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QUANTITATIVE AND QUALITATIVE COMPARISON OF TRIBOLOGICAL PROPERTIES OF RAILWAY RAILS WITH AND WITHOUT HEAT TREATMENT

The paper provides a comprehensive presentation of the influence of operating parameters on the tribological properties of the wheel-rail couple. Apart from wear and a friction coefficient, the tribological properties also comprise stereological parameters of flaky wear products. The tribological tests were carried out according to an experimental plan, which took account of the complex influence of operational factors on the size and shape of flaky wear products. This enabled defining the type and intensity of wear, depending on the variable operational parameters. In order to explain the wear mechanism, quantitative, qualitative, and profilographometric metallographic examinations were made.

Keywords: fatigue wear, wear products, crack, metallographic examination, operational factors

1. Introduction

The changes occurring in the structure of materials during their work are extremely significant from the point of view of extending the life of the railway track material. During the operation of rails, fatigue wear occurs, whose effects are dangerous. In order to prevent fatigue wear, it is necessary to get to know the mechanism of its formation and, in particular, the changes it causes in materials [1].

The elements of a railway track structure which directly come into contact with the wheels of railway vehicles are its rails. Their condition determines to a large extent the safety of railway transport. The condition of rails is determined by, inter alia, the wear processes and the selection of materials from which the rails are made, appropriate to the operating conditions [2]. The application of inappropriate materials for rails increases their wear and, consequently, lowers safety on railroads, while increasing the costs incurred by railway operators in connection with repairs [3].

Presently, the largest problem is to keep balance between abrasive wear (vertical and side wear – occurring in the rails) and fatigue wear, the latter appearing in the form of contact-fatigue damage, leading to chipping of the surface, or even to cross cracks [4].

Due to a wide scope of the problem raised, the focus is on the question of durability and reliability of the currently used railway rails.

A quantitative analysis of products generated in the rolling-sliding contact and their computer processing are important tools in the examination of wear products. They allow us to identify the wear mechanism quickly and to evaluate the degree of the tribological system wear.

To sum up, the aim of this study is an attempt to explain the cause-effect relation between the influence of operational parameters and the wear of the wheel-rail contact zone, where fatigue processes are initiated. This way, getting to know and defining the nature of the phenomenon enables determining of the element's work reliability (appropriate selection of material, depending on the operational conditions). To achieve the aims planned, laboratory tests were made, in which the most significant operational parameters occurring in the real object and influencing the durability of the wheel-rail couple were reflected [5]. For this purpose, a dimensional analysis was applied, which reflects the real conditions presnt in this pivotal place, i.e. the contact point. A specific feature of laboratory tests is that it is possible to better control the direct influence of one selected factor than in the real operational conditions [6].

2. Material and research method

Pearlitic steels are the materials most often used for producing rails. Tests were made using specimens of heat treated rails (HT) and rails without heat treatment (WHT), made of pearlitic steel R260 with a chemical composition and mechanical properties compliant with the UIC 860 standard [8]. In the tests, products of wear generated in the friction couple in laboratory conditions, from both, heat treated rails (WDHT) and those without heat treatment (WDWHT), were used as well.

Thermal improvement aimed at diversifying the morphology of pearlite and, in particular, at changing its hardness and interlammellar distance as the most important microstructural parameter determining the mechanical properties of pearlitic steels (Tables 1, 2). The structure of the rail steel consisted of pearlitic steel, with the interlamellar

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TABLE 1

Mechanical properties of steel R260

Steel type	R_m [MPa]	R_e [MPa]	A_5 [%]	KCU_2 [J/cm^2]	HB
Heat treated	1230	750	13,6	31	335
Without heat treatment	973	515	12	26	286

TABLE 2

Melt analysis of the UIC 860 rail made of steel R260

Stal	C %	Mn %	Si %	P %	S %	Cr %	Ni %	Cu %	Al. %
R260	0,730	1,040	0,300	0,019	0,013	0,020	0,010	0,030	0,003

distance amounting for the heat treated steel to ca. 0.1 µm and for the specimen without heat treatment, up to ca. 0.4 µm [7, 8].

In order to verify the processes taking place in the friction zone, which lead to changes in the chemical composition of interacting materials, a chemical analysis was made for the steel with a pearlitic structure, R260, and for flaky wear products. The results of the examination are presented in Table 3.

TABLE 3

Melt analysis of steel with pearlitic structure R260 and of flaky wear products, performed by means of an emission spectrometer with an inductively coupled plasma (ICP)

Chemical elements	Percentage	
	R260	Wear debris
Mn	1,13	1,12
Si	0,31	0,3
P	0,021	0,022
Cr	0,01	0,06
Cu	0,02	0,02
Mo	<0,01	<0,01
Co	<0,01	<0,01
Al.	0,01	0,02
Ti	<0,01	<0,01
V	<0,01	<0,01
C	0,73	1,15
S	0,012	0,012
Fe	97,74	81,6*

* part of Fe→FeO

3. Testing conditions and procedure

Tribological tests were conducted on an Amsler testing machine. The device, with a tribological couple of a roller-roller type, serves for testing wear in case of rolling friction, sliding friction or a combination of both [9].

To determine the values of forces acting in laboratory conditions in relation to the real conditions, the theory of similitude was applied in the wheel-rail system and formula (1) was used, assuming geometrical similarity of the friction couples under consideration [10]:

$$\frac{P'}{R' \cdot L'} = \frac{P}{R \cdot L} \qquad \left(\frac{N}{m^2}\right)' = \left(\frac{N}{m^2}\right) \tag{1}$$

where:

P' and P – load in laboratory conditions and in a real object N,

R' and R – substitute radius in laboratory conditions and in a real object, in meters,

L' and L – substitute radius in laboratory conditions and in a real object in meters,

This way, the values of forces, and consequently, of stresses formed in the rolling-sliding contact in the friction couple were determined. By comparing the compressive stresses formed in the contact zone during rolling-sliding friction of two interacting components in both a real and laboratory object, it is possible to map with a rough approximation the conditions present in both friction zones (Table 4).

TABLE 4

Selected operational and geometrical parameters of rolling-sliding couple

Type of tests	Operational parameters				Geometrical parameters*	
	Load, N	Stress, MPa	Slide, %	Speed	Area [mm^2]	Contact width mm
Lab stand	Q_1= 500	pH= 437	γ_1 = 0.3	n = 100 min^{-1}	1.5	0,15
	Q_2= 1000	pH= 656	γ_2 = 2.6	n = 200 min^{-1}	2.0	0,2
	Q_3= 2000	pH= 875	γ_3 = 5,.0	n = 300 min^{-1}	3.0	0,3
In a real system	$P_1 = 5 \cdot 10^4$	pH= 434	γ_1= 0.3	v = 20 km/h	80.0	8.0
	$P_2 = 6 \cdot 10^4$	pH= 661	γ_2 = 2.6	v = 40 km/h	100.0	10.0
	$P_3 = 10 \cdot 10^4$	pH= 836	γ_3= 5.0	v = 60 km/h	150.0	18.0

For P and Q:1 – means a ride of an empty freight train, 2 – a ride of a passenger train, 3 – a ride of a fully loaded freight train.
For γ: 1 – means a straight track, 2 – curve, 3 – curve + slope/steepness,
* based on Hertz' formulas and [3]
The speeds provided refer to limits applicable for this section of Polish Railways.

The test conditions applied at the laboratory stand are similar to those in a real object [11]. Table 2 contains operational conditions typical of a selected section and their mapping at a laboratory stand.

Tribological tests were conducted based on a polyselective D-optimal experiment design by Hartley [12]. The experiment design required determining the boundary values of input quantities (operational factors), for which measurements of the output quantities' values are made. Based on the experiment design, which assumed three levels of the controlled factor, i.e. minimum, marked as "-1", central "0" and maximum "+1", measurements of the values of output quantities were carried out. The tests were repeated three times, the result being an averaged value. The outcome of correct execution of the experiment design are the output quantities, called "resultant factors". It has been found on the basis of an analysis of professional literature and the authors' own research [13-19] that the operational factors that have a significant influence on durability of the rail include the load, skid and speed [20-27].

4. Metallographic examination

The upper layer constitutes a precious source of information, for its changes depend on the physical and chemical processes which take place on the surface and right underneath, when compared to the core material. To determine the changes occurring in the surface layer, some samples were subjected to metallographic examination. Figure 1 shows the rolling surface of the rollers after interaction. On the surface of specimen (HT), numerous cracks and traces of chipping were found, whereas on specimen (WHT), laps and plastic deformations.

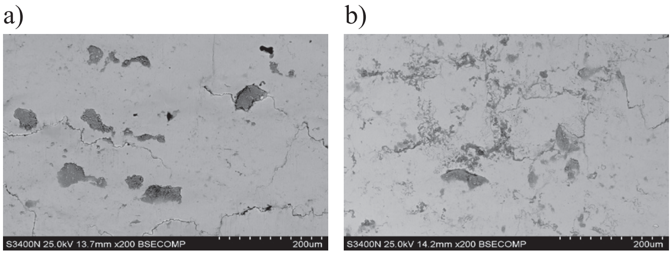

Fig. 1. Upper layer of: a) HT b) WHT

It was found in the metallographic examination of the upper layer after its service, that the cracks had been formed at a certain depth and propagated parallel to the rolling direction. As the subsuperficial fissure grows, the crack may reach its critical value, after which a piece of material may break off. The tribological examination conducted using an Amsler machine allowed obtaining results, on the basis of which stereological properties of flaky wear products were determined, i.e. the diameter (d), circumference (O) and surface area (A) (Table 5). The wear products were subjected to metallographic examination, enabling, first and foremost, the identification of the type of wear. Hence, the quantitative metallographic analysis allows quick identification of the wear process and evaluation of the degree of the tribological system's wear. During an interaction of components of a rolling-sliding couple, flaky wear products are formed, which come off the friction surface. Pictures of the wear products were taken with a camera coupled with a computer and equipped with a TV card and an OLYMPUS optical microscope. Computer analysis of geometrical features of the obtained lamellae was conducted using the Met-Ilo programme, intended for a quantitative image evaluation.

After analysing the wear products obtained in tribological tests of the heat-treated steel, they were found to be smaller and thinner (their thickness amounting to 23µm $^{+/-2\ \mu m}$ on average) than the wear products of the steel not subjected to heat treatment (for which the thickness amounted to 33µm $^{+/-2\ \mu m}$ on average). Moreover, the products after heat treatment are more brittle and have cracks inside, unlike the products not treated thermally, which have a form of homogeneous flakes. The wear products of the steel after heat treatment are deformed to a smaller degree than those without treatment and the fatigue cracks are present on phase boundaries (Fig. 2). A corroboration of higher brittleness of the flaky wear products obtained after interaction at a laboratory stand from samples after heat treatment consists of the fact that their number is larger than for the steel without heat treatment (Fig. 3).

TABLE 5

Results of laboratory tests of wear of the rail steel samples at various test parameters and results of the quantitative metallographic evaluation of flaky wear products

Operational factors	HT				WHT			
	Wear, mg	Geometrical parameters			Wear, mg	Geometrical parameters		
		d, mm	O, mm	A, mm^2		d, mm	O, mm	A, mm^2
500 N	42	138	394	17934	57	83	238	10822
1000 N	134	152	434	19738	73	91	259	11774
2000 N	468	184	526	23959	570	106	302	13765
0,3%	816	195	556	25310	1000	119	339	15427
2,6%	596	152	434	19738	707	91	259	11774
5,0%	1276	100	287	13065	1404	83	238	10852
100 min.$^{-1}$	81	124	353	16077	102	81	231	10534
200 min.$^{-1}$	764	152	434	19738	943	91	259	11774
300 min.$^{-1}$	625	192	548	24955	856	106	302	13744

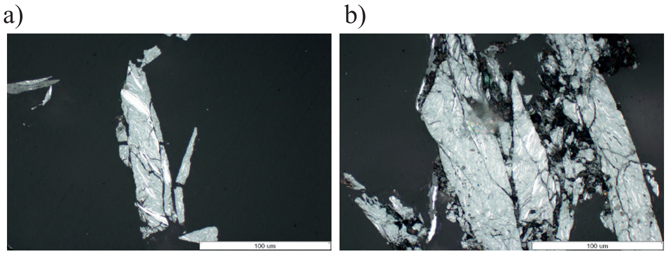

Fig. 2. Etched wear products of samples with visible white areas, indicating the presence of ferrite, a) after heat treatment, b) without heat treatment

The quantitative metallographic evaluation of flaky wear products enabled determining the tested particles' distribution and their density function (Fig. 3).

5. Profilographometric examination

In order to get to know the mechanisms of wear of tested rollers more precisely, profilographometric examinations of their surface were carried out (Fig. 4). A mechanical profilographometer was used to this end.

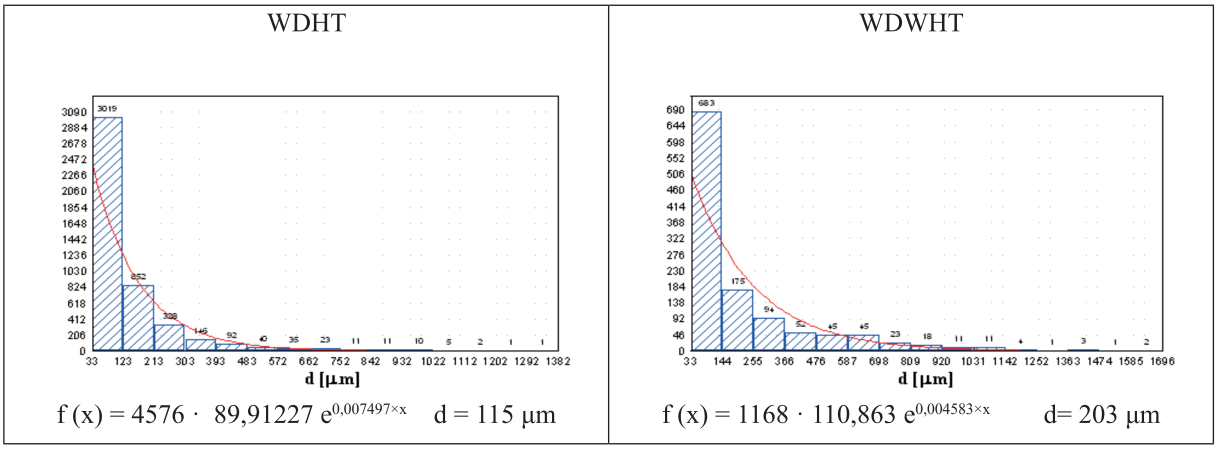

Fig. 3. An exemplary distribution of wear products' diameter (d), depending on the operational parameters, and their density function

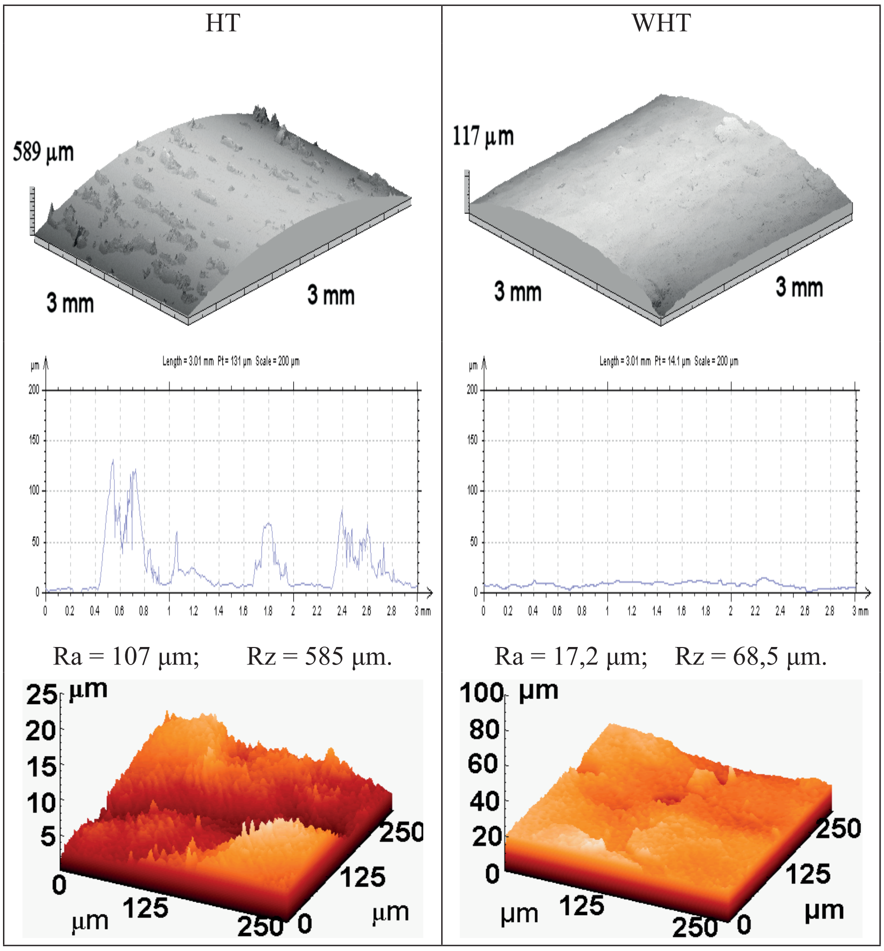

Fig. 4. Topography of interacting rollers' surfaces and their 2D profiles

The surface of a sample slice (WHT) had numerous laps after the interaction, unlike the surface of sample (HT), whose hardness amounted to ca. 350 HB. The numerous extrusions and intrusions may testify to the fatigue-like nature of wear (Fig. 4).

6. Analysis of research results

The paper presents an evaluation of tribological properties of a rolling-sliding contact, depending on the selected operational parameters. It allowed assessing the usefulness of the couple tested, depending on the selected test parameters.

Based on the test results, an observation was made that in general, the wear is lower for samples made of steel after heat treatment than in the case of steel without heat treatment. An exception to the rule appeared in tests at 0.3% skid, where it was found that the wear was lower for a sample of non-treated steel than for a roller made of steel after heat treatment. One of the reasons for this may be a reduction of the real contact surface, resulting from quicker coming off of the wear products, caused by greater friction force and formation of pits on the rolling surface (Fig. 1). The number of products for thermally treated steel is ca. 3000, whereas for the steel not subjected to heat treatment, ca. 1500 (Fig. 3), which shows higher brittleness.

It was found in the metallographic examination of the upper layer of a railway rail after its service, that the cracks had been formed at a certain depth and propagated parallel to the rolling direction (Figs. 1a, b). As the subsuperficial fissure grows, the crack may reach its critical value, after which a wear product may break off. As a result of the deformation, pearlite colonies and grains become elongated while arranging themselves parallel to the rolling surface of the specimens, thus creating under the surface a so-called banded structure, in which one can notice cracks on the boundaries of the deformed colonies and grains of pearlite. When analysing the surface layer of the roller after service in laboratory tests, it was found that the wear mechanism had an identical course to the one during operation in a track in real conditions [15, 28, 29].

Profilographometric tests have proved that the surface of samples (HT) has more pits and elevations than the surface of samples (WHT). The reduced depth of pits for heat treated steel is several times larger than for the steel not subjected to thermal treatment. This testifies to the fatigue-like nature of the wear process (Fig. 4).

7. Conclusions

The conducted analysis of the test results allows formulating the following conclusions:

1. As a result of load, skid and speed, the wear in the wheel-rail couple takes place through a multiple deformation of the surface layer in the contact zone, leading to the formation of flaky wear products, whose stereological features depend on the operational parameters and material properties.
2. The wear mechanism in both couples, as a progressing deformation of the upper layer (up to the depth of 200 μm), proceeds based on the principle of coalescence of subsurface microgaps and their dislocation in the same sliding surface or in intersecting surfaces, which in consequence leads to separation of surface fragments in the form of flakes. The similarity in the wear mechanism signifies appropriate selection of the conditions of laboratory tests, owing to which the conclusions resulting from the tests can be extended to the real object, i.e. the wheel-rail system.
3. Determination, based on a quantitative metallographic evaluation, of the stereological properties of flaky wear products enables forecasting the size and type of wear of a rolling-sliding couple. Geometrical dimensions of wear products increase with the increasing load and speed, while they decrease as skid increases.
4. The basic reason for fatigue wear of rails includes subsurface cracks which occur on the boundaries of deformed pearlite colonies and grain, which has been proven in metallographic laboratory tests.

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