. Mechanizmy zużywania były badane za pomocą obserwacji mikroskopowych powierzchni po teście tribologicznym oraz obserwacji metalograficznych przekrojów próbek. Na ich podstawie określono również zależność grubości warstwy odkształconej plastycznie oraz długości i głębokości pęknięć od parametrów badań.

1. Introduction

Wheel sets are essential in ensuring reliability and safety of rail-vehicles [1-4]. Operation experiences indicate that wear processes influence durability and reliability of wheels. Various factors influence these processes, as e.g. material properties of the steel for tyres and wheel rims and conditions of their contact [1]. It is obvious that, in this case, also brands and properties of rail materials have a meaning. A continuous development of steels for railway rails is presently observed. More and more often the bainitic steels become the subject for investigations [5-9]. However, in such investigations a little attention is directed towards the influence of their application on the railway wheels wear behavior. The presented hereby paper constitutes an attempt of bridging this gap. An influence of the slippage and the rotational speed on wear of specimens of the tyre steel B6 brand being in contact with the first Polish bainitic rail steel [10] at a high pressure – under conditions of a dry rolling friction with a slippage – was determined in the paper.

2. Tested material and investigation methods

The tyre steel B6 grade of the chemical composition and hardness given in Table 1 was tested. This steel was

* AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF METALS ENGINEERING AND INDUSTRIAL COMPUTER SCIENCE, DEPARTMENT OF PHYSICAL AND POWDER METALLURGY, 30-059 KRAKOW, 30. MICKIEWICZA AV., POLAND
** DEPARTMENT OF AUTOMOTIVE VEHICLE SERVICE, FACULTY OF TRANSPORT, SILESIAN UNIVERSITY OF TECHNOLOGY, 40-019 KATOWICE, 8 KRASIŃSKIEGO STR., POLAND

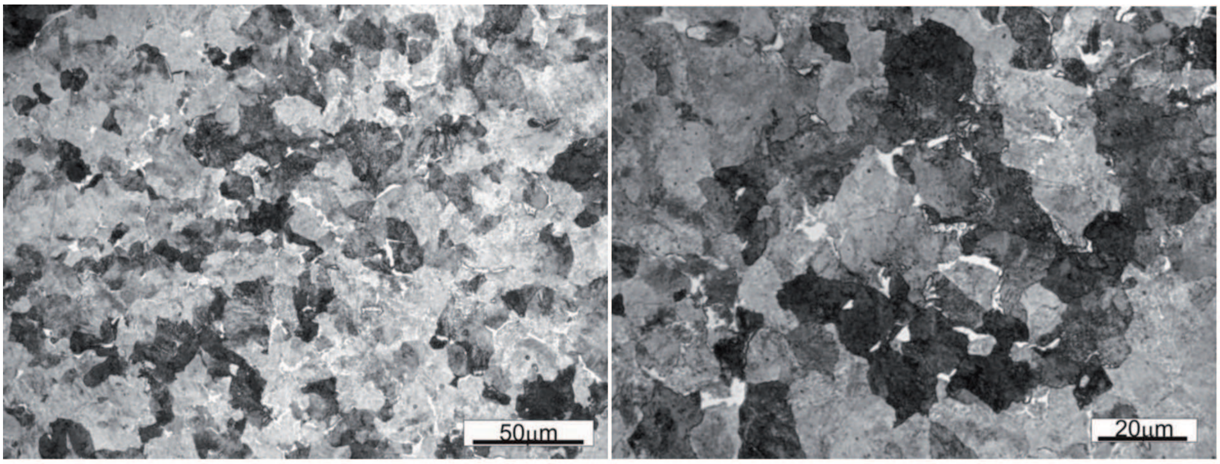

Fig. 1. Microstructure of the tested tyre steel

of a pearlitic microstructure with ferritic precipitates on grain boundaries (Fig. 1). In the range of optical microscopic observations the microstructure of the bainitic steel shows morphologic features of the upper bainite. Nevertheless the bainite transformation temperature and the M_S one enable to conclude that such microstructure have not to show significantly lowered fracture toughness [10]. During tribological tests it was in contact with the bainitic rail steel of the chemical composition and hardness presented in Table 2 and of the microstructure shown in Figure 2.

TABLE 1

Chemical composition of the tested tyre steel

Chemical composition, %									Hardness, HB
C	Mn	Si	P	S	Cr	Ni	Cu	Fe	
0.61	0.82	0.34	0.010	0.004	0.02	0.01	0.03	bal.	285

TABLE 2

Chemical composition of the bainitic rail steel

Chemical composition, %									Hardness, HB
C	Mn	Si	P	S	Cr	V	o	Fe	
0.19	1.91	0.16	0.017	0.008	1.47	0.34	0.34	bal.	375

Tests were carried out on the Amsler stand under conditions of a dry rolling fraction with a slippage. A constant pressure of 892 MPa was applied. This value corresponds to average Hertzian stress in contact of a locomotive wheel tread with a top of a rail head. Investigation parameters were: the slippage and rotational speed of the tyre steel specimen. The slippage was equal; 0.23%, 0.5%, 1.5% and 5%. Its two low values were used to simulate rubbing of the wheel tread with a top of a rail head whereas the highest one was chosen for the pair tyre flange – rail gauge side modelling. Slippage of 1,5% was chosen to simulate a wheel flange root – rail gauge corner contact. The rotational speed of the tyre steel specimen was equal: 100 rpm, 200 rpm and 300 rpm, that corresponds the rotational speed of locomotive wheels by the velocity of about 20, 40 and 60 km/h respectively. The testing machine does not allow to obtain higher speeds than 300 rpm. A mass loss of specimens was determined by periodically weighing them. In the present study a mass loss after 72 000 rotations of the B6 steel was analysed, when the steady state of wear rate was reached. The coefficient of friction in the tested system was also determined.

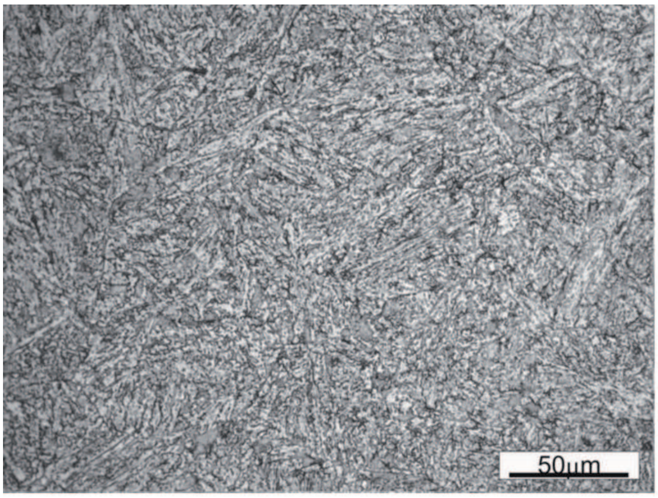

Fig. 2. Microstructure of the bainitic rail steel

The specimens after rubbing underwent metallographic examinations by means of the optical microscope. The surface appearance as well as cross-sections of the surface layer made in parallel and perpendicularly to the rolling direction were observed after tests. On the bases of photographs of cross-sections the thickness of plastically deformed layers was determined. In cases when cracks were observed, their length and depth was found (Fig. 3).

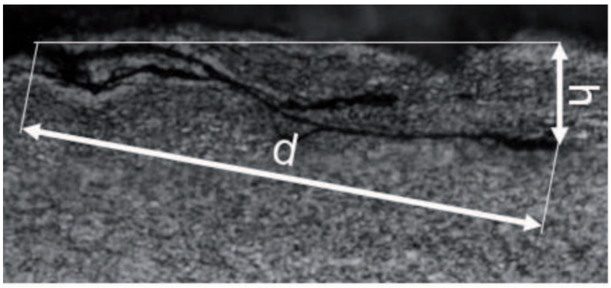

Fig. 3. Crack length (d) and depth (h) determination

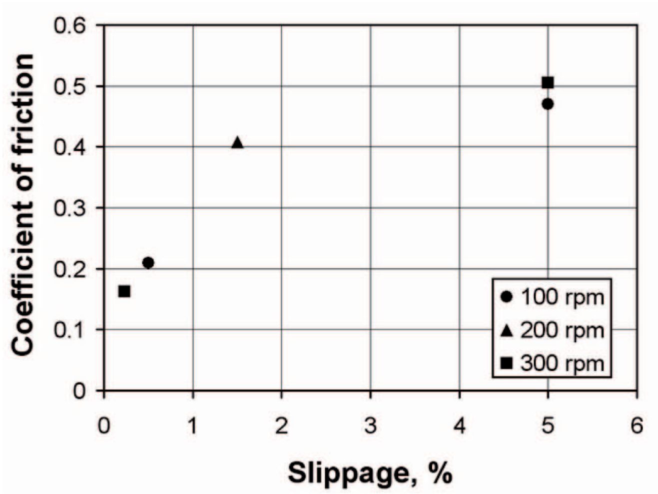

Fig. 5. Coefficient of friction vs. slippage and rotational speed

3. The obtained results and their discussion

The selection of the slippage and rotational speed values was based on data concerning conditions of wheels and rails operation [1, 11]. The results of investigations of the slippage and rotational speed influence on the specimens wear after the tribological tests are presented in Figure 4. In a similar fashion, the slippage and rotational speed influence on the friction coefficient is presented in Figure 5. Since the influence of the rotational speed on wheel tread and flange wear was studied there are results for maximum as well as minimum speeds, both for low and high slippage. These results are completed by another one for intermediate slippage as well as speed. It can be observed that the increased slippage facilitates the tyre steel wear. It should be emphasized that increasing of the rotational speed intensifies this influence. Similarly the increased slippage increases the friction coefficient, whereas, the increased rotational speed seems to have a smaller influence. The reason

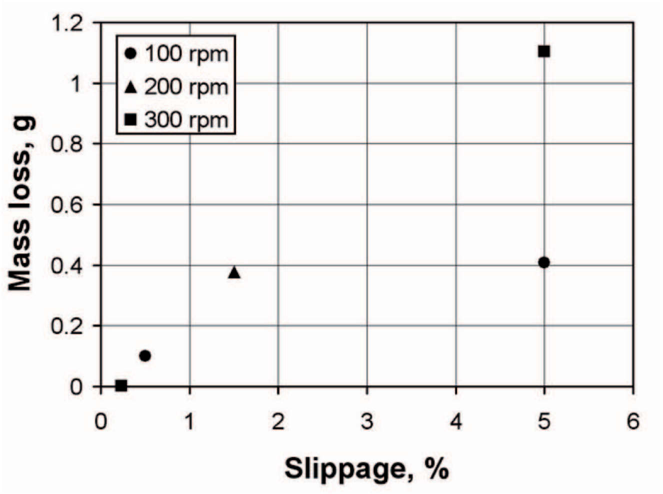

Fig. 4. Mass loss of specimens made of the B6 steel after 72,000 revolutions

of such situation should be the change in the wearing mechanism. To confirm the idea the microscopic observations of the surface and near-to-surface layer – after the tribological tests – were performed.

The surface appearance of the specimens after these tests is presented in Figure 6. When the slippage increases the surface development after the tribological test also increases. At the smallest slippage small cavities and corrugation occurs. A larger slippage promotes gap formations which can indicate the adhesive wear and plastic flow of the material. When the slippage equals 1.5% and 5% the adhesive wear is very intensive (Fig. 6c-e).

Metallographic observations of the parallel cross-sections were performed to determine the thickness of the plastically deformed – due to the tribological test – layer (Fig. 7). This thickness was measured in the micrographs as the depth under the specimen surface at which the microstructure seems to be undeformed. The final result is an average from 10 measurements. Observations were carried out in places where there were no cracks in order to characterise the plastically deformed layer without effects related to the crack propagation. This enables to analyse the deformation state in the surface layer. The averaged results of the plastically deformed layer thickness are presented in Figure 8. This thickness increases when the slippage increases from 0.23% to 1.5%. It corresponds to the mass loss and friction coefficient increase. Thus, the 1.5% slippage increases the plastic deformations zone and also the intensity of such deformations, which supports a higher mass loss of the tyre steel. As the result of the higher mass loss at the slippage of 5% the material is being removed so intensely that the plastic deformation zone is even decreasing, at a low rotational speed. There is also a possibility that the increased slippage cumulates the plastic deformation in the thinner near-to-surface layer, which can strengthen it more intensely than wear.

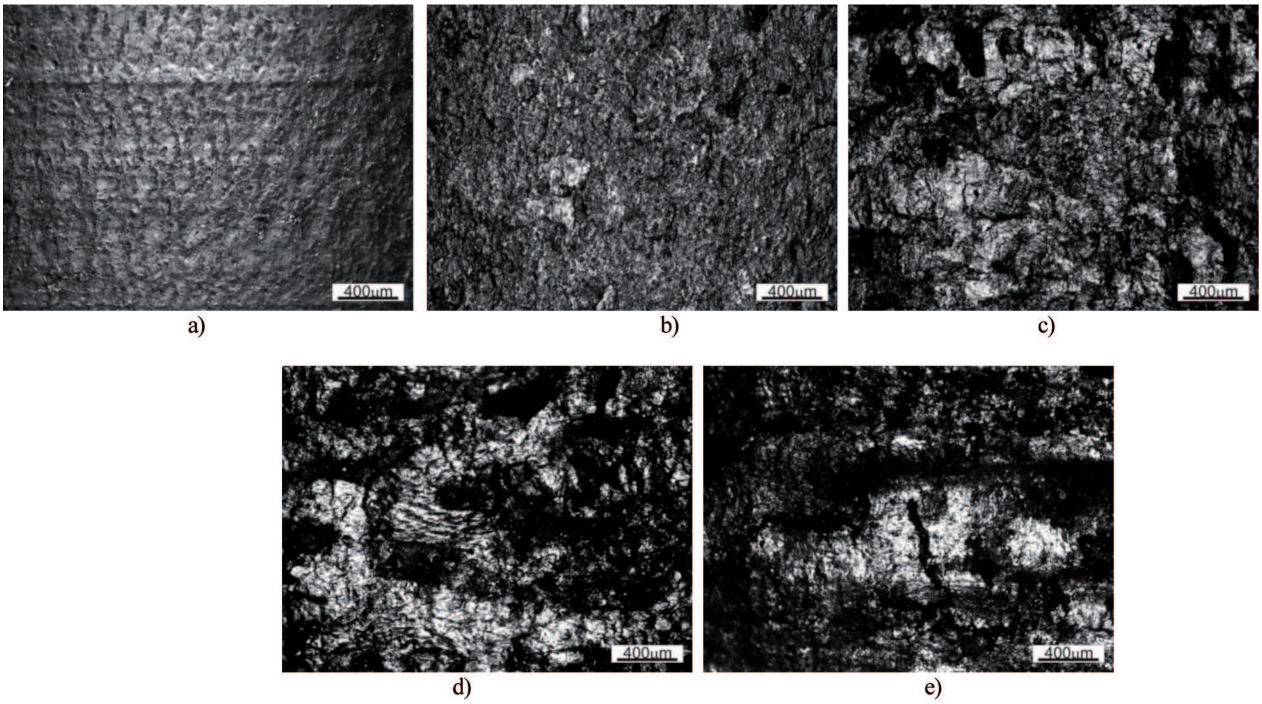

Fig. 6. Surface of tyre steel specimens after tribological tests: a) slippage 0.23%, rotational speed 300 rpm; b) slippage 0.5%, rotational speed 100 rpm; c) slippage 1.5%, rotational speed 200 rpm; d) slippage 5%, rotational speed 100 rpm; e) slippage 5%, rotational speed 300 rpm. The longer side of the photo is perpendicular to the ring axis and parallel to the material flow direction

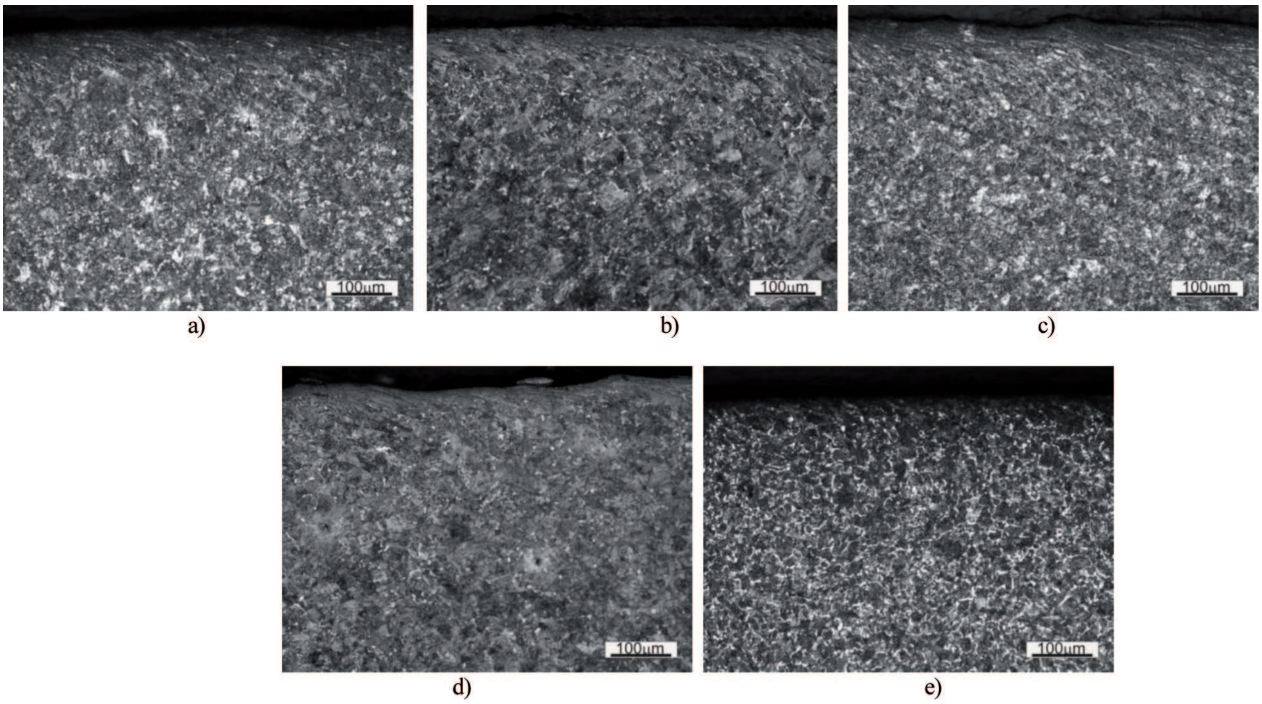

Fig. 7. Morphology of the near-to-surface layer of specimens made of the tested tyre steel (after a tribological test). The cross-sections were made parallel to the rolling direction: a) slippage 0.23%, rotational speed 300 rpm; b) slippage 0.5%, rotational speed 100 rpm; c) slippage 1.5%, rotational speed 200 rpm; d) slippage 5%, rotational speed 100 rpm; e) slippage 5%, rotational speed 300 rpm

Inversely, the smaller slippage increases the plastic deformation zone but the intensity of deformations is smaller which more influences the wear than strengthening. The results of the mass loss measurements at a low rotational speed seem to indicate just that (Fig. 4).

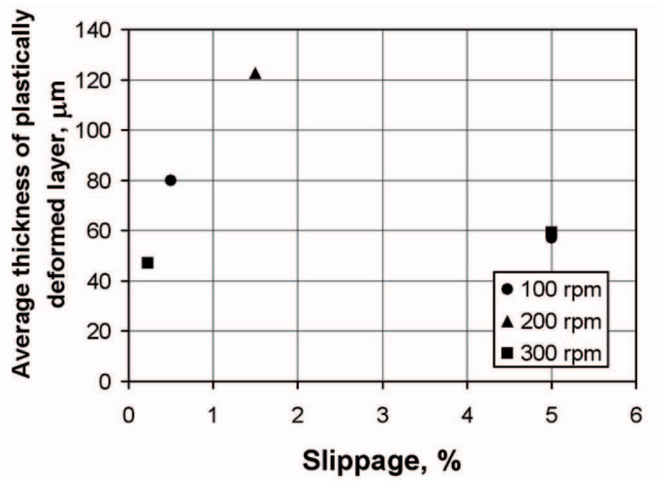

Fig. 8. Average thickness of plastically deformed layer after tribological tests

The analysis of the cracks morphology was performed on the polished sections perpendicular to the direction of the specimen motion (Fig. 9). Magnifications applied in the analysis of the surface layer were selected in a way enabling the clear and complete illustration of the cracks morphology. Such observation geometry allowed for a more precise analysis, especially of crack depths. The averaged length and depth of cracks are illustrated in Figures 10 and 11. Cracks were found for all tested slippages and velocities. Usually the crack length increase corresponds to the increased mass loss in dependence of the applied slippage and rotational speed values. It can be observed, that the slippage value has a decisive influence on the crack length, regardless of the applied rotational speed. However, the crack depth does not show such simple dependence, since in this case the rotational speed starts to have an influence. This should correspond to the previously described influence of the slippage and rotational speed on the wear intensity and the surface layer strengthening. The crack depth should be first of all related to the position of the largest tangent stresses point. This point will move farther inside the material when the surface layer will be wearing (its distance from the surface should not be changing a lot), while the slippage increase will shift this point towards the specimen surface [12]. However, the degree of the surface layer deformation, which – in these tests – was determined only indirectly, should be also taken into account in the considerations. It explains why the crack depth, in case of a small rotational speed, seems to be independent from the slippage (a small increase of a mass loss when the slippage increased). However, an increase of crack depths, in case of a high rotational speed, still requires explanations. It is probable that this increase is related to the intensity of the crack propagation into the material, dependent on the surface layer strengthening (which – in turn – depends on the rotational speed).

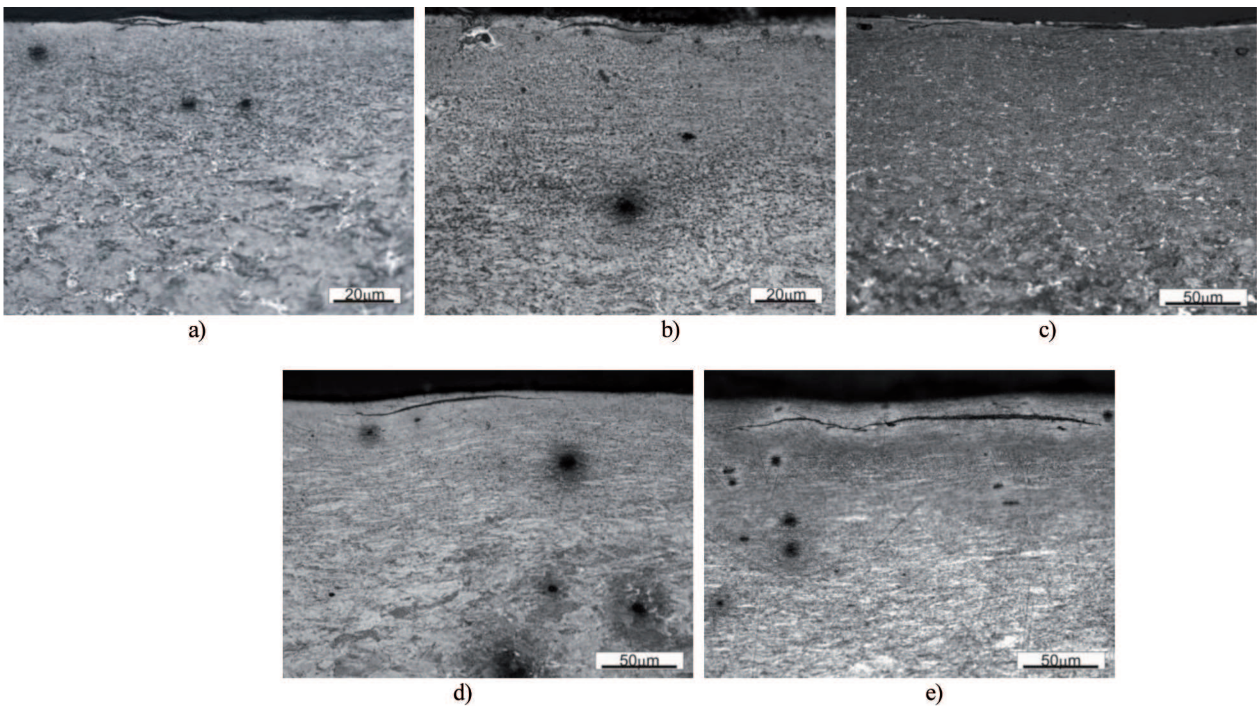

Fig. 9. Morphology of the near-to-surface layer of specimens made of the tested tyre steel (after a tribological test). The cross-sections were made perpendicular to the rolling direction: a) slippage 0.23%, rotational speed 300 rpm; b) slippage 0.5%, rotational speed 100 rpm; c) slippage 1.5%, rotational speed 200 rpm; d) slippage 5%, rotational speed 100 rpm; e) slippage 5%, rotational speed 300 rpm

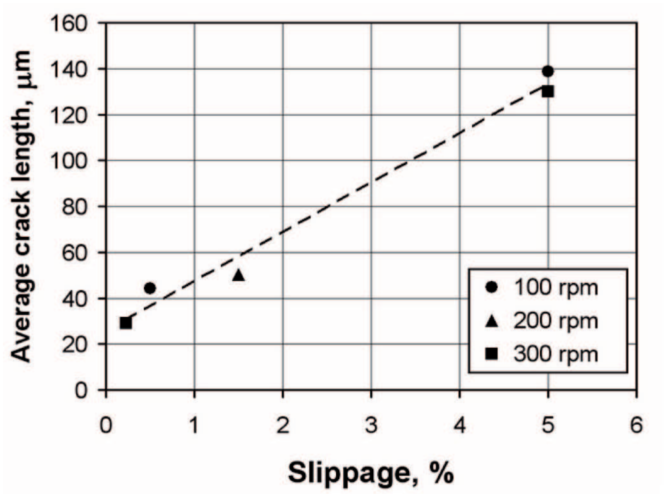

Fig. 10. Average crack length in near-to-surface layer after tribological tests

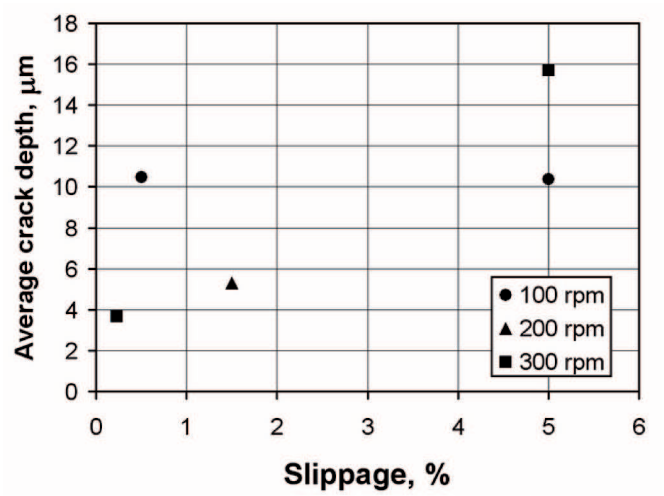

Fig. 11. Average crack depth in near-to-surface layer of the tested material

One of the main reasons of the observed adhesive wear intensification with the slippage increase seems to be the crack length elongation in the near-to- surface layer. A material is easily torn out in a contact when the crack is already formed under the surface.

4. Conclusions

Investigations presented in the hereby paper and the analysis of the obtained results allowed formulating the following conclusions:

- Three wear mechanisms: abrasive and adhesive occur in the investigated steel, at the assumed contact conditions.
- The slippage increase intensifies the wear since it facilitates the adhesive wear and plastic deformation of the near-to-surface layer.
- With the slippage increase the length of the cracks, occurring in the near-to-surface layer material, elongates.
- The slippage increase to 1.5% increases the plastically deformed zone. A further slippage increase to 5% decreases the plastically deformed zone, however probably the deformation intensity in the near-to-surface layer is higher, which more influences its strengthening than the mass loss.

Acknowledgements

The authors would like to thank Mr Jakub Rucki and Mr Wojciech Skuza for the help in performing metallographic examinations and their statistical elaboration.

REFERENCES

[1] T.M. Beagley, Severe wear of rolling/sliding contacts. Wear **36**, 317-335 (1976).

[2] F. Bucher, K. Knothe, A. Theiler, normal and tangential contact problem of surfaces with measured roughness. The 5th International Conference Contact Mechanics and Wear of Rail/Wheel Systems, Tokyo, Japan 25-28 July 2000, pp. 96-103.

[3] T. Jendel, Prediction of wheel profile wear – comparisons with field measurements. The 5th International Conference Contact Mechanics and Wear of Rail/Wheel Systems, Tokyo, Japan 25-28 July 2000, pp. 117-124.

[4] T. Makino, M. Yamamoto, T. Fujimura, Effect of material on spalling properties of railroad wheels. The 5th International Conference Contact Mechanics and Wear of Rail/Wheel Systems, Tokyo, Japan 25-28 July 2000, pp. 279-286.

[5] K.M. Lee, A.A. Polycorpou, Wear of conventional pearlitic and improved bainitic steels. Wear **259**, 391-399 (2005).

[6] F.C. Robles Hernández, N.G. Demas, D.D. Davis, A.A. Polycarpou, L. Maal, Mechanical properties and wear performance of premium rail steels. Wear **263**, 766-772 (2007).

[7] M. Witaszek, The influence of pressure and sliding velocity on the wear of a bainitic rail steel in the presence of lubricant. Tribologia, **220** 4, 203-209 (2008).

[8] M. Witaszek, J. Krawczyk, K. Witaszek, The influence of slippage on wear and microstructural changes of a bainitic rail steel. Tribologia **234** 6, 237-246 (2010).

[9] H. Yokoyama, S. Mitao, S. Yamamoto, M. Fujikake, Effect of the angle of attack on flaking behaviour in pearlitic and bainitic steel rails. The 5th International Conference Contact Mechanics and Wear of Rail/Wheel Systems, Tokyo, Japan 25-28 July 2000, pp. 154-160.

[10] J. P a c y n a, The microstructure and properties of the new bainitic rail steels. Journal of Achievements in Materials and Manufacturing Engineering **28**, 19-22 (2008).

[11] U. O l o f s s o n, T. T e l l i s k i v i, Wear, plastic deformations and friction of two rail steels – a full-scale test and a laboratory study. Wear **254**, 80-93 (2003).

[12] H. K r a u s e, G. P o l l, The influence of tangential tractions at the surface on the stresses in contacting bodies during rolling-sliding contact. Wear **88**, 221-232 (1983).

Received: 10 February 2011.