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THE INFLUENCE OF SELECTED PVD COATINGS ON FRETTING WEAR IN A CLAMPED JOINT BASED ON THE EXAMPLE OF A RAIL VEHICLE WHEEL SET

WPŁYW WYBRANYCH POWŁOK PVD NA ZUŻYCIE FRETTINGOWE W POŁĄCZENIU WTŁACZANYM NA PRZYKŁADZIE MODELU ZESTAWU KOŁOWEGO POJAZDU SZYNOWEGO*

In this article, laboratory test results concerning the influence of selected PVD coatings on the initiation and development of fretting wear in clamped joints are presented. TiN and CrN+a-C:H:W coatings were applied to shafts, and the results of wear tests compared with those for uncoated shafts. Wear tests were conducted at a test bed which simulated the operation conditions of the wheel sets of rail vehicles moving along a straight track. The sample elements for testing were assembled by forcing the sleeve onto the shaft with the tolerance of 0.02 mm. To assess fretting at shaft top layers being tested, macroscopic observations, microscopic observations with the use of a scanning microscope, x-ray microanalysis of the chemical composition by means of the EDS method and the measurement of the top layer topography in the place of wear were performed. Test results presented concern the shaft top layer because it is that layer which mainly determines the life of a clamped joint. The results of the macroscopic observations of the sleeve hub top layer were presented, too, for comparison of the image of wear between mating surfaces.The results of the observations of the various shaft top layers indicate the mitigation of the development of fretting wear in the case of shafts with coatings; CrN+a-C:H:W coatings influence the mitigation of fretting wear better indeed. The main damage comprised by fretting in all the samples being tested is material build-up occurring as a result of adhesion. That build-up undergoes oxidation during operation. Micropits and microabrasion of the top layer are observed in places.

Keywords: *clamped joint, fretting wear, PVD coating.*

W artykule zaprezentowano wyniki badań laboratoryjnych dotyczące wpływu zastosowania wybranych powłok PVD na inicjację i rozwój zużycia frettingowego w połączeniach wtłaczanych. Na wały nałożono powłoki TiN a także CrN+a-C:H:W, wyniki badań zużyciowych porównano z wynikami badań wałów bez powłok. Badania zużyciowe wykonywano na stanowisku badawczym, które symulowało warunki pracy zestawów kołowych pojazdów szynowych poruszających się po torze prostym. Montaż elementów próbki przeznaczonej do badań wykonano przez wtłoczenie tulei na wał z wartością wcisku 0,02mm. W celu oceny zjawiska frettingu dla badanych warstw wierzchnich wałów wykonano obserwacje makroskopowe, mikroskopowe przy użyciu mikroskopu skaningowego, mikroanalizę rentgenowską składu chemicznego metodą EDS oraz pomiar topografii warstwy wierzchniej w miejscu zużycia. Zaprezentowane wyniki badań dotyczą warstwy wierzchniej wałów, ponieważ to ona w głównej mierze determinują trwałość połączenia wtłaczanego. Zaprezentowano również wyniki obserwacji makroskopowych warstwy wierzchniej piasty tulei, w celu porównania obrazu zużycia pomiędzy współpracującymi powierzchniami.Wyniki obserwacji poszczególnych warstw wierzchnich wałów wskazują na ograniczenie rozwoju zużycia frettingowego w przypadku wałów z zastosowanymi powłokami, przy czym powłoki CrN+a-C:H:W korzystniej wpływają na zmniejszenie zużycia frettingowego. Głównym uszkodzeniem składającym się na zjawisko frettingu we wszystkich badanych próbkach są nalepienia materiału, powstałe w wyniku zjawiska adhezji. W czasie eksploatacji nalepienia te ulegają utlenianiu. Lokalnie obserwuje się mikrowżery i mikrowytarcia warstwy wierzchniej.

Słowa kluczowe: *połączenie wtłaczane, zużycie frettingowe, powłoki PVD.*

1. Introduction

Clamped joints are one of the most frequently used methods of element joining. This is related to the simplicity of assembly and therefore low costs of the process. The possibility of transferring relatively high loads causes clamped joints to connect elements working in various, sometimes tough operation conditions.

Rail vehicle wheel sets are one of the examples in which elements are connected by pressing. The assembly process takes place at a press equipped with a force recorder, thus the joint is protected from undesirable damage. Wheel sets are one of the most important rail vehicle elements. They directly influence passenger safety. Any damage oc-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** curring during operation may be the cause of a rail crash, that is why appropriate damage risk reducing methods should be used.

The effective elimination of damage and wear of wheel sets is not an easy task because of the peculiar conditions of their operation. Wheel sets are subjected to static forces following from the vertical load depending on the vehicle weight and to dynamic forces at the wheel/rail contact point which result from the rolling of a wheel set along a track. Vertical forces will cause axle deflection; in relation to that, during operation, as a result of the operation of dynamic forces, oscillatory tangential displacement will occur between mating surfaces. Such operation conditions cause damage not only to the rolling wheel surface or to the rails, but also in the area of the wheel/axle clamped joint. The following may be included among the most frequent kinds of wear and damage: adhesion-related damage to the axle, the shift of track wheels in relation to the axle, axle fretting and fatigue wear leading to cracks. The primary focus of this article is fretting wear because its development mechanism has not been fully recognised yet.

Fretting wear is counted among the tribological kinds of wear, and the necessary condition for the development of fretting wear is oscillatory microdisplacement, with the amplitude of 25-150 μm according to some authors, of mating elements. Because of the complexity of physical and chemical phenomena accompanying fretting wear, the unambiguous definition of that concept has not been given so far. Fretting wear may be demonstrated by corrosion traces at the surface of the elements, the increase of surface roughness, as well as by pits and microcracks.

The development of fretting wear is influenced by many various factors, however, it is difficult to give their exact number in view of the complexity of the phenomenon and because of its development mechanism which has not been fully investigated yet. The author of [5] made a tabular schedule of the most frequent factors influencing the development of fretting wear. He indicated, among other things, surface hardness and roughness, the number of cycles and air temperature and humidity. The authors of [15], among others, investigated the influence of roughness on the development of fretting wear. They suggested a large-scale procedure for the investigation of the roughness effect with the use of the finite element method. The influence of surface roughness on the development of the corrosion and fretting wear of pure titanium used for medical implants was examined in [3]. The authors of [10] state that the initial topography of the top layer has significant influence on the development and intensity of fretting wear. Research was conducted for several slip amplitude values. The influence of temperature on fretting wear was investigated by, among others, the authors of [8, 13].

It follows from the review of literature that most research into fretting wear concerns the elements pressed against each other with a normal force, and only few authors undertook research into the development of fretting wear in push fit joints. That kind of joint does, however, accumulate in it all the factors conducive to the development of fretting wear. There is a specific pressure between the surfaces of the connected elements, and the relative displacement of those surfaces occurs. This happens when one of the elements is loaded with a variable turning force or when the joint operates in the conditions of rotary bending or twisting with a variable moment [5]. The probable cause of the small volume of research into fretting wear in clamped joints is the problem with joint disassembly. Traditional forcing of one element from the other may damage the fretting wear occurrence zone and thus distort the wear image. In relation to that, an appropriate process enabling safe joint disassembly should be developed. In the case of rail vehicle wheel sets, such a process is related to high costs because wheel set dimensions require the creation of an appropriate test bed and appropriately long disassembly time.

Among the works concerning fretting wear testing in a push fit joint based on the example of rail vehicle wheel sets, research work [6] may be mentioned, for example, in which the author investigated the influence of the way of making the joint (a forced-in joint or thermocompression bonding), the value of the tolerance and the surface roughness of the elements before the joint was made on the development and intensity of fretting wear. The authors of [17] conducted the analysis of axle damage at the point of connection with the wheel. They demonstrated that fretting comprises abrasive and oxidation wear and delamination. Research conducted by the authors of [19] demonstrated that fretting wear intensity strongly depends on normal loads and slip amplitude. In that case, too, fretting is the combination of abrasive and corrosive wear and of delamination with distinct plastic deformation. Work [14] concerning wear processes and the way of their mitigation in rotary joints is also worth noting. As an example of such a joint, that work mentions a rail vehicle wheel set with automatic wheel track changing. Whilst the work does not concern wear tests in clamped joints, the fretting wear development mechanism in the joint under analysis is very similar. The author suggests selected processes to mitigate fretting wear. It follows from test results referred to that only molybdenum coatings mitigate fretting effectively.

The cited works concerned mainly the determination of the place and range of fretting wear development, and also the indication of the kinds of wear comprised by fretting. Research into an attempt to eliminate wear has not been conducted, however. Works [7] and [9] may be pointed out in that regard. In the first one, the authors analysed the influence of surface strengthening treatment (thermal improvement, grit blasting, nitriding, surface hardening) on the fatigue strength of samples with an engineering notch. Research did not concern the influence of the above technologies on the development of fretting wear directly. The other work pertained to the influence of selected shaft surface finish processes such as nitriding, rolling and surface hardening on the development of fretting wear in clamped joints. Test results demonstrated an insignificant influence of those processes on the mitigation of fretting wear development. It follows from the review of literature that research into the application of PVD coatings with a view to mitigating fretting wear has not been conducted. That is why such tests of the shaft/sleeve clamped joint in which the shaft was covered with TiN and CrN+a-C:H:W coatings were conducted in this article.

PVD coatings were initially used to extend the life of cutting tools. It was already then that the positive tribological properties of those coatings were noticed. With the passage of time, the range of applications of the coatings extended, and they are used as a protection against tribological wear more and more commonly at present. PVD coatings are distinguished by their high hardness and resistance to wear and corrosion, and they have good fatigue properties. Several works confirming those properties may be found in literature. Work [11] in which the author tested the tribological properties of a-C:H:W coatings with TiN and CrN intermediate layers may be mentioned as an example. Test results confirmed the improvement of the tribological properties of the elements to which coatings were applied. The aim of tests presented in [2] was to determine the mechanisms of damage arising on stainless steel used for the manufacture of olive oil presses and the assessment of the properties of TiN coatings influencing the mitigation of those mechanisms. Test results demonstrated the excellent wearing resistance of the coatings. In work [1], a-C:H:W coatings applied over a steel base surface were investigated. Test results demonstrated the good tribological properties of coatings in that case as well. Further works [4, 12, 16, 18] concerning research on the properties of multi-layer a-C:H:W coatings and of WC/C coatings also confirm the reduction of the wear of the elements to which low-friction coatings were applied.

2. Properties of the tested shaft top layer

The research programme assumed the assessment of fretting wear in a clamped joint in which selected PVD coatings were applied to shafts.

As part of the tests, the following alternatives of the shaft top layer finish were used:

- shaft with an uncoated top layer – (sample number: S_02),
- shaft with the top layer coated with titanium nitride (TiN) – (sample number: S_06),
- shaft with the top layer to which a low-friction coating (CrN+a-C:H:W) was applied – (sample number: S_14).

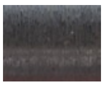
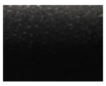
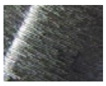
The basic properties of coatings used in further tests are shown in table 1.

Table 1. Coating properties according to Oerlikon Balzers catalogue data

Properties	Coating	
Coating composition	TiN	CrN+a-C:H:W
Microhardness [HV0.05]	2300	1500
Coefficient of friction against steel when dry, μ	0,4	0,1-0,2
Coating thickness [μm]	1-4	1-2
Coating temperature [°C]	180-500	180-350
Residual compressive stresses [GPa]	−2,5	−1
Colour	gold	anthracite

In the case of examination of fretting wear in clamped joints, the input roughness and hardness of the top layer of the mating elements play an important role in fretting wear development. The diagrams of roughness and waviness profiles of the shaft top layer in the function of length are shown in fig. 1, and the values of roughness parameters in table 2.

Table 2. Results of the measurement of top layer roughness parameters

Roughness parameter	Wartość zmierzona [μm]			
	Uncoated shaft	Shaft with a TiN coating	Shaft with a CrN+a-C:H:W coating	Sleeve
				
Ra	1,16	1,34	1,68	2,78
Rz	6,25	7,09	11,57	14,55

It follows from table 2 and fig. 1 that the top layer of coated shafts has greater roughness parameters in relation to the surface of uncoated shafts. This is related to the structure of the coatings, which is distinguished by porosity. The pores are the natural outcome of the coating application process. Those are cavities in the coating in the form of narrow channels filled with substances which do not constitute the coating. Those substances may include air or other gases. Various liquids or solids are sometimes found as well.

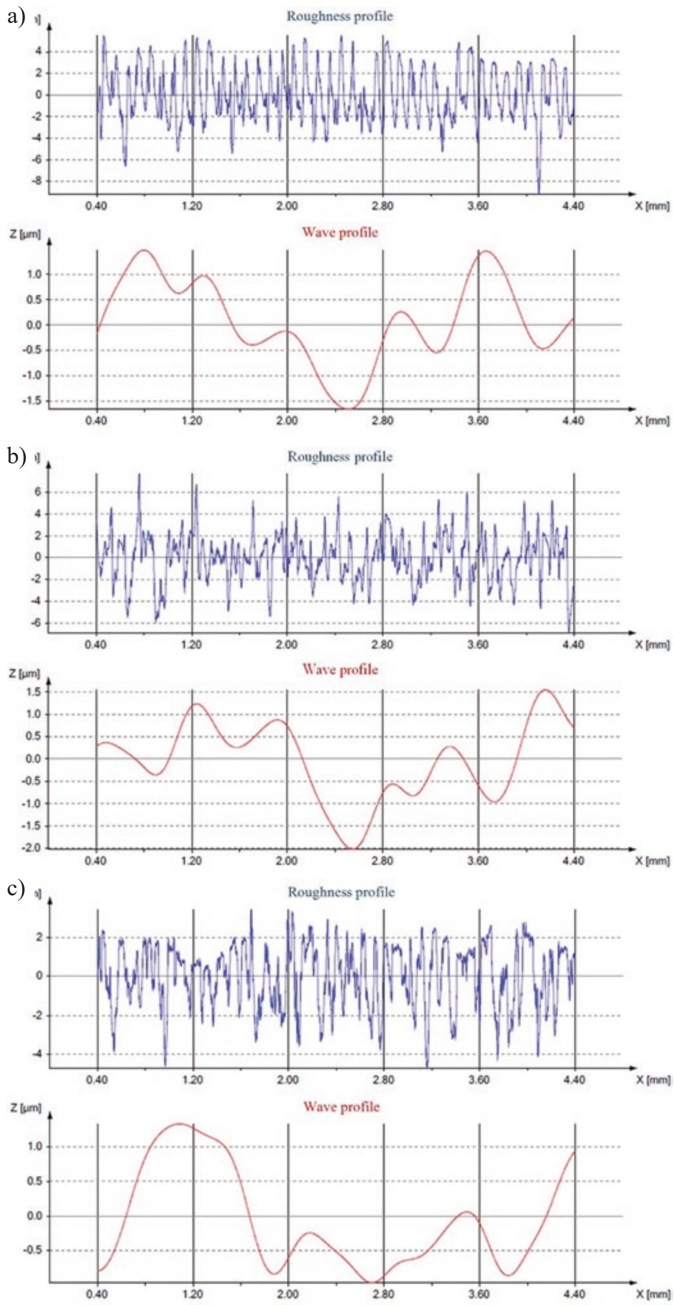


Fig. 1. Diagram of the roughness and waviness profile of a) an uncoated shaft, b) a shaft with a TiN coating, c) a shaft with a CrN+a-C:H:W coating

3. Test methodology

Coatings commonly used as the protection of cutting and pressing tools was conducted to mitigate the development of fretting wear in a clamped joint.

Experimental tests concerned:

- determination of the actual condition of the top layer of the mating elements after wear tests,
- determination of the influence of coatings on the development and intensity of fretting wear.

While selecting a wear test bed and samples, it was assumed that the tests were to simulate the operation conditions of a rail vehicle wheel set. For that purpose, an appropriate fatigue testing machine was chosen and the dimensional similarity at the place of connection of sample elements retained.

The sample for testing consisted of a sleeve, whose hub top layer had the hardness of 160 HB and of the shaft with the top layer hardness of 170 HB. The joint was assembled by pressing the sleeve onto the shaft with the tolerance ensuring joint durability.

Sample dimensions are presented in fig. 2. The shaft length and diameter depended on test bed dimensions. Dimensional proportions between the joint diameter and length, and the value of the tolerance in relation to the dimensions of the rail vehicle wheel set were retained, however.

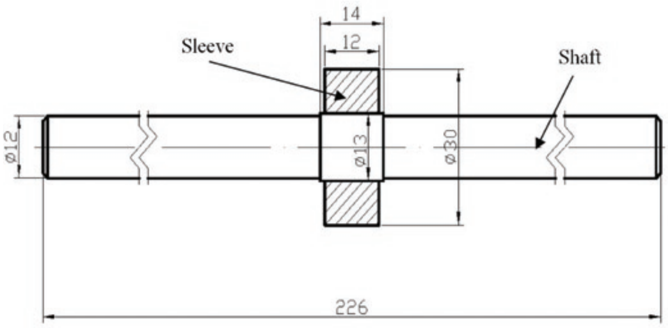


Fig. 2. Dimensions of the sample subjected to wear tests

The similarity did not pertain to the dimensions only, with the same structural materials having been used, too. The shaft was made of C45 steel, and the sleeve of P58 steel.

Wear tests were conducted at a UB-M fatigue testing machine ensuring the parameters simulating the actual operation conditions of a wheel set. The fatigue testing machine structure permits the generation of a periodically variable load on the sample with pure rotational bending.

The load on the sample should generate a bending moment which will cause shaft deflection. In such a situation, during operation, oscillatory tangential displacement of the sleeve in relation to the shaft will occur, which is a necessary condition for the initiation of fretting wear.

In fig. 3, the test bed for wear testing of the sample, the way of sample loading and the resultant bending moment are shown schematically. A similar bending moment distribution is obtained in the case of wheel sets loaded with the weight of a rail vehicle body at a straight track.

During wear tests, samples were loaded with the force of 550 N. As a result of such a load, normal stresses of 102 MPa occur at the sleeve/shaft contact surface. That value is close to the range of normal stresses at the axle seat surface of the real wheel set. Under the assumption of the typical operation conditions of a rail engine wheel set at a straight track, normal stresses at the axle surface are, according to the UIC regulations, 98 MPa.

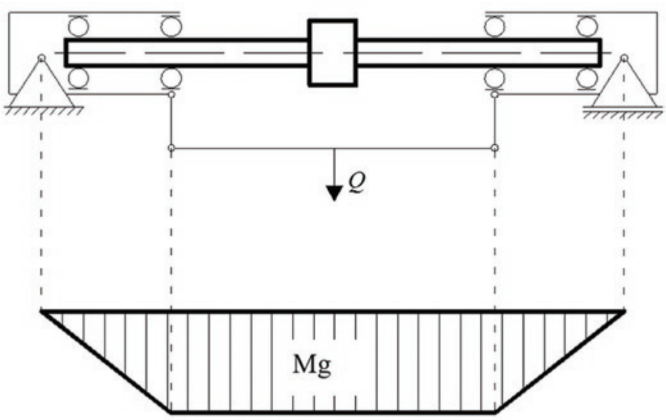


Fig. 3. Diagram showing sample fixing in the fatigue testing machine and the load, Mg – Bending moment

A strength analysis conducted in the ANSYS software demonstrated that loading with the force of 550 N would cause the maximum shaft deflection of 0.52 mm (fig. 4), and the maximum reduced stresses of 356 MPa (fig. 5) without causing plastic deformation at the same time. Such strength parameters will enable, during tests, oscillatory tangential displacement initiating the development of fretting wear to be obtained. The other parameters of wear tests are summarised in table 3.

Following wear tests, several laboratory tests were carried out to determine the influence of coatings on the development of fretting. Among other things, the tests of the topography of the models and the microscopic observations with the use of an electronic scanning microscope, type JEOL JSM-6460LV, equipped with an EDS spectrometer, were conducted. Tests were possible only after the samples were prepared as appropriate. Traditional forcing of the sleeve from the shaft would cause the destruction of fretting wear which has arisen, which would prevent its in-depth analysis. Hence, a joint disassembly technology was developed, which consists in cutting the joint parallel to the shaft axis. As a result, three samples were obtained whose observations permitted drawing relevant conclusions concerning the use of the coatings under analysis to extend the shaft's life.

Table 3. Summary of wear test parameters

Sample No.	Force pressing the sleeve onto the shaft N	Load on the sample N	Bending moment Nm	Stress amplitude MPa		Number of cycles 10^6
				ϕ 12 mm	ϕ 13 mm	
S_02	4800	550	27,5	162	128	8
S_06	7000	550	27,5	162	128	16
S_14	6600	550	27,5	162	128	10

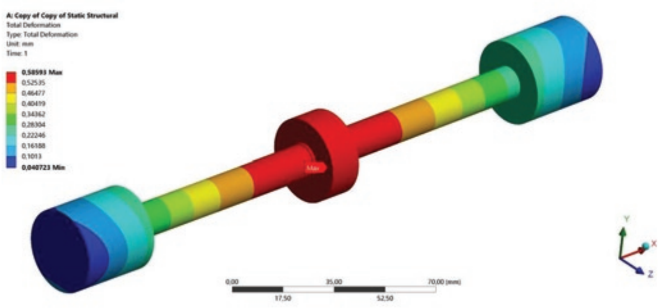


Fig. 4. Distribution of the sample deflection line

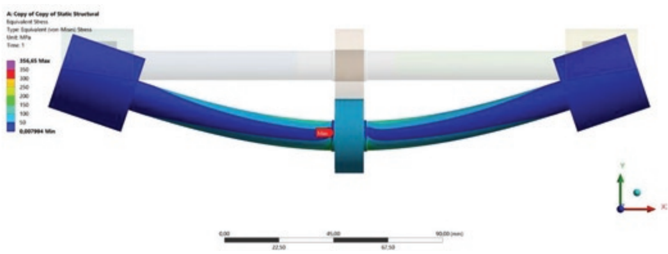


Fig. 5. Distribution of reduced stresses occurring in a sample loaded with the force of 550 N

4. Results of experimental tests

First, test results for an uncoated shaft are presented. They are a reference base for the remaining samples under analysis. A similar fretting wear image is observed at the surface of the axle and wheel in the wheel/axle joint of the wheel set. In the further part of this article, the results of wear tests for shafts with coatings applied to them are presented.

4.1. Shaft with an uncoated top layer

The results of the macrographic tests of the top layer demonstrated the occurrence of fretting wear on either side of the shaft axle seat and sleeve hub (fig. 6). The location of wear, close to joint edges, should be explained by the mechanism of the development of fretting in clamped joints, which was discussed in detail in [5].

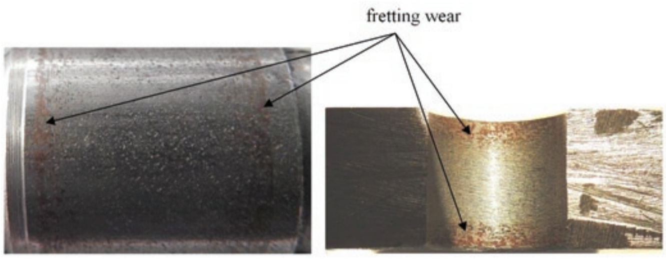


Fig. 6. Fretting wear at the surface of an uncoated shaft and sleeve hub

Wear occurs in the form of a ring at the entire circumference of the shaft axle seat. The width of the area affected by wear is approx. 2-3 mm on either side and that area is located approx. 2 mm from the axle seat edge.

The tests of the topography of the top layer at the place of fretting wear indicated a considerable increase of roughness parameters. The Ra parameter at the place of fretting wear is 3.23 µm. The sample results of the testing of top shaft layer topography at the place of fretting wear, achieved with the use a TOPO 01P contact profilometer equipped with an induction measuring head with the radius of 2 µm and cone angle of 90°, are presented in fig. 7.

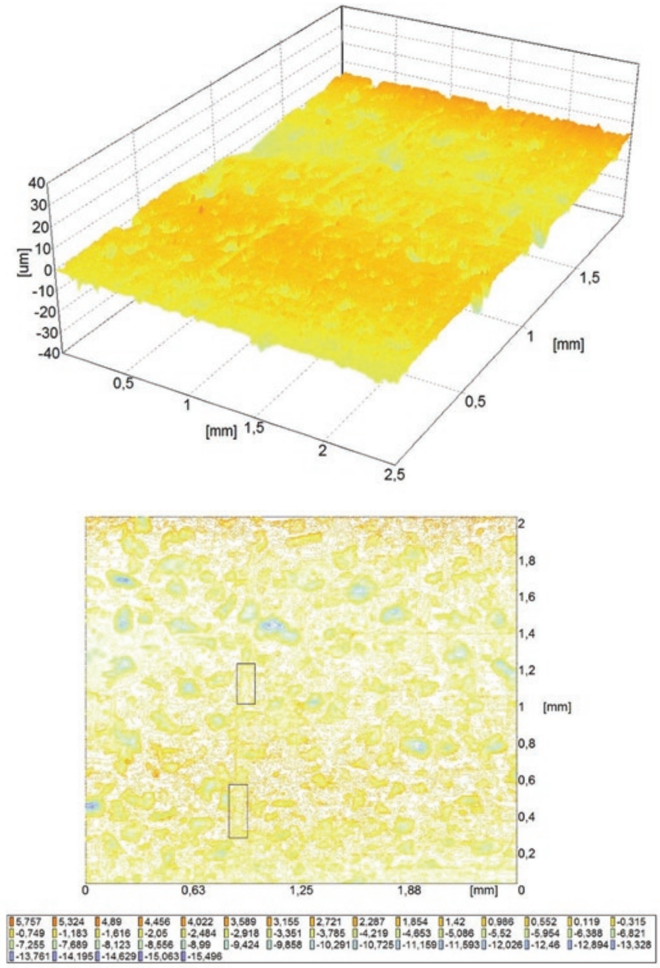


Fig. 7. Results of the testing of top layer topography at the place of fretting wear

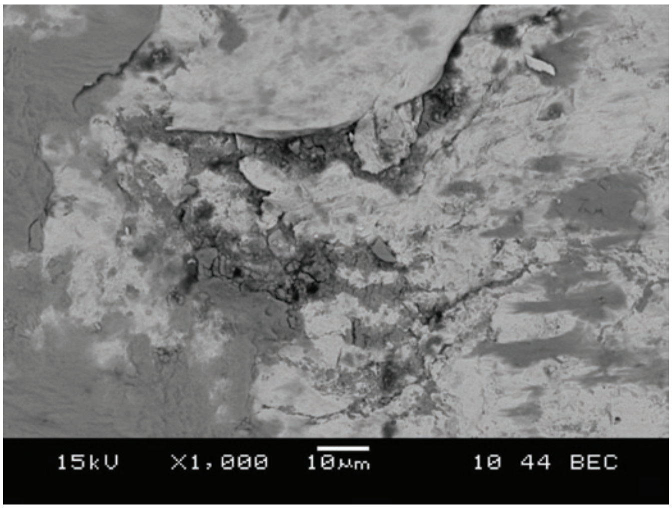


Fig. 8. Image of the shaft surface in the fretting wear zone as seen under a scanning microscope

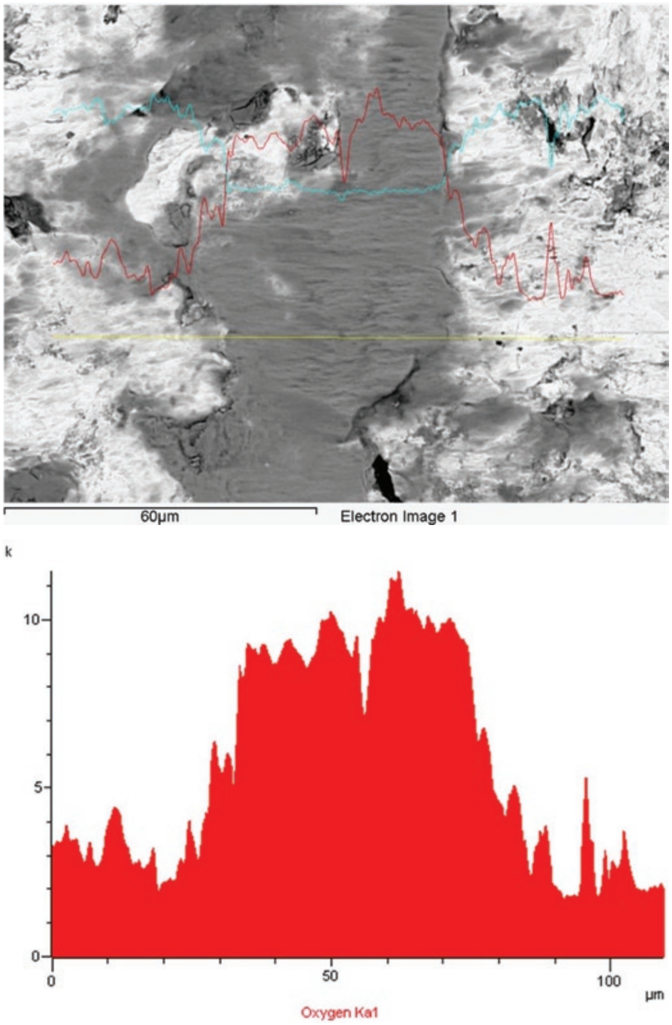


Fig. 9. Results of x-ray examinations of the chemical composition conducted by means of the EDS method at the shaft surface in the fretting wear zone

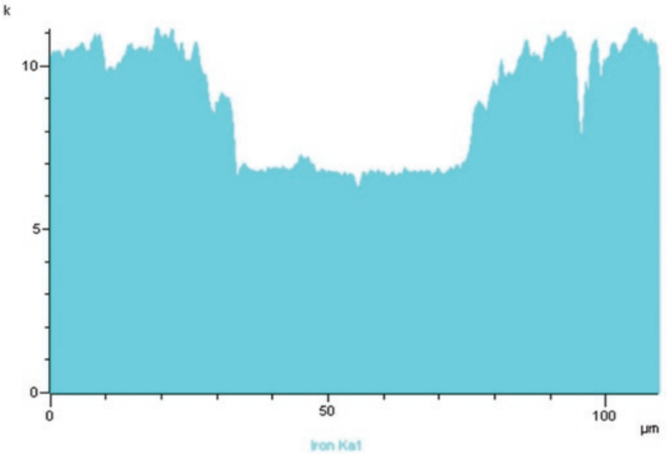


Fig. 9. (continued) Results of x-ray examinations of the chemical composition conducted by means of the EDS method at the shaft surface in the fretting wear zone

The increase of roughness parameters is mainly related to material build-up. That build-up is the wear products which came into being during the process of forcing the sleeve onto the shaft, when the microprojections of the top layer of the elements with a smaller hardness gradient were being torn off and moved continuously until the completion of the forcing process. The source of wear products and formation of the build-up is adhesion.

In fig. 8, the sample image of the shaft surface at the place of fretting wear is shown as seen under a scanning microscope. In that image, widespread damage in the form of material build-up as well as micropits and microcracks of the top layer can be observed.

During operation, as a result of oscillatory tangential displacement of the mating surfaces, the build-up undergoes plastic deformation and then oxidation thus creating an image which is typical of iron corrosion. In fig. 6, that is visible in the form of a brown ring at the place of fretting wear. The oxidation of the deformed build-up takes place as a result of oxygen penetration into worn-out places through fissures which came into being as a result of shaft deflection. To confirm the above statement, the analysis of oxygen and iron concentration in the area affected by wear was conducted. X-ray examinations of the chemical composition were carried out by means of the EDS method, and the results of those examinations are presented in figure 9.

4.2. The shaft with a TiN coating

The macrographic observations of the coated shaft surface demonstrated the occurrence of fretting wear in the form of a ring comprising the entire circumference of the axle seat on either side. Wear intensity is considerably smaller in relation to the shaft without a coating. Fretting wear is also observed at the surface of the sleeve hub on its both edges, and wear intensity is definitely greater in relation to the shaft with a TiN coating (fig. 10).

Fretting wear is distinguished by different intensity at each side of the axle seat. The width of the area affected by wear is approx. 1 mm at the left side and that area starts approx. 4 mm from the axle seat edge. On the right side, the width of the wear area is approx. 2-3 mm and that area starts approx. 5-6 mm from the joint edge.

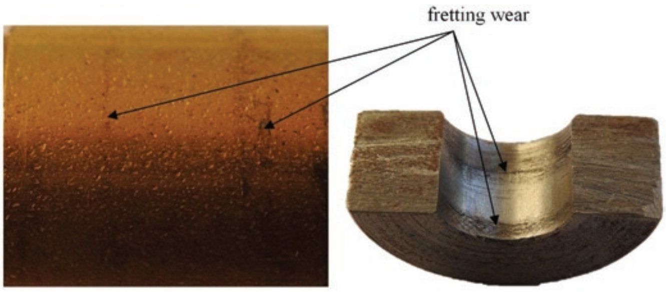


Fig. 10. Fretting wear at the surface of the shaft with a TiN coating and at the sleeve hub

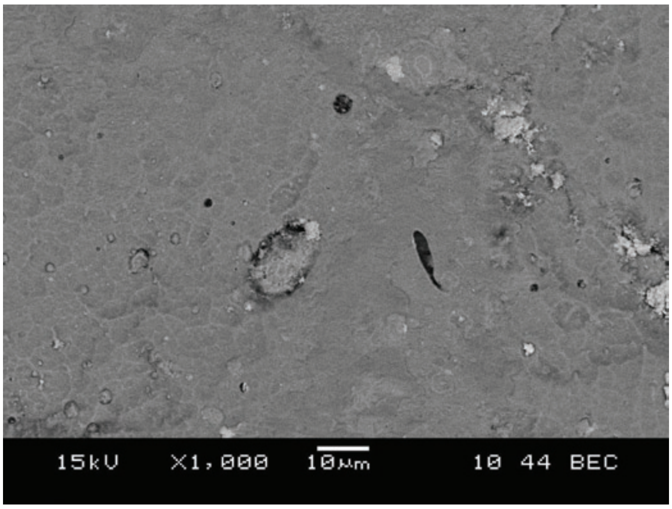


Fig. 11. Fretting wear traces at the surface of the shaft with a TiN coating

In the case of the sleeve hub, the start of fretting wear is observed as early as next to the edges and the wear area is considerable. The width of the „strip" varies from 3 to 4 mm on either side.

As was the case with a clamped joint with an uncoated shaft, here the main kind of wear also comprised by fretting is, too, material build-up which originates from the shearing of the microprojections

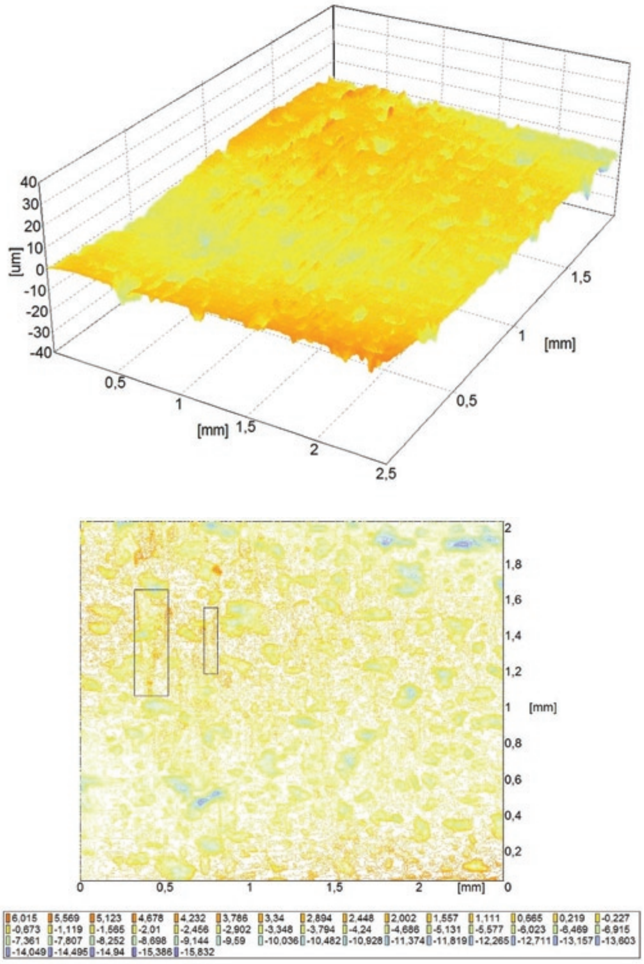


Fig. 12. Results of the testing of top layer topography at the place of fretting wear

of the sleeve hub surface (fig. 11). That build-up undergoes plastic deformation and oxidation during operation. A big difference in the shaft surface hardness gradient in relation to the sleeve surface causes mainly the sleeve to become damaged.

The testing of roughness parameters at a place distinguished by a greater intensity of fretting wear did not show significant differences in relation to the state before wear tests. This follows from the small height of damage which mainly coincides with the microirregularities at the axle seat surface. A sample result of the measurement of roughness parameters at the place of fretting wear is presented in fig. 12.

4.3. The shaft with a CrN+a-C:H:W coating

The macrographic examinations of the top layer of the shafts demonstrated the occurrence of fretting wear to a small extent. In the case of the sleeve hub top surface, fretting wear is also observed in places. As in previous cases, damage occurs close to joint edges (fig. 13). Damaged areas are distributed randomly at the circumference of the shaft axle seat.

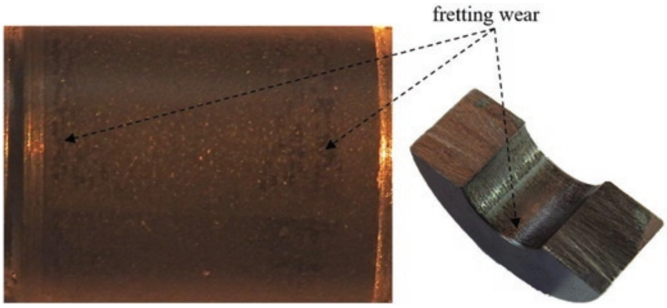


Fig. 13. Fretting wear at the surface of the shaft with a CrN+a-C:H:W coating and at the sleeve hub

The area of the biggest noted traces of fretting wear is approx. 2-2.5 mm^2. Fretting wear zones are distinguished by their brown colour.

Wear occurs mainly in the form of wear product build-up, a fact confirmed by the images from the scanning microscope. A sample image of the shaft top layer in the fretting wear zone is shown in fig. 14.

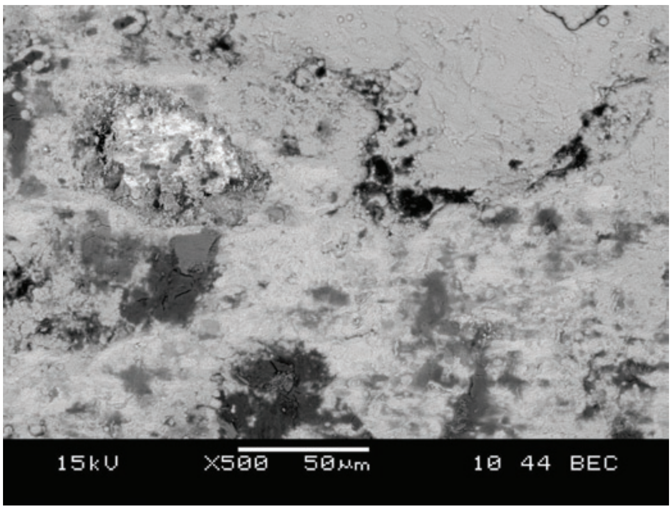


Fig. 14. Fretting wear traces at the surface of the shaft with a CrN+a-C:H:W coating

The access of oxygen to the damaged zones causes wear products to oxidise. This is confirmed by chemical element distribution maps for the shaft surface in the fretting wear zone as shown in fig. 15.

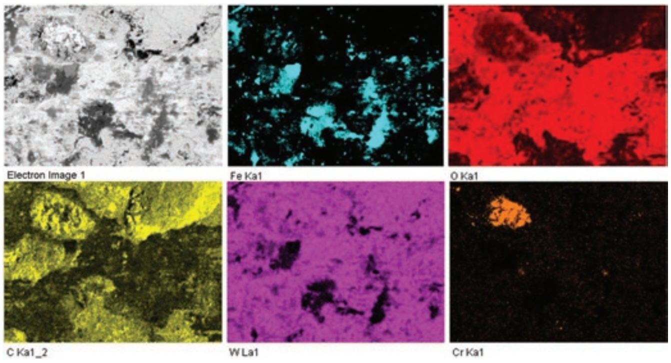


Fig. 15. Chemical element distribution maps for the shaft surface in the fretting wear zone

Oxygen occurs in 90% of the surface being tested thus forming oxides with other chemical elements.

5. Conclusion

The aim of this article was to present the results of research on the mitigation of the development of fretting wear in clamped joints. It follows from the review of literature that the mitigation of wear in that kind of joints is connected with the elimination of adhesion. This is possible in the case of matching the elements distinguished by the appropriate geometry and hardness of the top layer.

Shafts without PVD coatings and shafts with TiN and CrN+a-C:H:W coatings were subjected to wear tests. Coatings were applied to shaft surfaces because in a real joint between the wheel and axle of a rail vehicle wheel set it is the axle which is the element determining the life of the entire wheel set.

The results of the tests of the uncoated shaft surfaces demonstrate the intensive image of fretting wear, which confirms the susceptibility of the joint to the creation of adhesive bonds. Fretting wear occurs at the entire shaft circumference in the form of a ring 2-3 mm wide on either side of the axle seat. The area affected by wear starts approx. 3 mm from the joint edge.

In the case of shafts with a TiN coating, the smaller wear intensity is observed, however, also in the form of a ring, 1 mm wide for the left side and 2-3 mm on the right side of the axle seat. The different geometry and hardness of the shaft and sleeve causes the occurrence of fewer places prone to the creation of adhesive bonds.

Out of the proposed coatings, CrN+a-C:H:W ones have the greatest influence on the mitigation of the development of fretting wear. Despite smaller hardness and roughness in relation to TiN coatings, wear on shafts covered with the former coating is less intensive. In that case, wear occurs in places and each time occupies the area of 2-2.5 mm^2. This may be due to the chemical composition of the coating. Good anti-wear properties of hydrogenated amorphous carbon are completed by tungsten. Hence, that coating is distinguished by the small coefficient of friction of the steel surfaces thus reducing damage to those.

Microscopic examinations demonstrated that fretting comprises mainly material build-up from the shearing of microprojections of the sleeve top surface, which build-up sticks to the shaft surfaces. In relation to the top layers of shafts with coatings, the sleeve top layer has the smallest hardness, therefore that layer will be more susceptible to damage. Research also demonstrated that, during operation, the build-up undergoes plastic deformation as a result of the occurrence of oscillatory tangential displacement of the mating surfaces and oxidation as a result of contact with atmospheric air. The quantitative examinations of the chemical composition of the wear products demonstrated 40% concentration of oxygen and 50% concentration of iron. The remaining 10% of the chemical composition is constituted by the elements comprised by the top layer of the shafts. Moreover, micropits and microcracks, particularly visible at uncoated shafts, are observed in wear zones.

In this article, the results of research on fretting wear based on the example of rail vehicle wheel sets have been presented, but those results may also be referred to other examples of clamped joints operating in rotational bending conditions.

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References

1. Astrid Gies, Thomas Chudoba, Norbert Schwarzer, Jürgen Becker. Influence of the coating structure of a-C:H:W coatings on their wear-performance: A theoretical approach and its practical confirmation. Surface and Coatings Technology 2013; 237: 299-304, https://doi.org/10.1016/j.surfcoat.2013.07.065.
2. Bahri A, Kaçar E, Akkaya S S, Elleuch K, Ürgen M. Wear protection potential of TiN coatings for 304 stainless steels used in rotating parts during olive oil extraction. Surface and Coatings Technology 2016; 304: 560-566, https://doi.org/10.1016/j.surfcoat.2016.07.067.
3. Bose Sivakumar, Lokesh Chandra Pathak, Raghuvir Singh. Role of surface roughness on corrosion and fretting corrosion behaviour of commercially pure titanium in Ringer's solution for bio-implant application. Applied Surface Science 2017; 401: 385-398, https://doi.org/10.1016/j.apsusc.2017.01.033.
4. Dong-Wook Kim, Kyung-Woong Kim. Tribological characteristics of Cr/CrN/a-C:H:W/a-C:H coating under boundary lubrication conditions with glycerol mono-oleate (GMO) and molybdenum dithiocarbamate (MoDTC). Wear 2015; 342-343: 107-116.
5. Guzowski S. Analiza zużycia frettingowego w połączeniach wciskowych na przykładzie osi zestawów kołowych pojazdów szynowych. Wydawnictwo Politechniki Krakowskiej, Kraków, 2003.
6. Guzowski S. Warunki rozwoju zużycia frettingowego w połączeniu koło-oś zestawu kołowego. Zeszyty Naukowe Politechniki Śląskiej, Transport 1995; 27: 111-118.
7. Karwala K, Kulikowski H, Tułecki A. Technologiczne problemy trwałości zestawów kołowych pod kątem przystosowania pojazdów szynowych do zwiększonych prędkości. Rozprawa doktorska, Kraków, 1991.
8. Kesavan D, Vamshidhar Done, Sridhar M R, Ronald Billig, Daniel Nelias. High temperature fretting wear prediction of exhaust valve material. Tribology International 2016; 100: 280-286, https://doi.org/10.1016/j.triboint.2016.02.011.
9. Kowalski S, Guzowski S. Wpływ procesów technologicznych na zużycie frettingowe w połączeniu wciskowym. Tribologia 2010; 3: 85-94.
10. Lenart A, Pawlus P, Dzierwa A, Sęp J, Dudek K. The effect of surface topography on dry fretting in the gross slip regime. Archives of Civil and Mechanical Engineering 2017; 17 (4): 894-904, https://doi.org/10.1016/j.acme.2017.03.008.
11. Madej M. The effect of TiN and CrN interlayers on the tribological behavior of DLC coatings. Wear; 2014; Volume 317, Issues 1-2: 179-187 https://doi.org/10.1016/j.wear.2014.05.008
12. Matteo Benedetti, Vigilio Fontanari, Elisa Torresani, Christian Girardi, Lorenzo Giordanino. Investigation of lubricated rolling sliding behaviour of WC/C, WC/C-CrN, DLC based coatings and plasma nitriding of steel for possible use in worm gearing. Wear 2017; 378-379: 106-113, https://doi.org/10.1016/j.wear.2017.02.029.
13. Mi X, Cai Z B, Xiong X M, Qian H, Tang L C, Xie Y C, Peng J F, Min-Hao Zhu. Investigation on fretting wear behavior of 690 alloy in water under various temperatures. Tribology International 2016; 100: 400-409, https://doi.org/10.1016/j.triboint.2016.05.012.
14. Michnej M. Proces zużycia w połączeniu obrotowym na przykładzie modelu zestawu kołowego z samoczynną zmianą rozstawu kół. Praca doktorska 2012; Kraków.
15. Pereira K, Yue T, Abdel Wahab M. Multiscale analysis of the effect of roughness on fretting wear. Tribology International 2017; 110: 222-231, https://doi.org/10.1016/j.triboint.2017.02.024.
16. Richert M, Zawadzka P, Mazurkiewicz A, Smolik J, Leszczyńska-Madej B, Nejman I, Pałka P, Pietrzyk S. Deposition of W/a-C:H:Zr and W/a-C:H:W multilayer coatings on substrate made of porous graphite by arc - Electron beam hybrid method. Surface and Coatings Technology 2016; 300: 19-24, https://doi.org/10.1016/j.surfcoat.2016.05.035.
17. 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 & Fracture of Engineering Materials & Structures 2014; 37: 72-84, https://doi.org/10.1111/ffe.12085.
18. Stefan Nißen, Jan Heeg, Mareike Warkentin, Detlef Behrend, Marion Wienecke. The effect of deposition parameters on structure, mechanical and adhesion properties of a-C:H on Ti6Al4V with gradient Ti-a-C:H:Ti interlayer. Surface and Coatings Technology 2017; 316: 180-189, https://doi.org/10.1016/j.surfcoat.2017.03.020.
19. 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 2010; 43 (5-6): 906-911, https://doi.org/10.1016/j.triboint.2009.12.031.

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