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TRIBOLOGICAL PROPERTIES OF RAIL STEEL IN STRAIGHT MODERATELY LOADED SECTIONS OF RAILWAY TRACKS

WŁAŚCIWOŚCI TRIBOLOGICZNE STALI SZYNOWYCH W PROSTYCH ODCINKACH ŚREDNIOOBCIĄŻONYCH TOROWISK

The paper describes the examination results of tribological properties of three types of steels used and suggested for rails manufacturing. The tests concentrated on loads, sliding and rolling speeds similar to those occurring in real conditions i.e. rolling track operation. Average loaded conditions were assumed and applied at straight railway track sections. Slight track declivity and high/low speeds of locomotive were considered. „Amsler" stand was used for laboratory tests. Three types of steels i.e. two pearlitic steels: WHT – without heat treatment, HT – with heat treatment (with the microstructure of fine pearlite) as well as one bainitic steel suggested for rail production have been tested. The measurements of wear, hardness, friction coefficient as well as structural changes at surface layers of the tested rollers have been performed during the test.

Keywords: bainitic rail steel, pearlitic rail steel, abrasive wear, fatigue wear

W pracy opisano wyniki badań właściwości tribologicznych trzech stali stosowanych i proponowanych na szyny kolejowe. W badaniach tych stali na szyny stosowano obciążenia, poślizgi i prędkości toczenia podobne, jakie występują w warunkach rzeczywistych czyli w warunkach eksploatacji torowisk.

Przyjęto warunki obciążenia występujące, jako średnio obciążone i zainstalowane na prostych odcinkach torów kolejowych przy uwzględnieniu niewielkiej pochyłości toru i przy prędkościach jazdy wagonu przy małej i dużej prędkości.

Badania laboratoryjne przeprowadzono na tribotesterze „ Amslera". Przebadano próbki trzech stali to jest dwie stale perlityczne – jedną z obróbką termiczną (o mikrostrukturze drobnego perlitu) a drugą bez obróbki oraz jedną stal o strukturze bainitycznej, proponowaną do wprowadzenia do produkcji szyn.

W czasie badań mierzono zużycie, twardość, współczynnik tarcia oraz zmiany strukturalne w warstwach przypowierzchniowych badanych rolek wymienionych stali.

1. Introduction

Increasing requirements in the area of train speed and railway track loading the manufacturers of rail steel to improve mechanical properties of pearlitic steels used so far. The improvement might be achieved through heat treatment, which however, means higher production costs. Heat treated rails made of pearlitic steel have much better mechanical and tribological properties than rails traditionally produced. Heat treated steels have higher abrasive wear resistance than non-treated steels, but lower resistance to contact-fatigue damages appear at their operation [1]. The application of bainitic steel instead of pearlitic one seems to be an alternative way of improving the some mechanical properties of rails [2-7]. It is known that contact-fatigue strength of rail steel affects its rail trackway durability. Damages appear and develop rapidly mainly when the load and the level of stress exert an impact in the most intense operation zone of the rail. Moreover, the type and properties of rail steel used is also essential. Rail durability in the track or its operation time depends to mainly on steel metallurgical purity, operational factors as well as administrative and management factors responsible for maintenance of railroads [8].

As the wheel load upon the rail grows, the risk of damage increases of the upper part of a head profile rather than upon its surface. Once the axial and tangential load is too heavy in the point of the greatest effort (Bielaiew point), permanent deformations and plastic strains occur together with disarrangement of cohesion forces [12]. It happens mainly when rail abrasive

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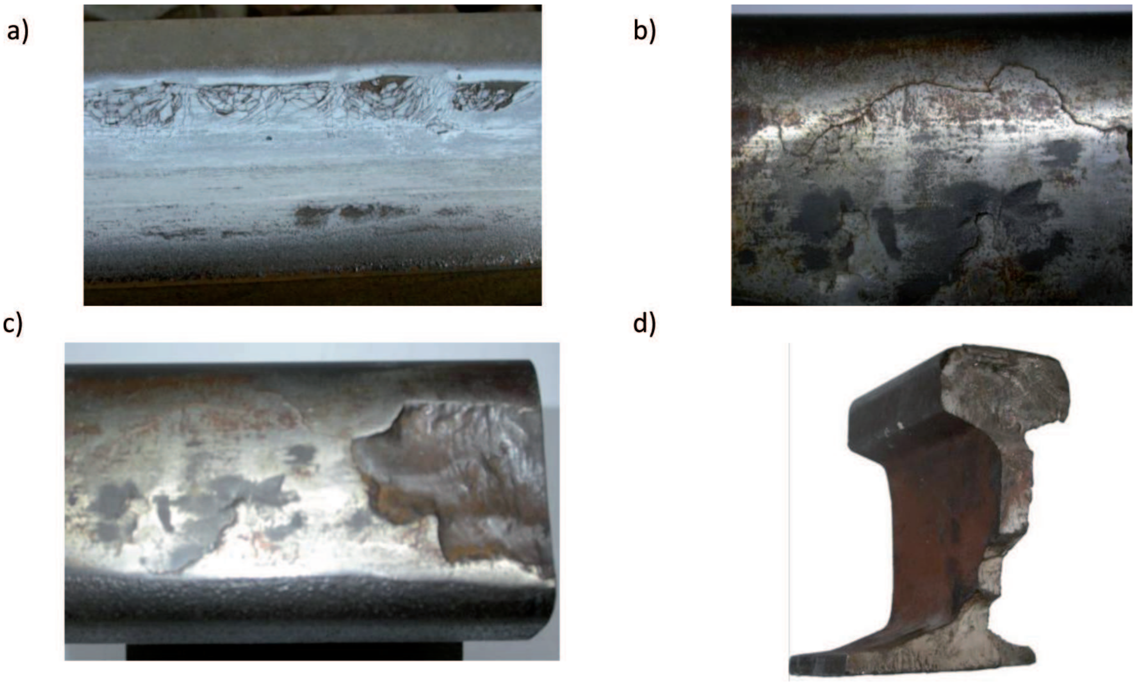

Fig. 1. Damages of heat treated pearlitic rails: a) areas of slight cracks concentration, b) large cracks, c) flaky wear of rolling surface, d) right – through crosswise crack

wear decreases as the result of pearlitic microstructure refinement in heat treated rail steels (Fig. 1).

Higher speeds of trains, especially goods trains (when the axes are large loads), significantly influence the frequency of rail renewal as the result of contact – fatigue damages. It was found that in case of standard track with relatively light axial load of 150 kN, the increase of speed from 40-50 km/h to 70-80 km/h leads to twofold increase in frequency of rail renewal [10].

Tribological and metallographic examinations should help define the diagnostic levels and categorize rail steels for appropriate operational conditions, hence prolong rails durability on the track [9]. On the basis of the observations of friction surface after interaction, it is possible determine changes and mechanisms in the wear process which occur as the result of cyclic interaction between axial and shear forces. Long-lasting and costly examinations of the tested real object are therefore not relevant. The aim of the paper is to compare tribological properties (wear, friction coefficient) of currently used rail steels in relation to the proposed new bainitic steel in identical laboratory conditions and to work out some guidelines for potential users specifying which steel types are the most appropriate for particular track section [11].

2. Tested material

Three types of steel for manufacturing of UIC 60 rails were tested i.e. pearlitic R260 (without heat treatment – denoted with A in Table 1); pearlitic (heat treated – denoted with B); bainitic (denoted with C). Not heat treated pearlitic steel is the standard rail steel. Heat treated pearlitic steel was widely used until contact-fatigue damages leading to crosswise fracture started to develop quite regularly. Investigated in this work bainitic steel is the first Polish bainitic rail steel used for currently tested railway rails. The steel acquires bainitic microstructure over the entire rail cross-section when the rail leaves the final rolling stand being then subjected to air cooling process. Microstructures of each rail steel are presented in Fig. 2. Their chemical composition and mechanical properties are presented in Tables 1 and 2.

TABLE 1

Chemical composition of tested steels (% wt.)

steel	C	Mn	Si	P	S	Cr	V	Mo	Fe
A	0.72	1.11	0.28	0.026	0.014	–	–	–	bal.
B	0.70	1.09	0.27	0.029	0.012	–	–	–	bal.
C	0.19	1.91	0.16	0.017	0.008	1.47	0.34	0.34	bal.

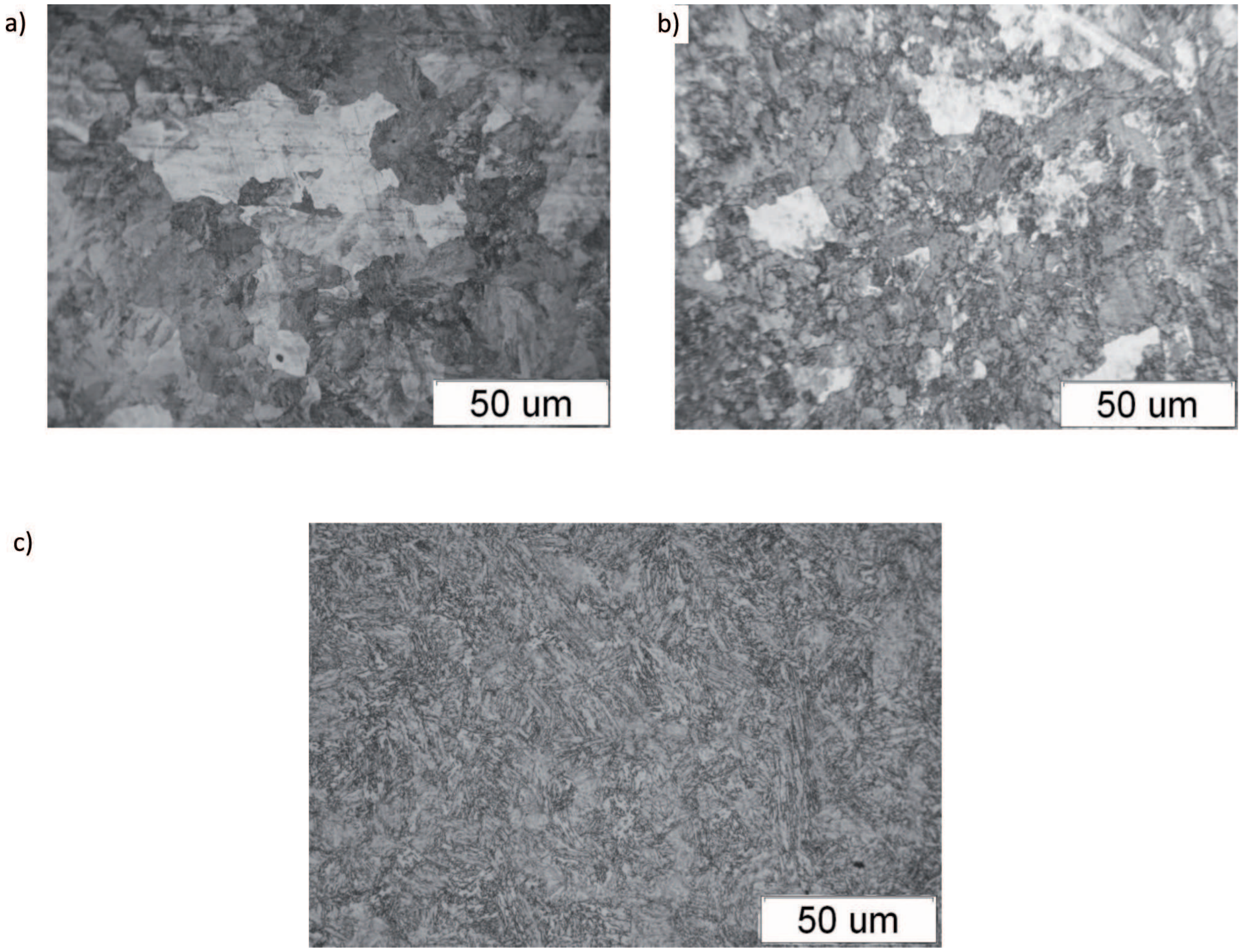

Fig. 2. Microstructures of tested rail steels: a) pearlitic – without heat treatment – steel A, b) pearlitic – heat treated – steel B, c) bainitic – steel C, etched with 3% nital

TABLE 2

Mechanical properties of tested rail steels

steel	R_m [MPa]	R_e [MPa]	A_5 [%]	KCU2 [J/cm^2]	HB
A	973	515	12	26	280
B	1230	750	14	31	330
C	1204	850	13	32	375

It is obvious that bainitic steel features mechanical properties similar to these characteristic for heat treated pearlitic steels. However, the yield stress and hardness are much higher.

3. Test conditions

Comparative studies of rail steel were conducted on an Amsler testing stand (Fig. 3) according to PN-H-04332:1982 standard recommendations. Tribological tests were performed in the rolling sliding contact under conditions of a dry rolling friction and were repeated three times. The result (mass decrement and friction coefficient) was the mean value. The ø38 mm rollers were made of the tested steels and interacted with a specimen-counter also of a roller shape. In operational conditions the railway rails interact with e.g. B6 steel (of pearlitic microstructure with ferrite precipitates upon grain boundaries) which is used for railway tyres. However, for the purpose of the laboratory tests 100Cr6 steel with microstructure composed of alloy carbides in martensite matrix and 62 HRC hardness was used as a specimen-counter. The decision to choose this type of steel was made since this particular type of steel is widely used as the specimen-counter material in tribological tests and therefore the obtained results can easily be compared with those available in literature.

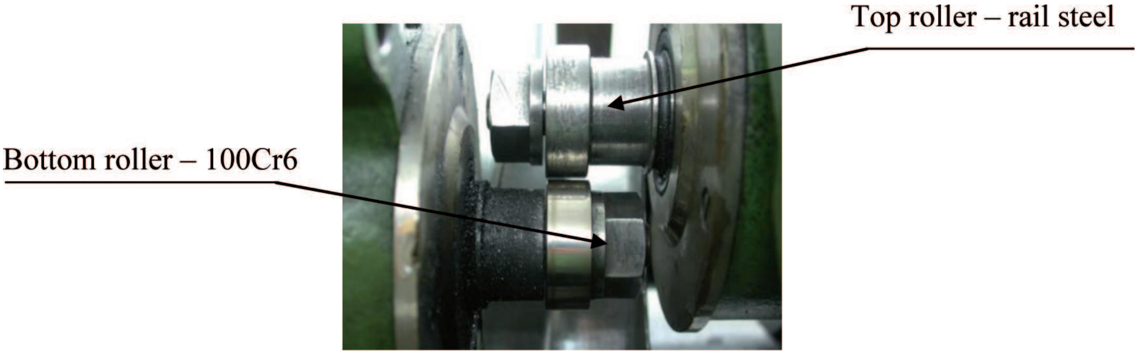

Fig. 3. Friction centre at laboratory stand (Amsler stand) for wear tests

Laboratory tests reflect the most crucial operational parameters which occur in a real object and which affect durability of a wheel-rail couple. In real conditions the minimum wheel load (Table. 3) occurs during the ride of an empty goods train, whereas the ride of a fully loaded freight train corresponds to the maximum wheel load. The minimum sliding value (γ=0.3%) occurs at the ride of a train along the straight section of a railway track, whereas the maximum value (γ=5%) along a curve with a declivity and /or acclivity. Restrictions found along the track section Jaworzno Szczakowa – Mysłowice in Poland, which serves as a frame of reference, determine consecutive velocities of the train. By selecting compressive stress in a contact zone with the rolling-sliding friction in operational conditions it is possible to reflect, with a rough approximation, the conditions of a real wheel-rail contact (Table 3).

TABLE 3
Load values and their corresponding contact pressures in laboratory tests and in a real object

Load in		Contact stress in wheel rail couple	Contact stress in lab roller-roller system
Real system	Lab stand		
63,5 kN/koło	1000 N	661 MPa	618 MPa

In order to reflect the conditions in a moderately loaded straight section of railway tracks with a slight track slope, the load of Q=1000 N and the skid γ=2.6% was applied at a laboratory stand. The tests for rotational speed (n) = 100 and 300 r.p.m. were performed to reflect the limit velocities (Vmin = 20km/h and Vmax = 60 km/h).

4. Verification of tribological tests assumptions

Verification of the assumed tribological tests conditions is based on comparing wear mechanisms of the same type of material in laboratory and real couples. The samples from chosen track sections were taken for tests which helped determine the wear mechanisms of the rail. Then similar tests were performed on the rail samples in laboratory conditions. Having verified of the tribological tests proved that both the wear mechanism and the wear products as in rails as in rollers were similar. Fig. 4 presents the roller and the rail wear respectively.

In both cases (real and laboratory) the wear mechanism is manifested by cracks which occur at a certain depth and their propagation being parallel to the rolling direction (Fig. 4). It is a progressing deformation of the rail surface layer down to the depth of 200 μm and the roller to 40 μm. This mechanism is manifested by propagation of subsurface gaps and their deformation in the same skid plane or in crossing planes. In consequence it leads to coming off the surface pieces in the form of flakes. Similarity in the wear mechanism proved the right selection of laboratory tests conditions. It can therefore be assumed that the conclusions resulting from the tests might also be true for a real object e.g. wheel-rail.

5. The mechanism of cracks formation in the surface layer of pearlitic rail

The paper deals with standard (WHT) rails which are the point of reference for the other two materials. Therefore a through description of their wear mechanism in the laboratory conditions should be given first. This mechanism involves the deformation process of pearlite grains which elongate and are arranged parallel to the rolling surface of specimens, thus creating a so-called banded structure. While the rollers work, pearlite grains dislocate and are in parallel to the interacting surface because of low resistance (c.a.300 MPa) as compared with the core material (ca. 1000 MPa). It can be said that fatigue cracks formation is accompanied by further cold-work hardening thus resulting in higher brittleness [6]. This leads to formation of critical cracks for the loads acting in a tribological system. Their critical length and the rate of cracks development are the function of material properties and also depend on operational factors i.e. load, skid and speed. Interaction between operational factors and tribological center in the rolling-sliding contact causes further wear process which finally results in wear products development (Fig. 5).

Non-metallic inclusions of MnS type and ferrite bands upon grain boundaries of former austenite occur which seems to be mostly disadvantageous because of the subsurface cracks developing in the tested samples. Manganese sulfides, in places they appear, considerably weaken the material which results in cracks initiation in its deformed surface layer. Hence, the wear is more intensive (Fig. 6).

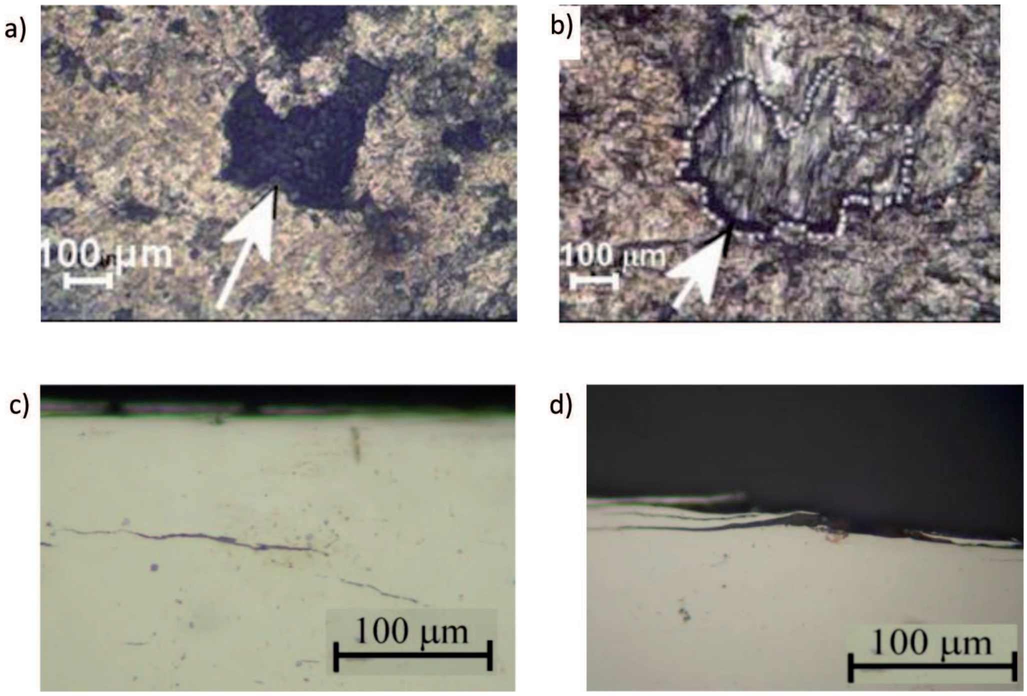

Fig. 4. Comparison of operational wear results of the pearlitic railway rail without heat treatment versus laboratory wear of the roller made of this rail: a) rolling surface of the aril, b) rolling surface of the roller after interaction, c) non-etched metallographic specimen of the rail surface layer, d) non-etched metallographic specimen of the roller surface layer

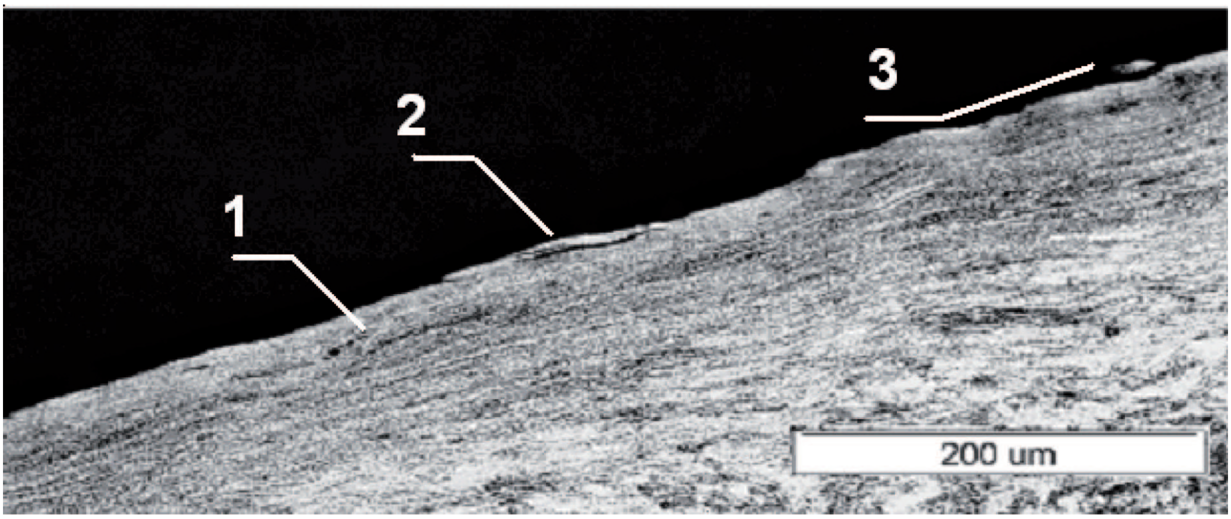

Fig. 5. Surface layer of a roller made of WHT pearlitic steel at consecutive stages of chipping off flaky wear products:
1 – initiation of subsurface cracks; 2 – crack propagation; 3 – wear products coming off the friction surface

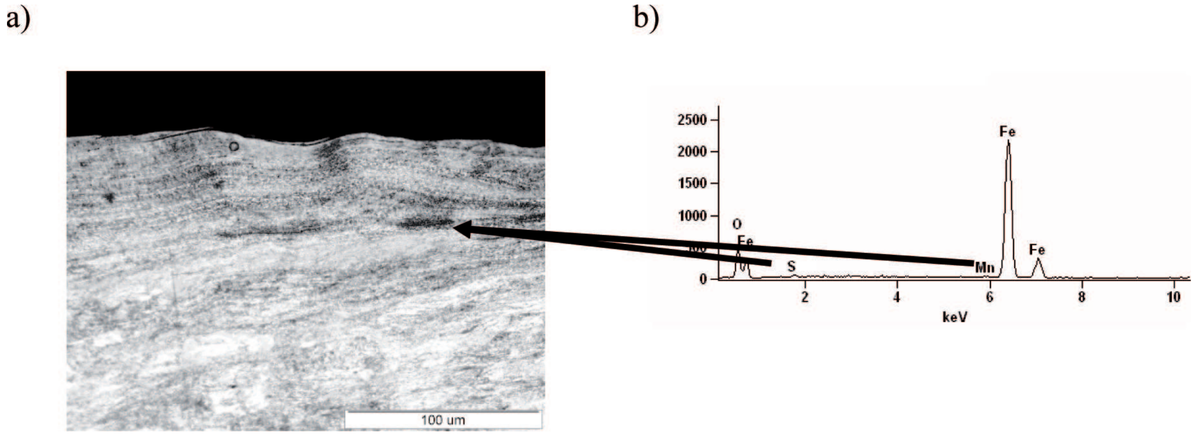

Fig. 6. Manganese sulfide as the point of easy initiation of cracks in the surface layer: a) elongated MnS precipitates in WHT rail steel, b)microanalysis spectrum of the place where MnS occurs

6. Results and discussion of tribological tests on rail steels

Tribological tests conducted in the conditions of load Q=1000N, skid γ=2.6% and rotational speed of 100 and 300 r.p.m. proved a significant impact of rail steel type upon the mass decrement as well as the fraction coefficient (Table 4). It can be observed that bainitic steel features the least wear and the fact does not depend upon the rotational speed. However, (WHT) pearlitic steel demonstrates the higher wear. The increase of rotational speed causes bigger mass decrement in case of each tested type of steel. There is no direct correlation between the friction coefficient and mass decrement, which proves that wear mechanisms in the tested steels are nor alike. After tribological tests were completed the sample surfaces of the tested rail steels were subjected to thorough examinations in order to justify these differences (Fig. 7). Substantial variations in the morphology of the sample surfaces with pearlitic and bainitic microstructures are noticed. In case of bainitic steel the surface (Fig. 7) and subsurface deformations (Fig. 8) are slight and elongated in the direction of friction. However, textured areas upon the sample surfaces with pearlitic structure are much bigger and elongated in the direction of friction at a certain angle. The increase in rotational speed seems to intensify the adhesive wear. It is probably the reason for mass decrement of each tested steel together with the increase of speed as presented in Table 4.

TABLE 4

Mass decrement and friction coefficient of rail steel for two selected operational conditions of tribological tests

Operational parameters			Mass decrement, mg			Friction coefficient, μ		
Q, N	γ, %	n, r.p.m.	A	B	C	A	B	C
1000	2.6	100	856	625	299	0.46	0.47	0.38
1000	2.6	300	1077	852	543	0.51	0.45	0.47

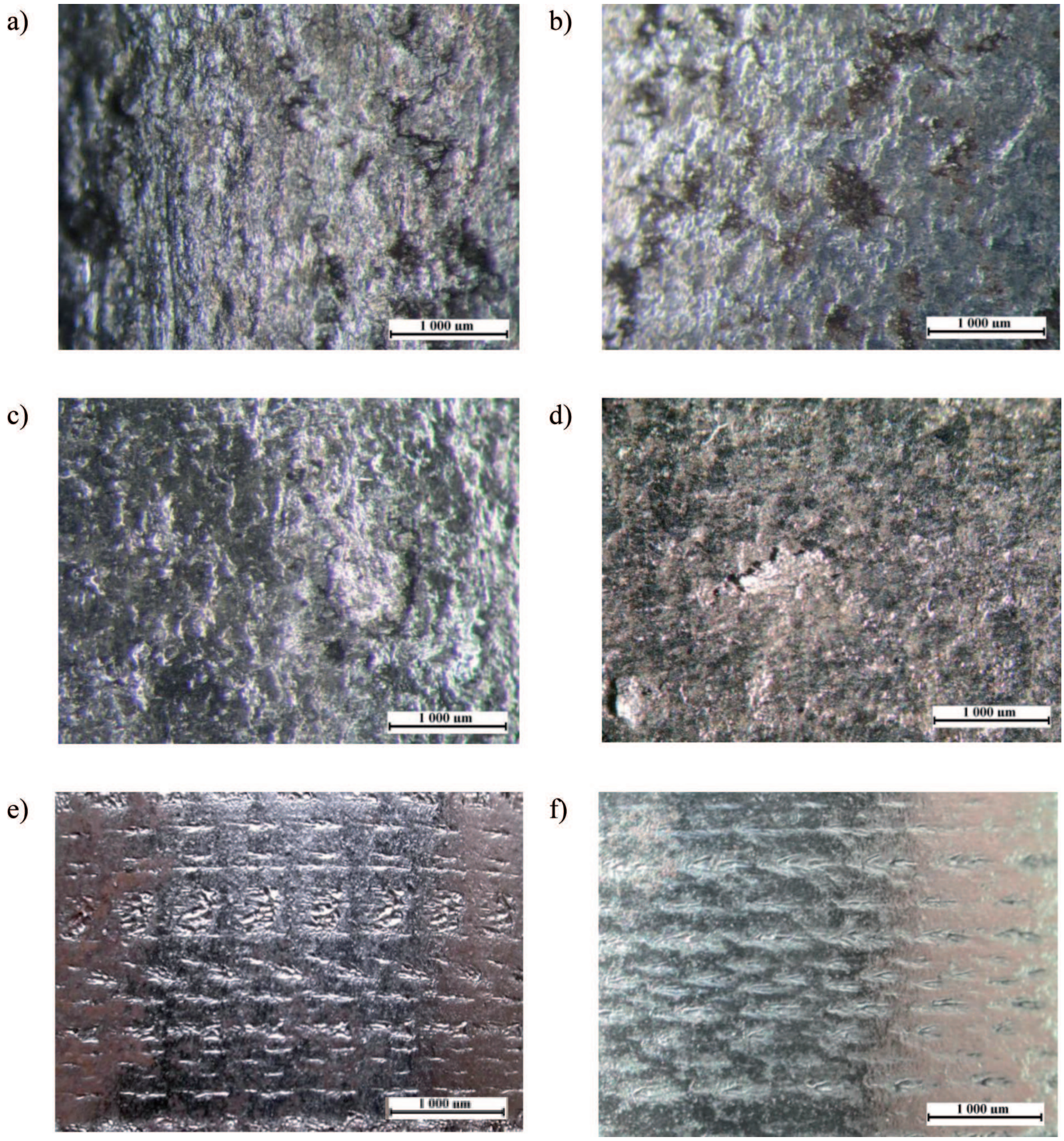

Fig. 7. Sample surfaces of tested rail steels after tribological test (Q=100 N, γ=2.6%):
a) pearlitic steel without heat treatment, n=100 r.p.m., b) pearlitic steel without heat treatment, n=300 r.p.m.,c) pearlitic steel heat treated, n=100 r.p.m., d) pearlitic steel heat treated, n=300 r.p.m., e) bainitic steel, n=100 r.p.m., f) bainitic steel, n=300 r.p.m.

Spalling develops upon the surface of heat treated pearlitic steel (B). The effect became more intensive with the increase of rotational speed. The lack of spalling upon the surface of bainitic steel (C) might suggest that it would display slighter inclination to develop damages presented in Fig.1 as compared with heat treated pearlitic steel (B). It should however be remembered that the bainitic steel retains high mechanical properties, some of which even much higher than in case of the heat treated pearlitic steel (Table 2), therefore the rollers mass decrement are lower.

More detailed description of the wear mechanism required further microstructure tests in the surface layer of the samples which had been subjected to tribological tests and the results are presented on Fig. 8. It can be clearly seen that plastic deformation of the core material takes place at a certain depth (material flow) in case of pearlitic steel (A and B) but not in case of bainitic steel. This results in the wear mechanism described in details in Chapter 5. In case of thermally treated pearlitic steel (B) it leads to spalling, which (the flaking process) becomes more intensive with the increased rotational speed.

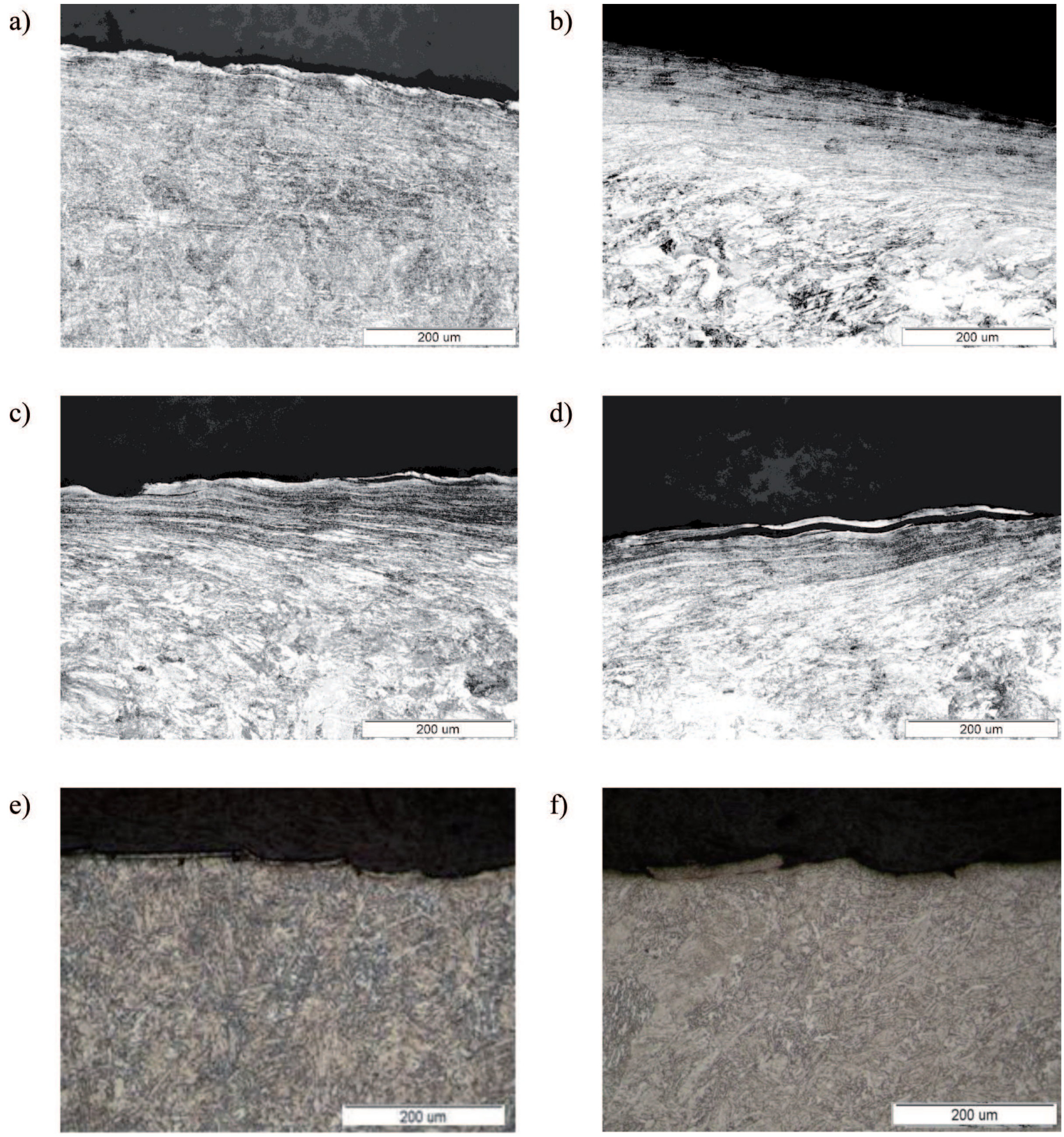

Fig. 8. Microstructure of the surface layer of the examined samples after tribological test: a) pearlitic steel without heat treatment, n=100 r.p.m., b) pearlitic steel without heat treatment, n=300 r.p.m., c) pearlitic steel heat treated, n=100 r.p.m., d) pearlitic steel heat treated, n=300 r.p.m., e) bainitic steel, n=100 r.p.m., f) bainitic steel, n=300 r.p.m., etched with 3% nital

Precisely defined operational conditions of rail cannot be the only factor which would restrict the suitability of a particular material for rails manufacturing. It is necessary, though, to take into account the effect of diversion of operational conditions from the assumed ones. Therefore the measurement results of mass decrement were referred to similar measurements in different load and skid conditions based on polisectional, D- optimal, partial investigation plan (Harthey's plan). The application of the partial plan enabled to reduce the number of tests. The plan involved the studies of three levels of controllable factors ie. minimum (designated with '1'), central (designated with '0') and maximum (designated with '1'). Then it was possible to draw diagrams showing the changing values of mass decrement when the change of skid or/and load occurs (Fig. 9). In case of both pearlitic steels (A and B) the increase of rotational speed intensifies the effect of higher skid upon lower mass decrement. On the other hand, in case of pearlitic steels (A and B), lower skid will result in significant mass decrement regardless of rotational speed applied. In case of low rotational speed (for A and B pearlitic steels) the skid applied in the above mentioned studies was not the most unfavorable factor for mass decrement (this specially applies to HT steel – B). However, in case of steels with pearlitic microstructures the higher load increased the volume of mass decrement. In case of bainitic steel (C) the above description differs significantly. Only the increased skid and load greatly intensifies the mass decrement. In case of low rotational speed the increased load at minimum skid leads to slight decrease of the mass decrement. It can be said that in case of bainitic steel the load only intensifies the effect of higher skid upon more excessive mass decrement. Thus this type of steel seems especially useful for rails at straight but heavily loaded tracks especially where low speeds are maintained. Moreover, the forecasted maximum mass decrement (in extremely unfavorable conditions) as in case of bainitic steel (C) is the lowest, while with WHT pearlitic steel (A) it reaches the highest value.

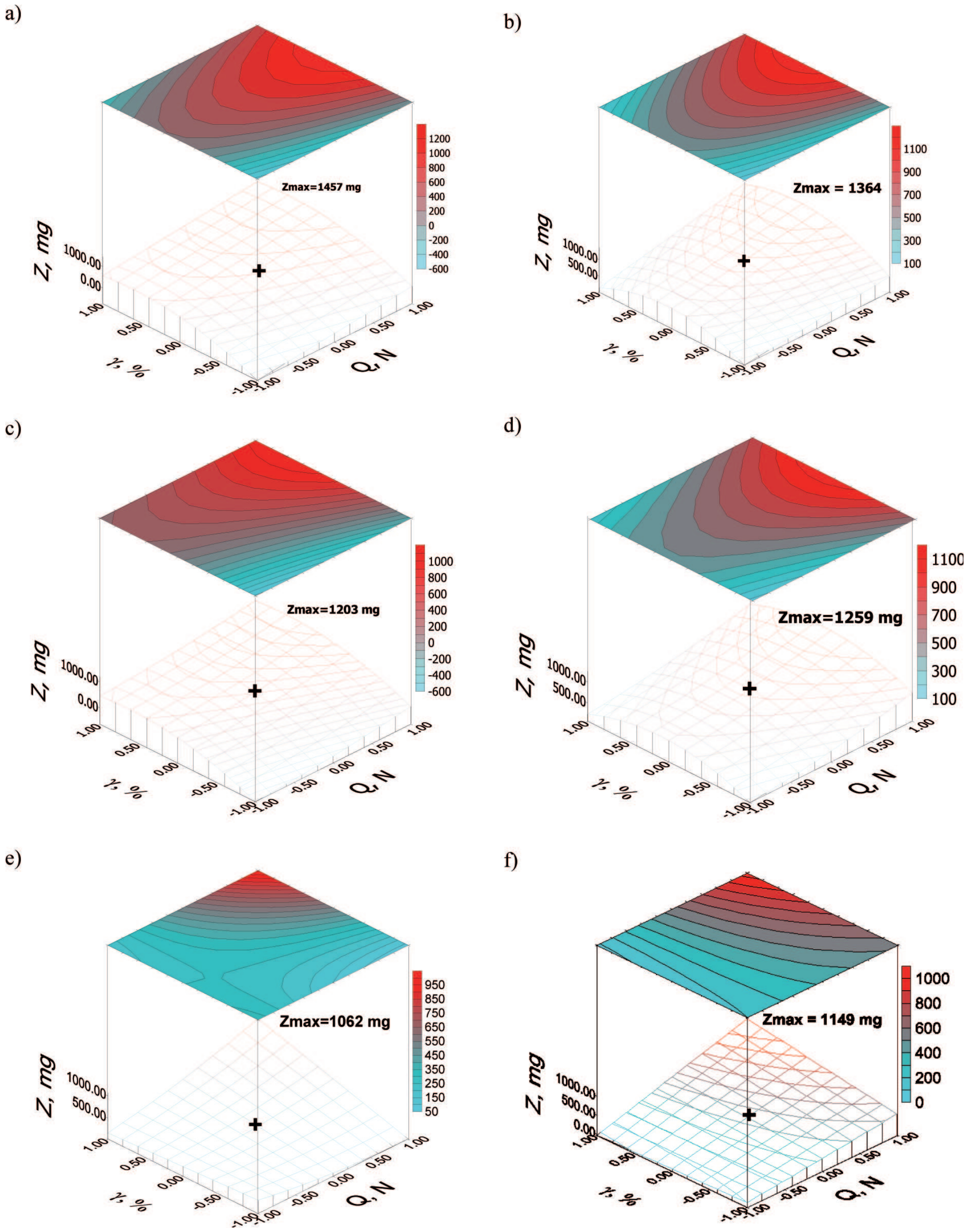

Fig. 9. Mass decrement of the examined steel samples after tribological test for the determined rotational speed in relation to mass decrement in the conditions of different load and skip: a) pearlitic steel without heat treatment (A) – n=100 r.p.m., b) pearlitic steel without heat treatment (A) – n=300 r.p.m., c) pearlitic steel heat treated (B) – n=100 r.p.m., d) pearlitic steel heat treated (B) – n=300 r.p.m., e) bainitic steel (C) – n=100 r.p.m., f) bainitic steel (C) – n=300 r.p.m.. Asterisk indicates mass decrement at load

7. Conclusions

The obtained results of the initial tribological tests conducted on Amsler stand allowed to select such laboratory conditions of a roller-roller couple which would partly reflect the real operational conditions of a wheel-rail couple. On the laboratory stand the lateral displacement in the rollers have not been reflected as real cases occur as a result of the so-called snaking traffic wheel on the rail. Contact stress in the laboratory and real object can be alike which means that wear mechanisms are comparable as well. This helps to extend the obtained laboratory test results to the real operational conditions of railway rails. The wear mechanism of rails made of WHT pearlitic steel and bainitic steel is based upon the examinations of the wear mechanism of WHT pearlitic rails in real conditions and is the sequence of the following phenomena:

1. Cracks initiation in the rolling subsurface caused by shear stresses
2. Cracks propagation towards the surface
3. Cold-work hardening of the surface layer increasing its brittleness
4. Development of critical cracks for loads operating in tribological system
5. Cracks concentration and separation of surface fragments in the form of flakes.

If the rail is made of thermally treated pearlitic steel, cracks propagate in the direction of a core, they cumulate and in consequence crosswise fracture of the rail occurs. It happens as the result of too higher surface hardness (1000 μHV to about 20 μm under the surface) and pose a real risk for the rail transport.

On the basis of the results of the performed tribological test at the laboratory stand and metallographic examinations of surface layers of rollers and rails, the following conclusions can be drawn and might serve as guidelines when appropriate choice of rail materials is made for selected track sections depending upon the operational conditions:

1. WHT pearlitic rail steel demonstrate the highest mass decrement at the maximum load, skid and speed but can resist contact-fatigue wear. Therefore they are recommended for straight track sections (slight skid).
2. HT pearlitic rail steel demonstrate the least mass decrement at the maximum skid and load and therefore are recommended for sections with curves and frequent braking.
3. Bainitic rail steel demonstrates the least wear at the maximum load and the minimum skid and therefore should be used for straight track sections with heavy load.

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