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STUDY OF FRETTING WEAR IN THE WHEEL-AXLE CLAMPED JOINT MODEL OF RAIL VEHICLES

STUDIUM ZUŻYCIA FRETTINGOWEGO W MODELU POŁĄCZENIA WTŁACZANEGO KOŁO– OŚ ZESTAWU KOŁOWEGO POJAZDÓW SZYNOWYCH

Key words: fretting wear, clamped joint, surface layer, wheelset.

Abstract: Wheelsets are among the key components of a rail vehicle. Their task is to guide the vehicle on the track. Any damage or wear may lead to derailment and cause a crash that may cost lives of hundreds of people. Therefore, a significant problem in the designing of wheelsets is the aim of the reduction of the excessive wear of wheelsets during operation. Wear tests of wheelsets under real working conditions are hindered due to their dimensions, the cost of construction of an appropriate testing station, and technological difficulties associated with proper disassembly of the wheel from the axle, which would not lead to the impairment of the overall picture of wear. The article discusses the methodology of a study of the fretting wear of the wheel/axle interference fit model of a wheelset. Thanks to the application of the appropriate criteria of the similarity of the model to the real object, the wear pictures developed may be referred to the wheelset wheel-axle clamped joint.

Słowa kluczowe: zużycie frettingowe, połączenie wtłaczane, warstwa wierzchnia, zestaw kołowy.

Streszczenie Zestawy kołowe są jednym z najważniejszych elementów pojazdu szynowego. Ich zadaniem jest prowadzenie pojazdu w torze. Jakiekolwiek uszkodzenia lub zużycia mogą doprowadzić do wykolejenia pojazdu i katastrofy, w której życie mogą stracić setki ludzi. Dlatego ważnym problemem podczas projektowania zestawów kołowych jest próba ograniczenia nadmiernego zużycia zestawów kołowych wynikającego z ich eksploatacji. Badania zużyciowe zestawów kołowych w rzeczywistych warunkach pracy są utrudnione ze względu na ich wymiary, koszty budowy odpowiedniego stanowiska oraz ze względu na trudności technologiczne odpowiedniego demontażu koła z osi, który nie uszkodziłby powstałych obrazów zużycia. W artykule omówiono metodykę badania zużycia frettingowego modelu połączenia wtłaczanego koło–oś zestawu kołowego. Przy zachowaniu odpowiednich kryteriów podobieństwa modelu do obiektu rzeczywistego powstałe obrazy zużycia można odnieść do połączenia koło–oś zestawu kołowego.

INTRODUCTION

Every day, around the world, thousands of people and hundreds of thousands of tons of commodities are transported by rail vehicles. Therefore, vehicle owners are faced with a difficult challenge of ensuring the high reliability of their fleet. Over time, the operation of technical facilities, including rail vehicles, leads to a reduction of their durability, which increases the risk of damage and wear. In the case of rail vehicles, one of the systems that are most vulnerable to damage are wheelsets. This is due to their working conditions.

During operation, a wheelset is exposed to external loads, which exert a negative impact on its durability. These include the following:

- Thermal load emerging during breaking;
- Vertical loads due to vehicle weight;
- Lateral forces acting at the point of contact between the wheel flange and the rail head, which emerge during sway; and,
- Dynamic forces at the point of the contact of the wheel and the rail.

Vertical loads from vehicle weights subject the axle to bending moment, which, in combination with other

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loads, may lead to damaging the wheelset through the development of fretting wear as a result of oscillatory tangential displacement.

In order to effectively eliminate the development of fretting wear in interference fits, it is necessary to get familiar with the mechanism of its emergence and to know the factors that initiate its development, and then to propose measures to eliminate fretting wear. However, a literature review indicates that few scientists study fretting in interference fits. This is due to difficulties associated with the construction of the proper test stands. Large wheelset dimensions result in the high costs of the construction of such a test stand and lead to logistic problems. Another problem is posed by disassembly of the fit. Traditional disassembly of the wheel from the axle could interfere with the picture of the wear developed, preventing its effective analysis.

Therefore, it seems reasonable to conduct a wear study using a wheelset wheel/axle interference fit model. As it has been proven by authors of a publication **[L. 3]**, upon maintaining of the proper criteria of similarity between the model and the real object, it is possible to transfer the results of model tests to the real object.

FRETTING WEAR

Fretting is one of the processes of damage to the surface layer of machine components. It is classified as tribological wear. Fretting wear is a result of oscillatory tangential displacement of the surface of bodies with low amplitude due to variable force – normal or tangential – to the surface of the point of contact. Relative displacement amplitude ranges from 0.02 to 150 µm.

Fretting is a phenomenon characterized either by a complex wear mechanism in which the following are occurring simultaneously or after one another: adhesive wear, surface fatigue, exfoliation, oxidizing, abrasion by rough peaks, and loose wear **[L. 12]**. The picture of fretting may include signs of corrosion on the surface of components, increased surface roughness, microcracks in the surface layer, pinholes, and the consequences, for instance, in the case of interference connections, may include a reduction of assembly pressure. All of these changes on the component surface, in the case of variable loads, may lead to fatigue failure. This is unacceptable for wheelsets.

Typical conditions for the development of fretting wear make us deal with this phenomenon in many component fits and connections in transport vehicles, we are not always aware of every phenomena that is taking place. Damages in the surface layer of components due to fretting are often attributed to other types of damage. This is because fretting wear, which is initiated during the first stage of operation, often leads to other damages, such as fatigue failure, which makes their identification very difficult.

The fretting phenomenon is encountered, for instance, in aviation and rail transport. An example here is provided by publication **[L. 8]**, in which the author examined the fretting wear of parts of a threaded bolt in the bolt-nut assembly of the An-124 aircraft wing flap servos. Fretting wear in rail transport vehicles has been dealt with, among others, by authors of studies **[L. 1, 11]**, who examined fretting in wheelsets.

Moreover, fretting wear occurs in bolt connections **[L. 10]**, in artificial joint connections, and orthopaedic components that connect broken bones **[L. 2, 4, 7]**. The development of wear in this case is influenced by physiologic saline, containing about 1 % NaCl, and the frequency of movement of the limbs, being around 1 Hz.

Results of wear studies conducted by many scientists have shown that any changes in interference value, the roughness of assembly surfaces, or connection modes result in changes in wear intensity, its location, and range. The author of **[L. 5]** proves in his work that the friction coefficient between mating surfaces is not a constant, but a variable. This is due to the phenomenon of adhesion.

The intensity of adhesion is influenced by a number of factors, which are related to material properties, the condition of the surface layer, and the impact of normal and tangential loads.

THE CLAMPED JOINT FRETTING WEAR STUDY METHODOLOGY

The applied methodology of the fretting wear study has been divided into four stages. Stage I consists of the development of an interference fit model and the preparation of samples.

Stage II includes the selection of the test stand, the specifications of the study parameters and for conducting wear tests.

Stage III consists of the preparation of samples for laboratory tests.

Stage IV includes laboratory tests of fretting wear and the analysis of the results obtained.

Each of these stages has been discussed in detail in the following subchapters.

Stage I – development of the study model

The study model consists of a sleeve and a shaft. Both components have been made of steel C45, and its chemical composition is presented in **Table 1**.

Table 1. Chemical composition of steel C45
Tabela 1. Skład chemiczny stali C45

Chemical composition [%]								
C	Mn	Si	P	S	Cr	Ni	Mo	Cu
0.42–0.5	0.5–0.8	0.1–0.4	<0.04	<0.04	<0.3	<0.3	<0.1	<0.3

The proposed material is used for the production of components subjected to moderate loads, such as axles, shafts, bolts, levers, wheel hubs, etc., including wheelset axles.

The length and diameter of the shaft was made dependent on the requirements of the test environment. The sample dimensions at the point of connection **(Fig. 1)** have been selected to provide maximum similarity to the dimensions to a rail vehicle wheelset wheel/axle interference fit.

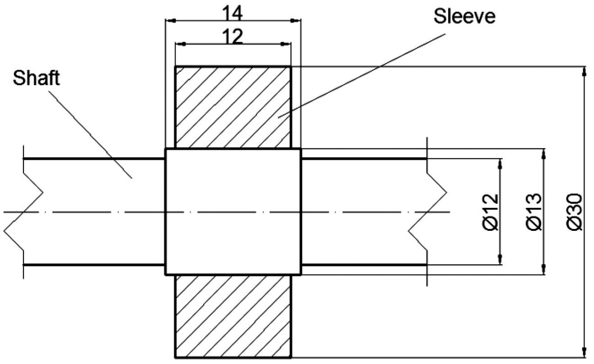


Fig. 1. Sample dimensions at the connection point
Rys. 1. Wymiary próbki w miejscu łączenia

The shafts were made by rolling, and left for examination in such condition, while the internal surface of the sleeve was additionally polished. Shafts prepared in this way are characterized by roughness profile parameters presented in **Fig. 2.**

Apart from measuring the roughness parameters, the hardness of the shaft and sleeve surface was also measured.

Assembly of the components was conducted by forcing in the sleeve onto the shaft. The core aspect of this connection is the appropriate interference value, which is to warrant the durability of the fit in the case of the influence of external force. Using formulas, the best interference value in the examined case would be 0.02 mm. During forcing, it is also necessary to take into account the emerging stress, which may exceed the plastic limit, leading to permanent plastic deformation of the surfaces being connected.

Assembly was conducted using a hydraulic press, while recording the interference value in the interference length function. The maximum force value necessary to install the sleeve on the shaft was 8.6 kN. The connection model is shown in **Fig. 3**.

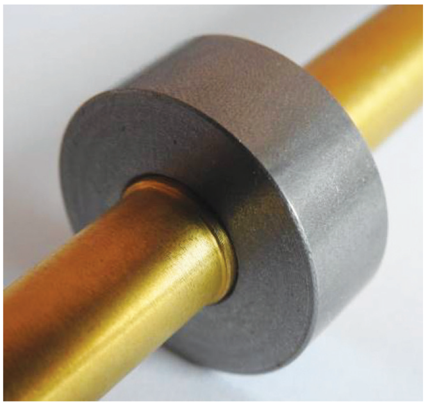
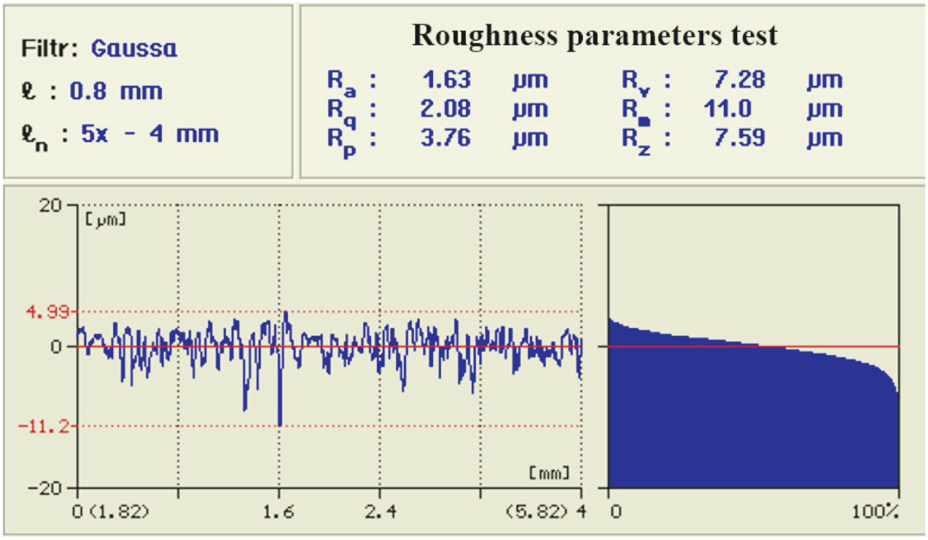


Fig. 3. View of the sample in the point of connection
Rys. 3. Widok próbki w miejscu połączenia

In the case of interference fits, the force necessary to install the sleeve on the shaft increases gradually along the length of the fit, achieving its maximum value at the final stage of the process. This has been confirmed by force measurements conducted during the assembly.



Filtr: Gaussa
ℓ : 0.8 mm
ℓ_n : 5x - 4 mm

Roughness parameters test

R_a : 1.63 µm
R_q : 2.08 µm
R_p : 3.76 µm
R_y : 7.28 µm
$R_{\blacksquare}$: 11.0 µm
R_z : 7.59 µm

Fig. 2. The results of the shaft roughness parameters test and the load capacity profile curve
Rys. 2. Wynik badania parametrów chropowatości wałka oraz krzywa profilu nośności

Stage II – wear tests

The sample prepared according to the description in Section 3.1 is then subjected to wear tests.

The study plan included cyclical loading of samples with bending moment under the conditions of rotating bending.

In this study, it was assumed that the tests would simulate the work of the rail vehicle wheelset under natural operating conditions. Therefore, it was necessary to develop a test stand that would make it possible to achieve the operating parameters similar to the real working conditions of the wheelset.

An exemplary machine, which meets the requirements, is the MUJ type fatigue-testing machine, which makes it possible to generate periodically variable loads with simultaneous bending of the rotating sample.

Fig. 4 presents the sample load diagram for the fatigue tester used in the study and the respective bending moment distribution.

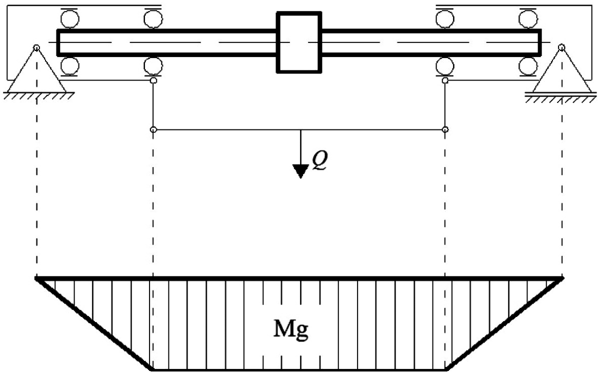


Fig. 4. Fatigue tester sample load diagram and the corresponding bending moment distribution. Mg – bending moment

Rys. 4. Schemat obciążenia próbki na maszynie zmęczeniowej i odpowiadający mu rozkład momentu gnącego. Mg – moment zginający

The sample load, presented on the drawing, results in the symmetrical distribution of bending moment. Under real conditions, the wheelset load causes a similar bending moment distribution, when the rail vehicle is moving along a straight track, and the sway phenomenon is eliminated. Additional forces acting on the wheelset due to vehicle movement in a turn will have less influence on development of fretting wear, and thus they can be disregarded in the adopted methodology of the study.

The sample should be loaded with a force sufficient to make sure that the resulting bending moment distribution on the wheel seat leads to the bending of the shaft, which will lead to oscillatory tangential displacement of the mating surfaces, which is a prerequisite for occurrence of fretting wear.

The test parameters were selected to ensure the highest possible intensity of fretting wear. Therefore, the parameters adopted are as follows:

- External sample load – $Q = 500$ *N,*
- Sample rotation – $n = 1360$ *rpm,*
- The number of cycles – $N = 10^7$.

All of the samples examined were subjected to the same number of load cycles, which should allow for a detailed examination of fretting wear development in an interference fit.

The number of cycles was based on a literature review. The author of **[L. 6]**, during initial tests, showed that fretting wear intensity reaches stability at the cycle number of (3-8)x10^6.

Stage III – sample preparation for laboratory tests

Conducting laboratory tests of fretting wear in an interference fit requires an appropriate preparation of samples for testing. Disassembly of the fit should be conducted in the manner that prevents disfiguring of the resulting wear picture.

Traditional disassembly of the sleeve from the shaft could damage the surface layer of the shaft and the effects of wear; therefore, an appropriate disassembly technique was developed. After cutting off the unnecessary shaft ends, the fit was cut perpendicular to the shaft axis, obtaining three samples for laboratory tests **(Fig. 5)**.

The sample in **Figure 5a** shows the internal part of the sleeve. This sample can be subjected to macroscopic examination of fretting wear. Within the framework of additional tests, a measurement of roughness parameters was conducted, as well as of surface hardness. As in the examined case, the surface of the sleeve hole was polished, and the roughness parameter R_a was 0.3 µm. The established surface hardness is 163 HB.

Figure 5b presents the shaft surface sample. Initially, roughness parameters were measured, as well as surface hardness. The measurement results indicated that parameter R_a was 1.63 µm, and surface hardness was 340 HB. The next step was a macroscopic examination to check the presence and extent of fretting wear. The fretting wear locations were subjected to microscopic examination, using a scanning microscope. During these tests, the real picture of damages on the shaft seat surface was analysed. This served as a basis for the identification of wear types, which are identified as fretting wear.

The sample in **Figure 5c** depicts an interference fit of the sleeve on the shaft. During tests of this sample, metallographic examination was conducted on etched and non-etched polished sections using an optical microscope. The purpose of the examination of non-etched polished sections was to determine the real outline of the point of the contact of the shaft and the sleeve and their damages and deformations. Examinations of etched polished sections allowed for the determination of the size and shape of grains and revealed deformations and damages of the

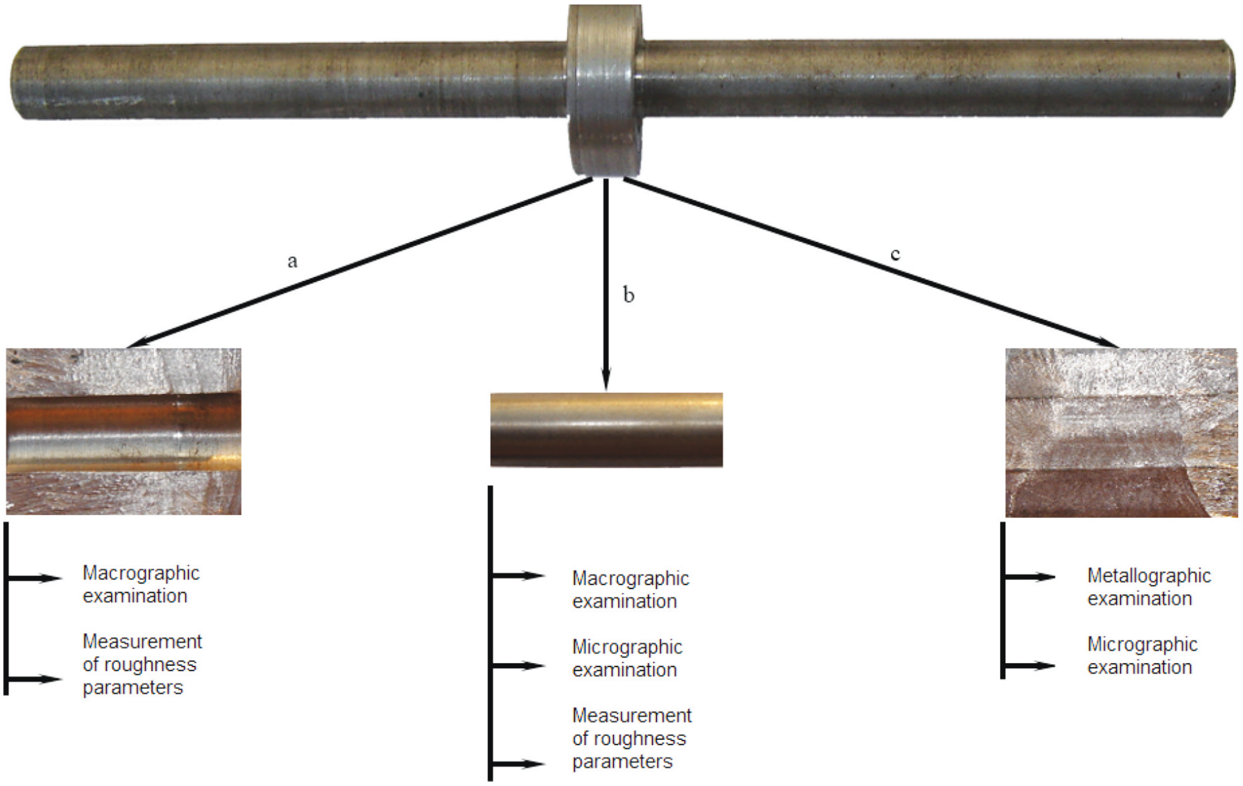


Fig. 5. Views of samples for laboratory tests
Rys. 5. Widok próbek przeznaczonych do badań laboratoryjnych

surface layer of the connected components. Microscopic examination using a scanning microscope allowed for the observation of wear products and the analysis of their chemical composition.

Stage IV – analysis of laboratory test results

Macroscopic examination of the surface layer of the inner part of the sleeve showed fretting wear in form of a thin strip on both sides of the sleeve nave **(Fig. 6).**

In the wheelset wheel/axle interference fit in rail vehicles, the replacement part is the wheel, while the axle, after appropriate preparation, is subject to further use. We will treat the fit analysed in a similar manner, thus fretting wear of the sleeve will not be subjected to further tests.

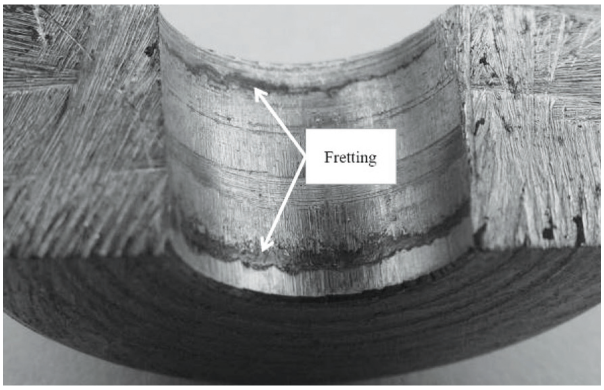


Fig. 6. Fretting wear in the inner part of the sleeve
Rys. 6. Zużycie frettingowe zaobserwowane w wewnętrznej części tulejki

Figure 7 presents exemplary images of fretting wear on the seat surface of two different samples observed during macroscopic examination.

In the first case, wear is present on both sides of the shaft in form of a ring along its entire perimeter. It is characterized by brown colour, which is typical for atmospheric corrosion of iron. The emergence of iron oxides proves that a gap has emerged between the shaft and sleeve surfaces due to bending of the sample, which, on the other hand, presents the contact of the damaged surface with oxygen. In the second case, fretting use was also observed on both sides of the shaft. The wear surface is smaller, and it is distributed randomly along the shaft perimeter.

The emergence of fretting wear at the edges of the shaft may be explained by the limited occurrence of wear products in this location and the large area of the actual contact between the mating surfaces. The adhesive links in combination with oscillatory tangential displacements create perfect conditions for the initiation of fretting wear.

After preparation of macroscopic documentation, the fretting wear sites were examined with a scanning microscope. The results of this examination are presented in **Fig. 8.**

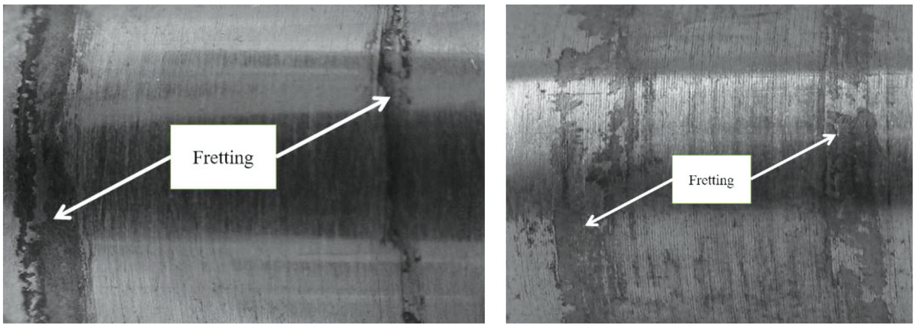


Fig. 7. Exemplary images of fretting wear on the shaft surface
Rys. 7. Przykładowe obrazy zużycia frettingowego na powierzchni wałka

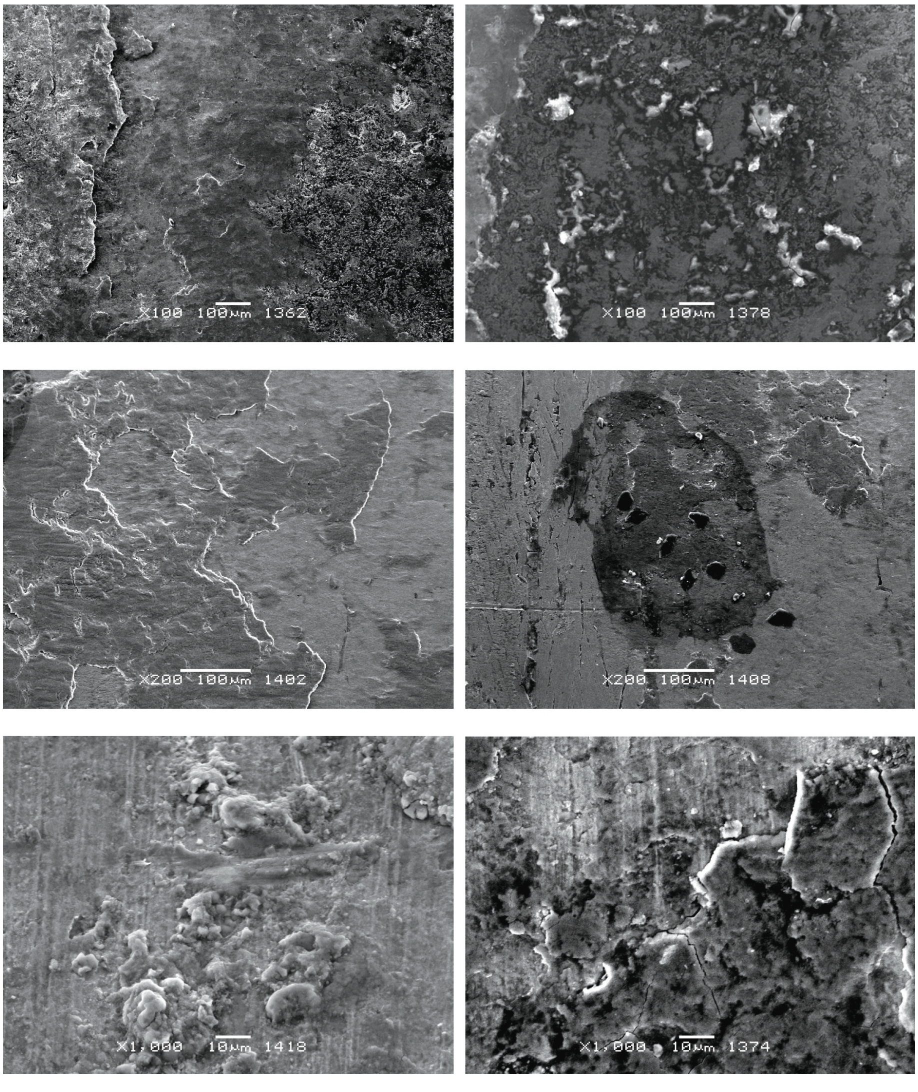


Fig. 8. Scanning microscope images of fretting wear on the shaft surface
Rys. 8. Obrazy z mikroskopu skaningowego zużycia frettingowego na powierzchni wałka

The presented scanning images of the shaft seats show that fretting wear occurs mainly in form of material accretions, which at a later stage are subject to plastic deformation and then oxidization. Moreover, local abrasion is observed, as well as micro-pits and particles of wear products, which may be a result of micro machining. The development and intensity of these damages are associated with the initial roughness of the mating surfaces and the interference value.

Metallographic examination of the shaft and sleeve contact surface in the area of fretting wear examined using an optical microscope is presented in **Fig. 9.**

The presented images of non-etched samples **(Fig. 9a)** show that, along the fit length, surface contact is uneven. Direct contact of surfaces produces alternating microcracks, particularly in the middle part of the connection that is filled with wear products. Examination of etched samples **(Fig. 9b)** also indicates roughness at the point of connection, in some locations filled with wear products. During metallographic examination, microcracks in the surface layer of the mating surface were also observed.

Exemplary results of the examination of the shaft and sleeve contact surface in the fretting wear area using a scanning microscope are presented in **Fig. 10**. Along the length of the connection, a gap has been observed, which is filled with wear products. In some places, wear products have been forced into the surface layer of the mating components, resulting in their damage.

Chemical analysis of wear products, which are presented in **Figure 11**, has confirmed contact of the damaged area with oxygen.

The gap between components causes oxygen to get between the surfaces during operation to oxidize wear products, which results in the emergence of iron oxides. In the example presented in **Figure 11**, wear products contain 38.5% iron and 21.4% oxygen.

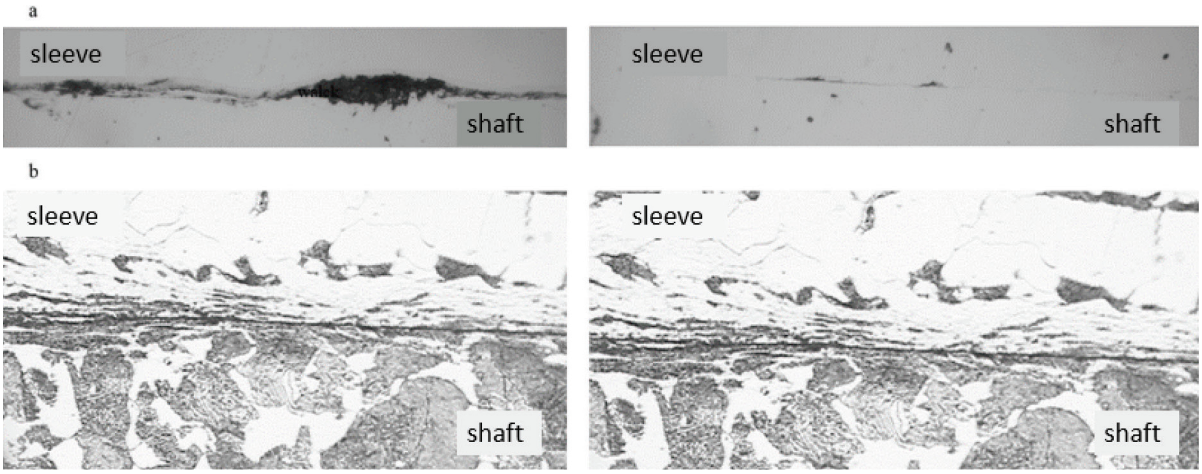


Fig. 9. View of the surface of contact of sleeve and shaft in the place of fretting wear: a) non-etched samples, mag. 400x; b) nital etched samples, mag. 500x

Rys. 9. Widok powierzchni styku wałka z tulejką w miejscu zużycia frettingowego: a) próbki nietrawione, pow. 400x; b) próbki trawione nitalem, pow. 500x

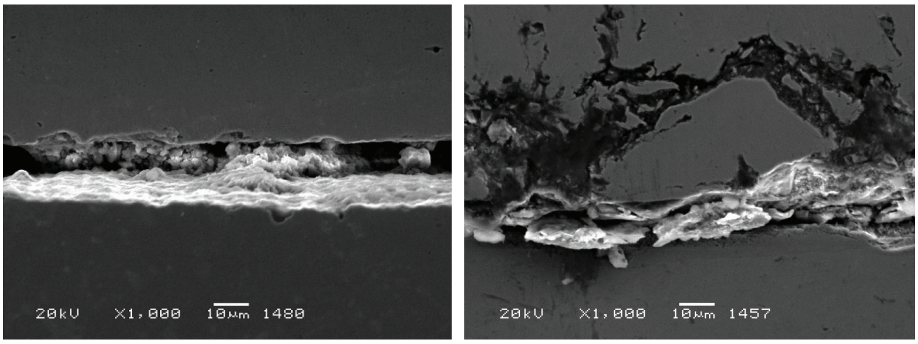
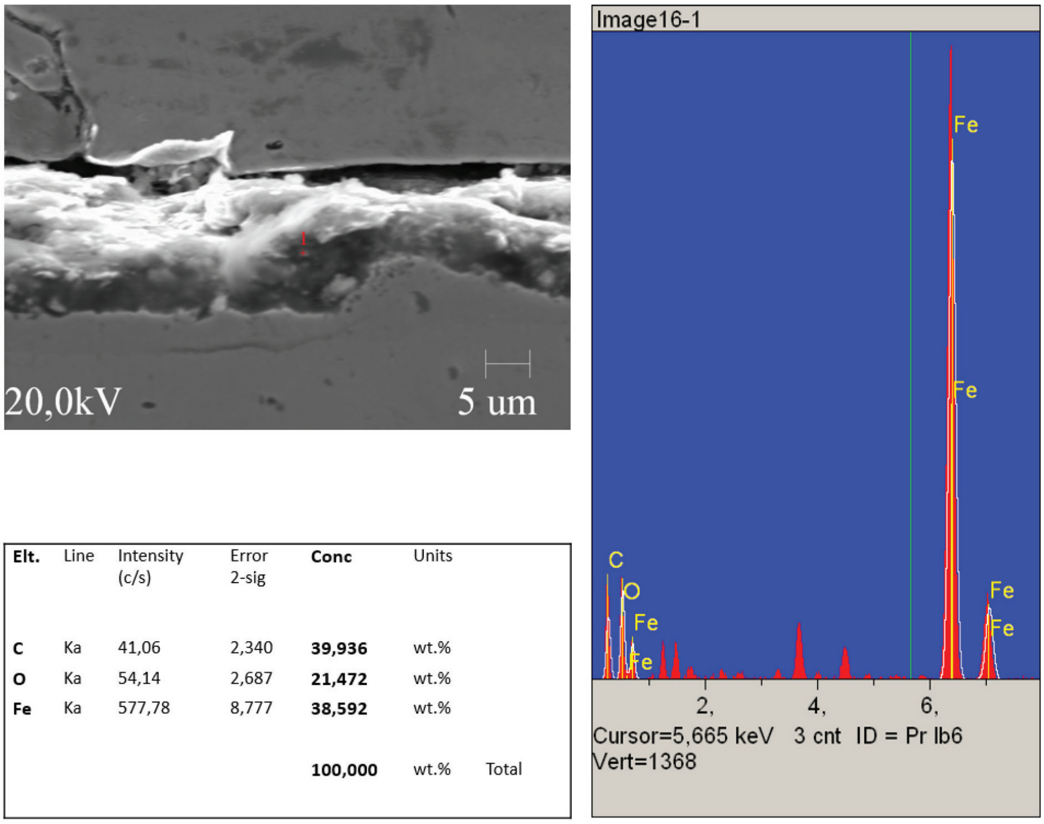


Fig. 10. Exemplary images of the contact surface, recorded with a scanning microscope

Rys. 10. Przykładowe obrazy powierzchni styku obserwowane na mikroskopie skaningowym



Elt.	Line	Intensity (c/s)	Error 2-sig	**Conc**	Units	
C	Ka	41,06	2,340	**39,936**	wt.%	
O	Ka	54,14	2,687	**21,472**	wt.%	
Fe	Ka	577,78	8,777	**38,592**	wt.%	
				100,000	wt.%	Total

Fig. 11. Analysis of chemical composition of wear products
Rys. 11. Analiza składu chemicznego produktów zużycia

CONCLUSIONS

The interference fit fretting wear analysis methodology discussed in the article is characterized by the ease of tests, thanks to the simple structure and small size of the sample, as well as by short testing time. All of these factors allow for a substantial reduction of the tests conducted.

The fretting wear study methodology presented allows for the determination of wear that is attributable to fretting phenomenon in interference fits subjected to rotational bending. This methodology allows for the determination of the real condition of the mating surfaces after a certain period of operation. It also allows for the determination of the impact of various factors on the initiation and intensity of wear. It contributes to the understanding of the fretting wear mechanism.

Maintaining of similarity of dimensions and – to the extent possible – the similarity of working conditions allows for transferring the results obtained to the real object, which, in this case, may be a wheelset.

The test results obtained show the extent of the fretting phenomenon on the shaft surface without additional machining that would enhance its durability. If we imagine that such research was conducted using wheelsets of rail vehicles, it would be necessary to undertake tasks to limit or even eliminate the development of fretting wear, due to the importance of wheelsets in vehicles. In order to limit fretting wear, it is proposed to apply additional thermal treatment, such as surface hardening or a thermal and chemical treatment such as nitration. Another solution that may contribute to the elimination of fretting may be the application of PVD coatings.

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