Journal of Machine Construction and Maintenance
PROBLEMY EKSPLOATACJI
QUARTERLY 2/2017 (105)
ISSN 1232-9312

p. 109–116

Sławomir KOWALSKI
State Higher Vocational School in Nowy Sącz
ul. Staszica 1
33-300 Nowy Sącz, Poland
E-mail: skowalski@pwsz-ns.edu.pl

SELECTED PROBLEMS IN THE EXPLOITATION OF WHEEL SETS IN RAIL VEHICLES

Key words: fretting wear, clamped joint, surface layer, exploitation, installation of wheel sets, finish rolling

Abstract: Wheel sets are one of the most important elements in each rail vehicle. They are responsible for leading a vehicle on the track. Thus, any damages or wear may cause derailment of the vehicle and a catastrophe where hundreds of people may lose their loves. Therefore, a significant issue while designing the wheel sets is to try to limit excessive wear that results from exploitation. Wear tests carried out on wheel sets in factual working conditions are difficult because of their dimensions, the constructions costs of an appropriate stand, and technological difficulties regarding the correct disassembly of a wheel from an axle while not damaging the developed wear figures. The article discusses exemplary wear of wheel sets in rail vehicles, which may emerge during the disassembly of wheel sets, as well as wear and damages that are caused by the exploitation of rail vehicles. Special attention was paid to the fretting phenomenon, which is hard to identify, and which might be a reason for fatigue wear. Hence, a major part of the article is devoted to that type of wear.

Wybrane problemy eksploatacji zestawów kołowych pojazdów szynowych

Słowa kluczowe: zużycie frettingowe, połączenie wtłaczane, warstwa wierzchnia, eksploatacja, montaż zestawów kołowych, rolkowanie

Abstract: Zestawy kołowe są jednym z najważniejszych elementów pojazdu szynowego. Ich zadaniem jest prowadzenie pojazdu w torze. Stąd też jakiekolwiek uszkodzenia lub zużycia mogą doprowadzić do wykolejenia pojazdu i spowodować katastrofę, w której życie mogą stracić setki ludzi. Dlatego ważnym problemem podczas projektowania zestawów kołowych jest próba ograniczenia nadmiernego zużycia wynikającego z 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 przykładowe zużycia zestawów kołowych pojazdów szynowych, które mogą wystąpić podczas montażu zestawów kołowych oraz zużycia i uszkodzenia wynikające z eksploatacji pojazdów szynowych. Szczególną uwagę zwrócono na zjawisko frettingu, które jest trudne do wykrycia, a może być przyczyną rozwoju zużycia zmęczeniowego. Dlatego też temu zużyciu poświęcono większą część artykułu.

Introduction

Dynamic development of rail transport and the need for the quick transport of people and goods caused that rail vehicles are designed in a manner that allows reaching increasingly higher speeds. Therefore, the components of a vehicle, directly responsible for safe travels, should be characterized with especially high durability and reliability. One of such components is posed by a wheel and steering system that encompasses wheel sets. They ensure progressive movement of a vehicle and keep it on a track. This important task makes the damages or wear of wheel sets resulting from their exploitation lead to derailment. Such a situation brings injuries to travelers and even casualties in extreme cases. Derailment also damages infrastructure, which is very expensive to repair.

Currently, there are various types of wheel sets under exploitation in rail vehicles, and their structure and dimensions differ regarding their use. Constructors, being aware of the danger brought by damages of wheel sets, employ various solutions, from using newer, better structural materials to additional strengthening of technological processes, allowing the improvement of their durability and reliability. Despite that, wheel sets can still be damaged. Thus, questions arise whether it is possible to eliminate the damages and wear of components in a running gear of rail vehicles and what decisions should be made in this respect.

1. Construction and working conditions of a wheel set

A classic wheel set is composed of an axle and two wheels embedded on it by clamping. Regarding construction and intended use, the group of wheel sets is divided into those with tyred wheels and solid wheels. Tyred wheel are made from a wheel centre, tyre, and a clamping ring. Moreover, we may differentiate driving wheel sets with some space for traction motors, or rolling wheel sets. The article discusses selected exploitation problems, based on classic wheel sets.

Wheel set elements of rail vehicles are heavily loaded and exposed to external factors. Apart from static load, coming from the vehicle weight, the wheel sets are also exposed to dynamic forces occurring during exploitation.

Dynamic forces that occur in wheel sets result from their rolling, and they emerge at the contact point between the wheel and the rail. Side forces load a wheel set while a train drives on a curve, or when snaking occurs.

As a result of the above-mentioned forces, the distribution of bending moment adopts a form presented in Fig. 1. Its maximum value occurs in the R_A and R_B reactions plain.

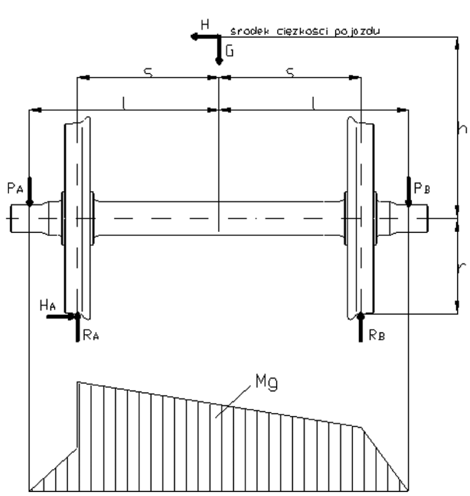


Fig. 1. Loading scheme of a wheel set and the resulting distribution of the bending moment [1, 2]. Mg – bending moment

Static forces that result from the load to the wheel set with the weight of the rail vehicle cause the axle to bend. During exploitation, the axle rotates, as a result of which the bending moment occurs causing micro-shifts of contact points of the cooperating elements. These are the perfect conditions for the initiation and development of fretting wear.

A wheel set is also loaded thermally. During rapid or continuous braking while driving in mountainous areas, a wheel rim gets heated which causes tensile stress that in turn may lead to cracks.

Despite the loads resulting from exploitation, there is a need to also mention the loads resulting from the installation of a wheel set, i.e. the tensions that occur while clamping the wheel to the axle.

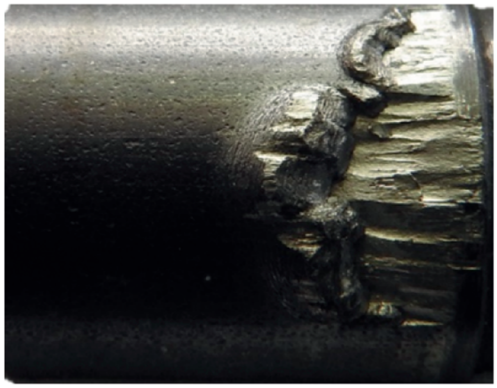
2. Tear and wear of wheel sets

Wear and tear of wheel sets may be divided into two groups. The first one covers tear and wear resulting from the installation of a wheel set in a production process, while the second one embraces wear that results from vehicle exploitation. Since damages from the first group occur very rarely, the wear in the second group are hard to anticipate, and they cannot be eliminated completely. They will always be present, regardless the adopted procedures. We may only try to limit their development.

The process of clamping a wheel to the axle causes surface pressures, which will ensure durability of the joint. However, if the clamping pressure is inadequate, the stress may exceed the permissible value and thus cause permanent plastic deformation of the elements' surface. During exploitation, they may become a source of fatigue cracks. An example of damages to the surface layers of the axle during the installation process are presented in Fig. 2.

In the case presented in Fig. 2a, incorrect selection of the clamping pressure damaged it through removing a large part of the surface layer. Another example of damage to the wheel set's axle during clamping may be gaps in the surface layer (Fig. 2b). Such a situation occurs where surfaces of joint elements will be characterized with a small level of roughness. This is when the adhesion phenomenon will occur, damaging the surface layer. Such a situation is frequent when the axle undergoes, e.g., a finish rolling process in order to improve the fatigue limit. In both cases, the axle must be replaced, which is connected with additional production costs.

An important function that is played by a wheel set causes that the problem of its wear and diagnostic methods remain the point of interest of numerous scientists. Thus, the article only mentions the most frequently encountered damages, and its main subject of interest is the wear emerging in the area of a clamping joint between a wheel and an axle. Exemplary scientific a



b

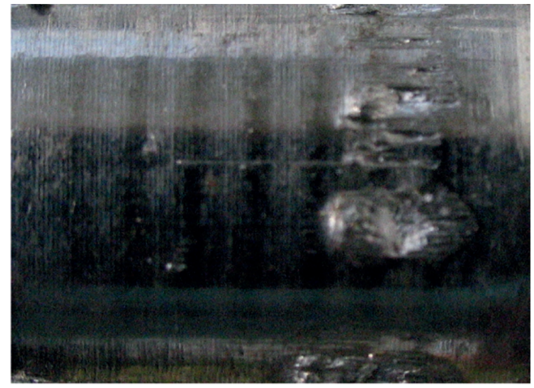


Fig. 2. Exemplary damages of a wheel set's axle during the clamping process

publications, where the problems of wear and tear are raised along with diagnostic methods for wheel sets are [2, 3, 4, 5].

The most frequently encountered exploitation damages of wheels and tyres, which are defined in, among others, [6] are the following:

– Faults in a form of a flat wheel, which may arise as a result of breaking with an activated parking brake;
– Material flaking on a rolling surface, which may result from mechanical loads to the wheel material;
– Metal overlaps and build-ups, which result from excessive thermal stress; and,
– Damages to a wheel flange in a form of spalling or radial cracks, which are most often caused by a wheel touching a permanent barrier.

Axles of wheel sets most often undergo [6] the following:

– Faults on the perimeter in a form of grooves and channels emerging on the whole perimeter of an axle or its part;
– Corrosion;
– Bending of the axle; and,
– Dents and longitudinal flaws.

All of the flaws mentioned above are highly dangerous during exploitation, and they may lead to derailment. However, according to the author, the most dangerous damage is the fretting wear, which develops in the connection between a wheel and an axle. The problems of fretting wear in the clamping joint between a wheel and an axle are not dealt with by many scientists. This is caused mainly by technological problems in the preparation of studies. These problems are raised in such works as [7, 8, 9, 10].

Fretting is a process of damaging surface machinery elements, causing the first fatigue contact [11]. It is a phenomenon of oscillatory slippage with a low amplitude of contacting elements that result in the damage and wear of the surface layer [12, 13, 14]. Fretting is a phenomenon characterized by a highly complex wear and tear mechanism, where the following actions overlay or emerge subsequently: adhesion wear, surface fatigue, exfoliation, oxidation, the abrasion of roughness peaks, and erosion with loose wear products. Divergences between researchers arise mainly from accepting one of these processes as the one that initiates the fretting wear. Fretting wear can be demonstrated through corrosion spots on the elements surfaces, increased surface roughness, micro-cracks in the top layer, pitting, and as a consequence, e.g., in case of push-in joint, of reduced installation pressure.

Results from wear tests carried out by the author [15] showed that any changes in the clamping pressure, the roughness of installation surfaces, or the manner of jointing results in a changed intensity of wear as well as its location and reach. It may be concluded that a condition for the development of wear in a clamping joint is the emergence of two independent conditions related to the jointed elements. First of all, a real contact between the surface areas of both jointed elements must take place, and second of all, there must be oscillatory contact shifts between them, even of minimum amplitude (such as a few micrometres). A finding that the fretting wear always occurs in the area of factual contact between the cooperating surfaces suggests that adhesion will be the phenomenon that initiates the development of the fretting wear.

The intensity of adhesive damages is influenced by a series of factors related to the qualities of material, the conditions of the surface layer, and impact from regular and contact loads. In case of adhesive tacking, a special role will be played by the following [16]:

– The physical and chemical qualities of the surface layer,
– Pressure in the contact point of adjacent elements,
– The lack of oxide layers on the contact's surface area,
– The oscillation amplitude of jointed elements, and
– The temperature and condition of stresses in the surface layer.

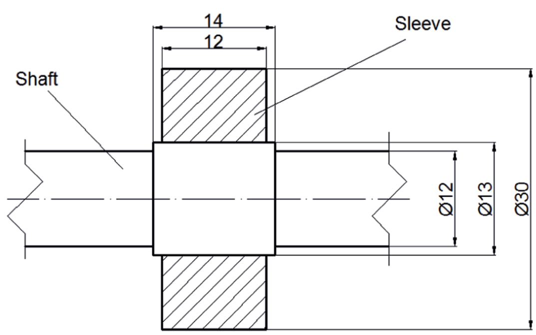
All of the above-mentioned factors contribute to the generation of tacking, especially in case of push-in joints carried out by clamping. The installation process will primarily contribute to damaging the oxide layer on the surface of jointed elements. As a result of micromachining and plastic deformations, the actual area of the contact point will be enlarged, especially in case of matchings, characterized with lower roughness at stronger push-in joints.

3. Methodology of research

Wear tests at the connection spot between the wheel and the axle are hard to carry out. The problem is the need to use a special stand, causing that the tests are very expensive. The time of tests on such a stand is very expensive as well. In case of testing fretting wear, an additional problem is to uncouple the joint while not damaging the surface layer of the axle, and thus not damaging the image of generated fretting wear.

Bearing that in mind, the tests over fretting wear were carried out on a wheel-axle joint model, which will be a shaft-sleeve clamped joint.

While selecting the wheel-axle joint model, the preservation of similar dimensions around the joint was taken into account. The proportion of the joint length, diameter, and push-in pressure were preserved. Figure 3 demonstrates the dimensions of the wheel-axle joint model and its view. The length of the model depended on the dimensions of the research stand.



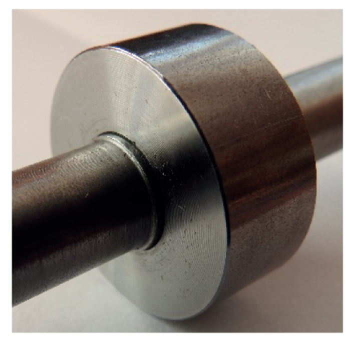


Fig. 3. Dimensions of the wheel-axle joint and its view

In order to ensure that mechanical characteristics of the model are similar to those of the real joint, the shaft was made from C45 steel, and the sleeve from E295 sleeve. In the first group of models, the shaft surface area underwent the finish rolling procedure. This is what happens in case of wheel sets. This process is intended to improve the axle's durability. In the second group of models, the surface layer was not strengthened, and the shafts remained in a condition they were after rolling.

The joint in the model was based on clamping the sleeve into the shaft. In that case, attention was paid to a proper push-in value, which will generate pressure between the jointed surfaces, ensuring the durability of the joint in the case of external loads. That condition was met for the 0.02 mm clamping value.

Wear tests were carried out on a stand with a fatigue resistance machine installed, which allows reaching a load to the model corresponding to real loads of a wheel set. Moreover, the machine allowed obtaining the periodically changeable load with pure bending of the rotating model. Therefore, the conditions needed for the development of fretting wear emerged, i.e. such a bending moment which will bend the shaft, and as a consequence, this lead to oscillatory shifts of contact points between the surfaces of the shaft and the sleeve.

Figure 4 presents a load scheme of the model on the fatigue resistance machine, and the corresponding bending moment. It was assumed in the tests that the wheel set rolls on a straight track. It was also assumed that forces that occur while rolling on a curve have a negligible influence on the development of fretting wear.

The following conditions for wear tests were provided:

– rotational speed – 1360 rpm,
– load to the sample – 400 N,
– number of cycles – 8×10^6 .

The assumed rotational speed of the model corresponds to about 75 km/h of a rail vehicle.

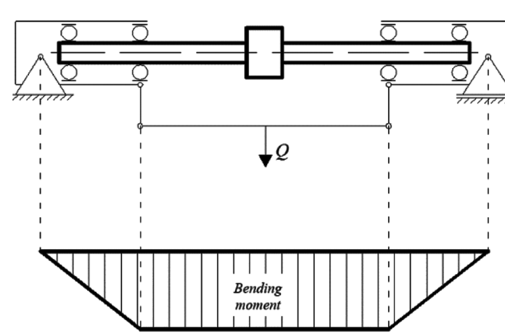


Fig. 4. Load to the wheel-axle joint model and the corresponding bending moment

Fig. 5. View on samples that underwent laboratory tests

Adequate disassembly technology adopted in the joint allowed obtaining three samples (Fig. 5), while not damaging the image of emerged fretting wear, which then underwent laboratory testing.

Macroscopic and microscopic tests were carried out within the scope of laboratory tests, as well as complementary examinations consisting in the determination of the toughness of cooperating surfaces and measurements of roughness in the surface layer. Additionally, the clamping force between the sleeve and the shaft was also measured.

Macroscopic observations allow one to determine the condition of the shaft's surface after the wear tests, as well as the place and reach of fretting wear.

Microscopic tests over the shaft with an optic microscope and a scanning microscope showed the real image of damages that emerge on the surface area of the shaft's seat. This in turn allowed the determination of the wear that makes the fretting phenomenon. Moreover, the joint sample underwent some microscopic tests. The purpose of the observations was to determine the real outline of the connection between the shaft and the sleeve, as well as their damages and deformations.

4. Laboratory tests results

Table 1 presents results from complementary measurements. The toughness measurement was carried out with a Vicker's hardness tester, and converted into HB values. Geometric measurements of the surface layer were carried out with HOMMEL T500.

Table 1. Results of complementary measurements

Model	Clamping force [kN]	HB hardness		R_a parameter [μm]	
		shaft	bushing	shaft	bushing
Shaft with a surface when rolling – sleeve	8.6	167	160	1.86	0.30
Shaft with a rolled surface – sleeve	10.2	190	160	0.34	0.30

The finish rolling process applied to the shaft's surface area brought an expected result. The hardness of the surface rose by 10-15% in relation to the surface when rolling. This situation should lead to greater durability of the axle and the limitation in wear development. However, the rolling process caused "smoothening" of the surface. This is confirmed by geometric tests over the surface layer of shafts. The roughness parameter R_a of the shaft surface dropped by ~75% in relation to the shaft surface being rolled. Now, the geometry of the shaft's top layer is very similar to the geometry of the surface layer of the sleeve's internal part. In the case of clamped joints, the same or similar geometry of the surface layer may lead to adhesion tacking. This, in turn, will cause detachments of surface layer's fragments, leading to its damage, which in exploitation conditions, may result in fatigue wear development and cracking of the axle.

Figure 6 presents the results from macro-graphic observations of the surface layer of analysed shafts before and after the wear tests.

Macroscopic observations make the fretting phenomenon more visible in a form of a rim along the whole perimeter, which is located at the edges of the joint for both variants of the shaft surface layer finishing. In the case of the surface layer during rolling, the intensity of wear is greater when compared to the rolled surface. Despite strengthening the surface layer by finish rolling, the fretting phenomenon was eliminated only to a limited extent.

A characteristic feature of all tested samples is the occurrence of a brown colour at the fretting spot. This image is similar to atmospheric corrosion of iron. The influence of external forces coming from the vehicle weight causes the axle to bend. The researched model behaves in a similar manner. As a result of the shaft's

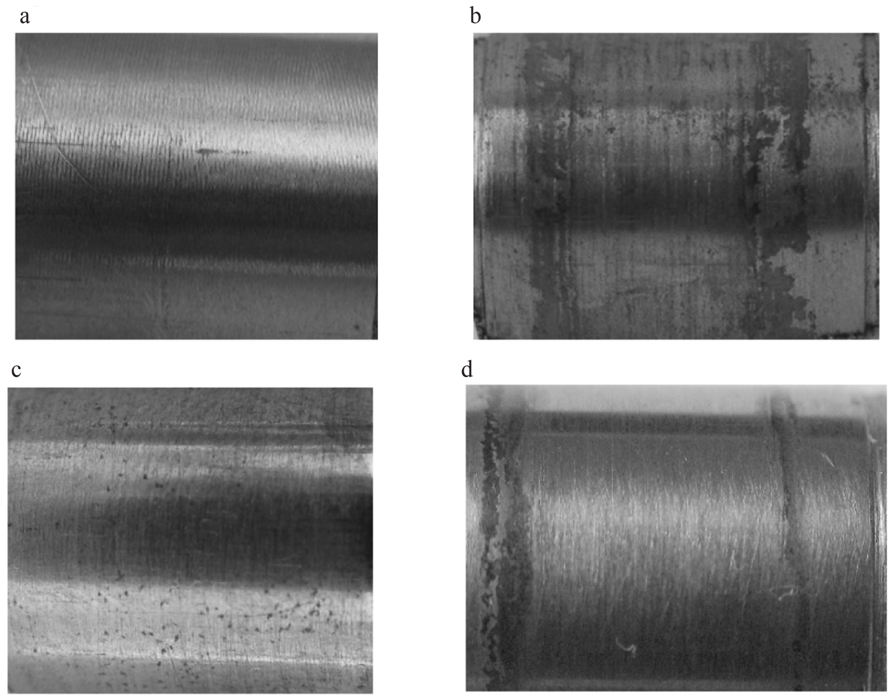


Fig. 6. Photographs of the surface layer, zoomed in 10x, (a, b) of shafts after being rolled, (c, d) of shafts with a rolled surface, (a, c) before wear tests, (b, d) after wear tests

bending during exploitation, the damaged area contacts oxygen, which causes the oxidation of the wear products, providing them with this characteristic colour.

The fretting wear spots were tested under a scanning microscope. Results from those observations are presented in Fig. 7 (for a shaft with surface when rolled) and Fig. 8 (for a shaft with rolled surface layer).

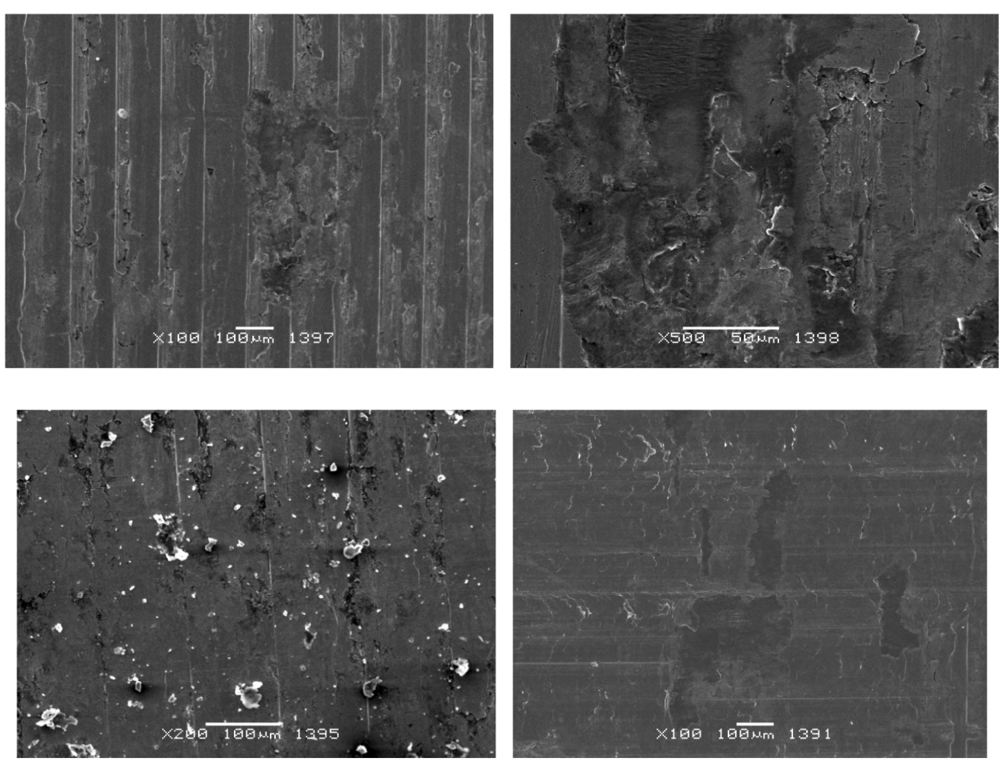


Fig. 7. Scanning images of fretting wear emerge on the surface of the shaft in a rolled condition

The observations prove that the fretting phenomenon occurs mainly in a form of material build-ups, which undergo plastic deformations and then oxidation. Local abrasion and micro-pits are also observed.

Scanning images of rolled shafts confirm that surfaces that are less rough are more prone to fretting wear.

Apart from the already mentioned images of wear, there are additional micro-gaps that can be spotted.

A source of damages to the surface in a form of micro-gaps and micro-build-ups is the adhesion phenomenon. Abrasion of the surface area most probably results from micro-machining processes. Micro-build-ups visible in scanning images as a brighter colour prove their oxidation.

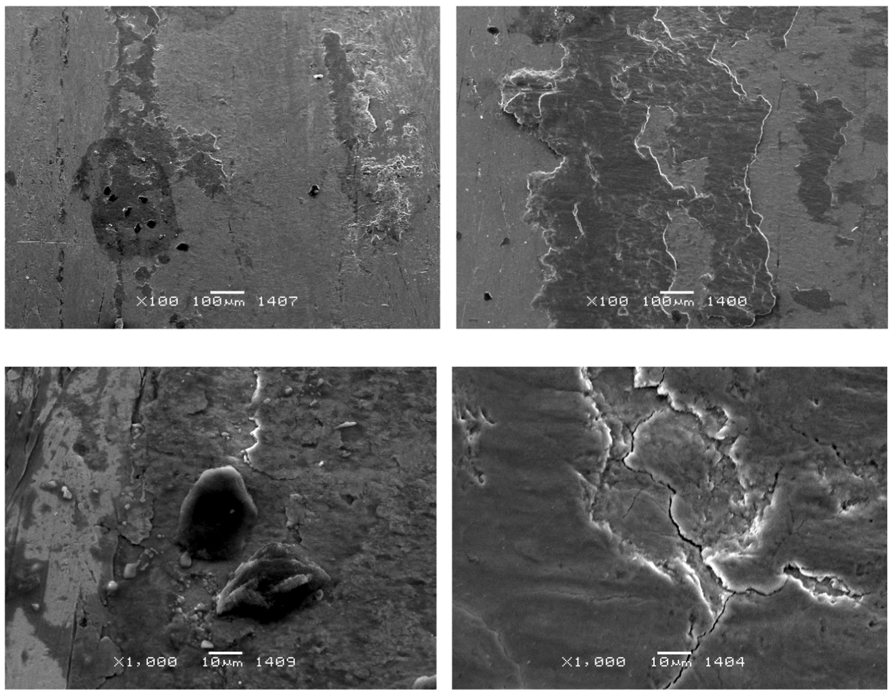


Fig. 8. Scanning images of fretting wear emerging on the surface of rolled shaft

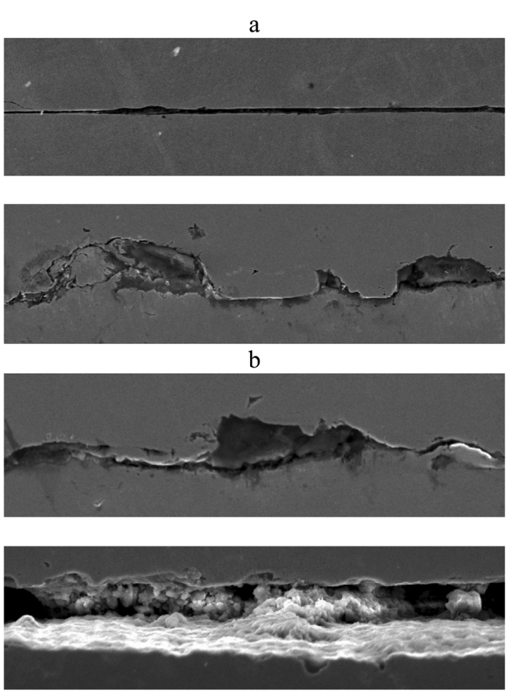


Fig. 9. Image of a contact point between the shaft and the sleeve in the area of fretting wear, zoom a – 500x, b – 1000x

Results of micro-graphic observations of the contact surface between the shaft and the sleeve in the area of fretting wear are presented in Fig. 9. Edges of the joint present an even gap not filled with any foreign bodies (products of wear). While moving towards the centre of the joint, we can observe a gap filled with micro-machining products generated while clamping the sleeve to the shaft. The middle part of the joint is characterized with a real connection of jointed surfaces.

No wear products on the joint's edges may be explained by the fact that, while clamping the sleeve on the shaft, these products shift towards the second edge. During exploitation, as a result of the sample bending and the emerging oscillatory shifts of contacting surfaces, the wear products are removed from the contact zone.

Conclusions

Fretting use tests in the wheel-axle clamped joint were carried out on a model of that joint. However, as proven by tests carried out by [17, 18], if adequate criteria of dimensioning and the material similarity of a given model to a real object are preserved, the results from wear tests carried out in laboratory conditions may be referred to the real object.

In order to eliminate the fretting wear, it is very important to understand the mechanism of its development. In the case of a clamped joint, one of the factors that initiate the fretting phenomenon is adhesion. The adhesion process in this case consists in creating and breaking adhesive tacking. They are formed as a result of real contact between the jointed surfaces resulting from the process of clamping of one element to the other. Then, micro-roughness is sheared and the surface layer is plastically deformed.

The limitation in the fretting wear development in the analysed case will consist in the elimination of the adhesion phenomenon. Such a state of affairs may be reached by increasing the hardness or roughness of cooperating surfaces. Generally available thermal processing solutions such as surface hardening or thermal and chemical processing, e.g., nitriding of the axle's surface layer may be employed. The mentioned processing procedures are not expensive, thus the final cost of wheel set production will increase only slightly, but the benefits brought by application of those processes may turn out to be highly beneficial in exploitation of wheel sets.

Another attempt to limit the fretting wear may be the use of PVD coatings distributed on the axles, characterized with significant durability and good thermal and chemical stability. The combination of those qualities causes that the coating are characterized by a high resistance to the creation of adhesive tacking. A limitation in the application of such coatings may be the costs of the distribution process, which would be reflected in the increase of the production costs of wheel sets' axles.

References

1. Guzowski S., Analiza zużycia frettingowego w połączeniach wciskowych na przykładzie osi zestawów kołowych pojazdów szynowych. Monografia 284: Wydawnictwo Politechniki Krakowskiej, 2003.
2. Stasiak L., Doświadczalna determinacja charakterystyk wytrzymałości zmęczeniowej osi zestawów kołowych pojazdów szynowych. Rozprawy nr 173. Wydawnictwo Politechniki Poznańskiej, 1986.
3. Szudyga M., Diagnozowanie metodą magnetyczną procesów zmęczeniowych stali stosowanej do kół i obręczy kolejowych zestawów kołowych. Rozprawa doktorska. Politechnika Śląska, Katowice 2011.
4. Sowa A., Sowiński M., Obraz niezdatności pojazdów szynowych w badaniach na stanowisku TENSAN/PLW. Pojazdy Szynowe 2/2014.
5. Zając G., Jurga S., Durability investigation of tram wheel tyres operated I the MPK Inc., Cracow. Problemy Eksploatacji 2/2009, 139–148.
6. Norma PN-EN 15313:2016. Kolejnictwo – Wymagania eksploatacyjne dotyczące obsługi zestawów kołowych – Utrzymanie zestawów kołowych pojazdów w eksploatacji i wyłączonych z eksploatacji.
7. Guzowski S., Warunki rozwoju zużycia frettingowego w połączeniu koło–oś zestawu kołowego. Zeszyty Naukowe Transport, Politechnika Śląska 2007, Z. 27, 111–118
8. Zheng J.F., Luo J., Mo J.L., Peng J.F., Jin X.S., Zhu M.H., Fretting wear behaviors of a railway axle steel. Tribology International. May 2010, Vol. 43 Issue 5/6, 906–911.
9. Kowalski S., Influence of molybdenum coating on fretting wear development in clamped joint. Journal of the Balkan Tribological Association. 2016, Vol. 22, No 2A-I, 1741–1752.
10. Song C., Shen M.X., Lin X.F., Liu D.W., Zhu M.H., An investigation on rotatory bending fretting fatigue damage of railway axles. Fatigue Fract Engng Mater Struct, 2014, 37, 72–84.
11. Pytko S., Szczerek M., Fretting – forma niszczenia elementów maszyn. Tribologia nr 6, 1994, 673–693.
12. Neu R.W., Progress in standardization of fretting fatigue terminology and testing. Tribology International, 2011, 44, 1371–1377.
13. Waterhouse R.B., Fretting corrosion. Pergamon Press Ltd, Oxford 1972.
14. Waterhouse R.B., Fretting fatigue. Applied Science Publishers Ltd., London 1981.
15. Guzowski S., Wpływ wybranych czynników na rozwój zużycia frettingowego w połączeniu wtłaczanym koło–oś. Pojazdy szynowe w transporcie europejskim: IX Konferencja Pojazdy szynowe, Kraków – Muszyna 8–10.12.1992, 403–410.
16. Pytko S., Pewne uwagi dotyczące badania korozji metali. IV Międzynarodowa Konferencja Bezpieczeństwo pracy urządzeń transportowych w górnictwie, Ustroń 5–7 listopada 2008, 353–358.
17. Furmanik K., Guzowski S., Analiza wymiarowa w badaniach modelowych zużycia frettingowego w połączeniu koło–oś. XV Konferencja Naukowo-Techniczna „Pojazdy Szynowe 2002", Nowe wyzwania i technologie dla logistyki, tom I, Szklarska Poręba 2002, 162–172.
18. Kowalski S., Application of dimensional analysis in the fretting wear studies. Journal of the Balkan Tribological Association. 2016, Vol. 22, No 4, 3076––3088.